

Article

A Coupled Load–Damage–Diffusion Model for Sulfate Transport in Concrete Under Static and Fatigue Loading with Drying–Wetting Cycles

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Abstract

External sulfate attack constitutes a major durability challenge for structural concrete, yet the influence of mechanical loads on sulfate transport remains incompletely understood. This study develops a coupled sulfate–water transport model that embeds the effects of axial static loads and fatigue loads into the effective sulfate diffusion coefficient through physically motivated correction factors, without explicitly resolving chemical reactions or physical crystallization. Numerical simulations were performed for coupled scenarios of static loading, fatigue loading, and drying–wetting cycles. Three principal findings emerge. First, drying–wetting cycles produce a stable convection enrichment peak at 1 to 3 mm from the exposed surface, rather than a monotonic decay profile. Second, axial static loads exhibit pronounced tension–compression asymmetry: tensile stress enhances sulfate transport, while compressive stress exerts a comparatively weak inhibition effect. Third, fatigue loading introduces time-dependent accumulation and nonlinear acceleration driven by the dynamic evolution of microcrack connectivity. The tensile zone consistently exhibits markedly higher sulfate enrichment and deeper penetration than the compressive zone, identifying it as the dominant region for coupled deterioration. These findings provide a quantitative foundation for durability assessment of concrete structures under complex loading environments.

Keywords: sulfate attack; drying–wetting cycles; axial static loading; fatigue damage; tension–compression asymmetry



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1. Introduction

Concrete is the most widely used construction material in bridges, hydraulic structures, pavements, and marine infrastructure [1–3]. In sulfate-bearing environments such as saline soils, coastal groundwater, and industrial effluents, however, concrete structures become susceptible to external sulfate attack (ESA), a progressive deterioration process that compromises strength, stiffness, and long-term durability [4–6]. The underlying mechanisms are multifaceted. Sulfate ions migrate into the pore network and react with hydration products to form expansive phases such as ettringite and gypsum; under cyclic moisture conditions, salt crystallization may further induce physical damage [7–10]. Because ESA couples ionic transport, chemical reaction, phase transformation, and mechanical degradation within a

single deteriorating system, it remains among the most actively researched yet incompletely resolved problems in concrete durability science [11,12].

In field conditions, ESA rarely occurs in isolation. Concrete bridge decks, pavements, and hydraulic structures are simultaneously subjected to external sulfate exposure, cyclic wetting–drying driven by water level fluctuation or tidal action, sustained static loads from self-weight and traffic, and repeated fatigue loads from vehicle passages and wave impacts [13–18]. Under such multi-factor coupling, sulfate ingress is no longer governed solely by a concentration gradient [19,20]. Moisture convection induced by cyclic wetting and drying, capillary suction, saturation-dependent pore connectivity, and load-induced microcrack evolution all modulate the effective transport capacity [21,22]. A predictive understanding of sulfate transport under the combined action of environmental cycling and mechanical loading is therefore essential for the service-life assessment of concrete infrastructure.

Over the past two decades, numerical models for ESA have advanced substantially. Early approaches relied on empirical relationships or simplified Fickian diffusion formulations [23]. More recent frameworks achieve chemo-transport–mechanical (CTM) coupling, simultaneously resolving multi-ion diffusion, chemical equilibria, phase precipitation, crystallization pressure, and mechanical damage [24–28]. While theoretically comprehensive, these models require extensive chemical–kinetic, thermodynamic, and mechanical parameters, many of which cannot be directly measured or independently calibrated from standard experimental data [29]. As Ikumi and Segura noted in their review of ESA numerical models, the appropriate level of model complexity depends on the specific output objectives [12]. For investigations centered on apparent sulfate concentration distributions and the transport-amplifying effect of mechanical loads, rather than on the exact quantities of individual reaction products, the parameter burden of full CTM models becomes a practical obstacle. A simplified yet physically grounded apparent transport model, with clearly defined boundaries and a tractable parameter set, is better suited to this purpose.

Experimental studies have established key phenomenological insights that any serviceable model must capture [30,31]. Dry–wet cycling generates alternating moisture gradients that drive concurrent diffusion and convection, producing characteristic sulfate enrichment peaks at depths of approximately 1 to 3 mm from the exposed surface; such peaks cannot be reproduced by monotonic diffusion profiles. Gao et al. [32] conducted sustained flexural loading experiments and revealed pronounced tension–compression asymmetry: the tensile zone exhibited substantially higher sulfate concentrations and penetration depths than the compressive zone, a difference attributable to load-induced microcrack opening in tension and crack closure in compression. Liu et al. [33] further demonstrated through fatigue tests that cyclic loading induces cumulative microcrack damage, progressively amplifying the effective diffusion coefficient over successive loading cycles. Despite these advances, three gaps persist in the modeling literature. First, existing simplified models typically treat load effects through a single uniform amplification factor, disregarding the fundamental mechanical distinction between tension-driven crack opening and compression-driven crack closure. Second, fatigue-induced cumulative damage has rarely been integrated with static load effects and moisture transport within a unified computational framework. Third, no existing apparent transport model enables simultaneous comparison of sulfate transport behavior in tensile and compressive zones under the combined action of static load, fatigue load, and drying–wetting cycles.

To address these gaps, this paper develops a coupled load–damage–diffusion apparent transport model for sulfate ions in concrete. The model does not explicitly resolve the chemical reactions that form ettringite and gypsum, nor does it treat salt crystallization; instead, it embeds mechanical load effects into the effective diffusion coefficient through

two physically motivated correction factors. The first is an axial static load pore-structure modification coefficient, derived from an equivalent hollow-sphere representation of the concrete mesostructure. The second is a fatigue crack-channel amplification coefficient, formulated within a matrix–crack dual-pathway transport framework. Dry–wet cycling is incorporated via a saturation-dependent moisture transport equation, whose gradient contributes a convective term to the sulfate flux. The model is implemented in MATLAB (R2023b) and parameterized against published experimental data from sustained flexural loading tests and fatigue loading tests. Numerical simulations are then performed for three progressively coupled scenarios: axial static load with drying–wetting cycles; axial static load with fatigue load and drying–wetting cycles; and a sensitivity analysis that decomposes the relative contributions of diffusion, convection, static load level, and fatigue load level to sulfate ingress. By quantitatively distinguishing sulfate transport behavior between tensile and compressive zones under arbitrary combinations of static load, fatigue load, and moisture cycling, the proposed framework provides a computationally efficient tool for durability assessment of concrete structures operating in complex service environments.

2. Model Establishment

2.1. Basic Assumptions and Variable Definitions

The model adopts the following fundamental assumptions:

- (1) Sulfate transport in concrete along the direction normal to the exposed surface is simplified as a one-dimensional problem, where x denotes the transport direction and t denotes the exposure time.
- (2) Concrete is treated as a homogeneous, isotropic porous medium. The spatial heterogeneity arising from coarse aggregates, mortar interfacial transition zones, and local crack distributions is not explicitly considered.
- (3) Sulfate chemical reactions and physical crystallization are not explicitly resolved. Variables associated with gypsum, ettringite, sodium sulfate crystals, crystallization pressure, and expansion strain are therefore not introduced.
- (4) Axial static loads and fatigue loads are not imposed as direct boundary conditions. Their effects are instead embedded in the effective sulfate diffusion coefficient through pore structure modification and crack channel correction factors.

The primary model variables are defined as follows. The term $s(x, t)$ denotes the pore saturation of concrete; $c(x, t)$ denotes the sulfate concentration in the pore solution; $C(x, t)$ denotes the apparent sulfate content obtained from layered powder tests or numerical output; and $D_{eff}^r(x, t)$ denotes the effective diffusion coefficient incorporating load-induced damage. The superscript $r = T$ designates the tensile zone and $r = C$ designates the compressive zone.

2.2. Moisture Transport Under Drying–Wetting Cycles

Drying–wetting cycles induce periodic variations in pore saturation, which in turn drive moisture migration and sulfate convection. Adopting pore saturation s as the state variable, the moisture transport equation is expressed as a nonlinear diffusion equation [34,35]:

$$\frac{\partial s}{\partial t} = \nabla \cdot [D_H(s) \nabla s] \quad (1)$$

where $D_H(s)$ is the saturation-dependent moisture transport coefficient. To account for the distinct transport capacities during wetting and drying phases, $D_H(s)$ is formulated as:

$$D_H(s) = \begin{cases} D_{w0} \exp(ns) & (\text{wetting phase}) \\ D_d & (\text{drying phase}) \end{cases} \quad (2)$$

where D_{w0} is the reference moisture transport coefficient during wetting, D_d is the moisture transport coefficient during drying, and n is an empirical exponent.

The pore liquid velocity induced by the saturation gradient is:

$$v = -D_H(s)\nabla s \quad (3)$$

This expression indicates that the saturation gradient generated by wetting–drying cycles constitutes the source of the convective transport in the model.

2.3. Sulfate Diffusion-Convection Transport

In the absence of chemical reactions and physical crystallization, the mass conservation equation for sulfate is given by:

$$\frac{\partial(\phi sc)}{\partial t} = -\nabla \cdot J_s^r \quad (4)$$

where ϕ is the concrete porosity; J_s^r denotes the total sulfate flux in the loaded region r . Under drying–wetting cycles, sulfate transport is governed by the combined action of concentration-gradient-driven diffusion and moisture-gradient-driven convection. The total sulfate flux in region r is expressed as:

$$J_s^r = -\phi s D_{eff}^r \nabla c + \phi s c v \quad (5)$$

The first term represents Fickian diffusion modified by the effective diffusion coefficient, and the second term represents convective transport by the pore liquid. Substituting Equations (3) and (5) into Equation (4) yields the governing equation for sulfate diffusion-convection transport:

$$\frac{\partial(\phi sc)}{\partial t} = \nabla \cdot [\phi s D_{eff}^r \nabla c + \phi s c D_H(s) \nabla s] \quad (6)$$

2.4. Effective Diffusion Coefficient

Mechanical loads alter the internal pore structure, microcrack state, and transport pathway connectivity of concrete, thereby modifying its sulfate transport capacity. In this study, the influence of load-induced damage is equivalently embedded in the effective diffusion coefficient. Accounting for the combined effects of pore tortuosity, saturation, axial static load pore-structure modification, and fatigue crack-channel amplification, the effective diffusion coefficient is defined as:

$$D_{eff}^r = D_0 H_\tau H_w(s) H_L^r H_F^r \quad (7)$$

where D_0 is the reference sulfate diffusion coefficient, H_τ is the pore tortuosity influence coefficient, $H_w(s)$ is the saturation influence coefficient, H_L^r is the axial static load pore structure correction factor for region r , and H_F^r is the fatigue crack channel correction factor for region r .

The tortuosity correction factor is expressed as:

$$H_\tau = 0.001 + 0.07\phi_0^2 + 1.8(\phi_0 - 0.18)^2 H(\phi_0 - 0.18) \quad (8)$$

where ϕ_0 is the initial porosity, and $H(\cdot)$ is the Heaviside function. The initial porosity can be estimated using the Powers model:

$$\phi_0 = \max \left[\frac{w/c - 0.36\alpha}{w/c + 0.32}, 0 \right] \quad (9)$$

$$\alpha = 0.239 + 0.745 \tanh[3.62(w/c - 0.095)] \quad (10)$$

The saturation influence coefficient is expressed using a sigmoid function:

$$H_w(s) = \left[1 + \left(\frac{1-s}{1-0.75} \right)^4 \right]^{-1} \quad (11)$$

This expression captures the following physically expected behavior: a higher pore saturation enhances pore fluid continuity and thus strengthens sulfate migration capacity, whereas a decrease in saturation reduces the continuity of ionic transport pathways and correspondingly diminishes the effective diffusion capacity.

2.4.1. Axial Static Load Correction

Axial static loads alter the internal pore structure, initial defect state, and aggregate-paste interface regions of concrete, thereby modifying the effective sulfate transport capacity. In this study, axial static loads are not imposed as direct boundary conditions; their effects are instead embedded in the effective diffusion coefficient through a pore-structure modification coefficient. To describe this influence in physically interpretable terms, a representative volume element of concrete is idealized as an equivalent hollow sphere following the equivalent porous medium concept. The internal cavity of the hollow sphere represents the concrete pores, while the outer solid shell represents the equivalent matrix composed of hardened cement paste, aggregates, and interfacial transition zones. Changes in the load-induced volumetric strain alter the pore volume fraction, which in turn modifies the transport pathways available for sulfate ions.

Under axial static loading, the equivalent volumetric strain in loaded region r is denoted by $\varepsilon_{v,L}^r$. If the axial static load deformation is characterized by the equivalent linear strain $\varepsilon_{l,L}^r$, the relationship between the volumetric and linear strains is given by:

$$\varepsilon_{v,L}^r = (1 - 2\mu)\varepsilon_{l,L}^r \quad (12)$$

where μ is the Poisson ratio. This study adopts a signed strain convention in which tensile strain is taken as positive and compressive strain as negative.

Based on the equivalent hollow sphere model, the porosity influence coefficient under axial static loading is expressed as:

$$H_s^r = \frac{1}{1 - \varepsilon_{v,L}^r} \left[1 - \frac{(4G_m + 3K_m)(1 - \sqrt[3]{1 - \varepsilon_{l,L}^r})}{4G_m + 3K_m\phi_0} \right]^3 \quad (13)$$

where K_m and G_m are the bulk modulus and shear modulus of the equivalent solid matrix, respectively. Equation (13) quantifies the effect of load-induced volumetric deformation on porosity. Accordingly, the porosity after the application of axial static loading can be written as:

$$\phi_L^r = \phi_0 H_s^r \quad (14)$$

Since the sulfate diffusion capacity depends strongly on porosity, a porosity-diffusion influence function is introduced to relate these two quantities:

$$H_p(\phi_L^r) = \alpha_p + (1 - \alpha_p) \frac{\exp(-\beta_p)(\phi_L^r/\phi_0)}{1 + [\exp(-\beta_p) - 1](\phi_L^r/\phi_0)} \quad (15)$$

where α_p is the ratio of the minimum diffusion coefficient to the initial diffusion coefficient, and β_p is a pore shape parameter.

To ensure that the modification coefficient reduces to unity in the absence of axial static loading, the axial static load diffusion modification coefficient is defined as the normalized ratio of the post-loading to the pre-loading porosity-diffusion function:

$$H_L^r = \frac{H_p(\phi_L^r)}{H_p(\phi_0)} \quad (16)$$

where H_L^r is the axial static load diffusion modification coefficient for loaded region r . When $H_L^r > 1$, the axial static load enhances the sulfate transport capacity; when $H_L^r < 1$, it suppresses the transport capacity; and when $H_L^r = 1$, the load exerts no appreciable influence on sulfate transport.

2.4.2. Fatigue Load Correction

Under fatigue loading, microcracks within concrete progressively initiate, propagate, and interconnect through repeated loading-unloading cycles. During the loading phase, cracks open and sulfate ions more readily penetrate into the concrete interior along the crack channels. During the unloading phase, the cracks may partially close; however, the irreversible damage and the incremental crack area accumulated up to that point continue to affect subsequent sulfate transport. To describe this process, this study adopts the matrix–crack dual-pathway transport assumption and partitions the total sulfate flux into a matrix transport contribution and a crack transport contribution.

Let A_m denote the matrix transport area, A_c the crack transport area, J_m the sulfate flux through the matrix, and J_c the sulfate flux through the cracks. The total flux can then be written as:

$$J = \frac{J_m A_m + J_c A_c}{A_m + A_c} \quad (17)$$

Correspondingly, the equivalent diffusion coefficient is expressed as:

$$D = \frac{D_m A_m + D_c A_c}{A_m + A_c} \quad (18)$$

where D_m is the matrix diffusion coefficient and D_c is the crack channel diffusion coefficient.

For ordinary concrete, the matrix area is typically far larger than the crack area. Therefore, Equation (18) can therefore be approximated as:

$$D \approx D_m + D_c \frac{A_c}{A_m} \quad (19)$$

Fatigue loading causes the crack area to increase progressively. Let A_{c0}^r denote the initial crack area in loaded region r and A_{cd}^r the crack area after fatigue damage. The incremental crack area is then:

$$\Delta A_c^r = A_{cd}^r - A_{c0}^r \quad (20)$$

The cracks are idealized as rectangular. Let ω_{l0} , ω_{b0} , and N_c denote the initial crack length, initial crack width, and number of cracks, respectively. The initial crack area is given by:

$$A_{c0}^r = N_c \omega_{l0} \omega_{b0} \quad (21)$$

Introducing the fatigue damage variable d_f^r , the crack area after fatigue damage becomes:

$$A_{cd}^r = \frac{A_{c0}^r}{(1 - d_f^r)^2} \quad (22)$$

The incremental crack area is:

$$\Delta A_c^r = A_{c0}^r \left[\frac{1}{(1 - d_f^r)^2} - 1 \right] \quad (23)$$

Defining the initial crack density parameter as:

$$C_{d0}^r = \frac{A_{c0}^r}{A_m} \quad (24)$$

the fatigue diffusion modification coefficient can be written as:

$$H_F^r = 1 + \frac{D_c}{D_m} C_{d0}^r \left[\frac{1}{(1 - d_f^r)^2} - 1 \right] \quad (25)$$

where H_F^r is the fatigue diffusion modification coefficient for loaded region r , D_c/D_m is the ratio of the crack channel diffusion coefficient to the matrix diffusion coefficient, and C_{d0}^r is the initial crack density parameter.

The fatigue damage variable is determined from the relationship between the cumulative number of loading cycles $N(t)$ and the fatigue life N_f^r . The fatigue life is obtained from the S-N relationship:

$$N_f^r = 10^{(a_r - S_r)/b_r} \quad (26)$$

where S_r is the maximum fatigue stress level or equivalent fatigue load level for loaded region r , and a_r and b_r are fatigue life parameters.

The fatigue damage variable is defined as:

$$d_f^r(t) = \min \left[\frac{N(t)}{N_f^r}, d_{\max} \right] \quad (27)$$

where $d_{\max}$ is the upper bound of the fatigue damage variable, introduced to prevent numerical divergence of the diffusion modification coefficient as the fatigue damage approaches unity.

2.5. Apparent Sulfate Content

Since chemical reactions and physical crystallization are not explicitly resolved in this study, no distinction is made between free sulfate, bound sulfate, and sulfate contained in gypsum or ettringite. The sulfate content measured experimentally is instead treated as the apparent sulfate content. In principle, the apparent sulfate content can be derived from the pore solution concentration as:

$$C(x, t) = C_0 + K_c \phi_{sc}(x, t) \quad (28)$$

where $C(x, t)$ is the apparent sulfate content at depth x and exposure time t , C_0 is the initial background sulfate content of the concrete, and K_c is the conversion factor from pore solution concentration to mass fraction of concrete.

In the numerical implementation, to facilitate direct comparison with layered powder test results, the apparent sulfate content is expressed using an approximate form of the one-dimensional semi-infinite medium diffusion solution:

$$C(x, t) = C_0 + A_{eff}^r F(x, t, D_{eff}^r) R(x) \quad (29)$$

with:

$$F(x, t, D_{eff}^r) = \operatorname{erfc}\left(\frac{x}{2\sqrt{D_{eff}^r t}}\right) \quad (30)$$

$$R(x) = 1 - R_s \exp\left(-\frac{x}{x_{loss}}\right) \quad (31)$$

where A_{eff}^r is the apparent content amplitude coefficient incorporating load effects, $R(x)$ is the near-surface correction function, R_s is the surface correction coefficient, and x_{loss} is the characteristic depth of the surface correction.

Under fatigue loading, the apparent content amplitude coefficient can be further expressed as:

$$A_{eff}^r = A_r[1 + \eta_{A,r}(H_F^r - 1)] \quad (32)$$

where A_r is the reference apparent content amplitude and $\eta_{A,r}$ is the correction coefficient accounting for the effect of fatigue on the apparent content amplitude.

2.6. Initial and Boundary Conditions

The one-dimensional computational domain extends from the exposed surface ($x = 0$) to an interior boundary ($x = L$) sufficiently distant from the exposed surface to be unaffected by sulfate ingress within the simulation timeframe.

At the initial time, the pore saturation and sulfate concentration within the concrete are assumed to be uniformly distributed, and the initial conditions are given by:

$$s(x, 0) = s_0, c(x, 0) = c_0, C(x, 0) = C_0 \quad (33)$$

During the wetting phase, the exposed concrete surface is in direct contact with the external sulfate solution. The boundary conditions at the exposed surface are specified as:

$$s(0, t) = s_w, c(0, t) = c_{ext} \quad (34)$$

where s_w is the surface saturation during the wetting phase, which can generally be approximated as the fully saturated state, and c_{ext} is the sulfate concentration of the external solution.

During the drying phase, the exposed surface exchanges moisture with the surrounding environment. The moisture boundary condition at the exposed surface can be written as:

$$-D_H(s) \frac{\partial s}{\partial x} = h_s(s - s_a) \quad (35)$$

where h_s is the surface moisture exchange coefficient and s_a is the equilibrium saturation corresponding to the ambient relative humidity.

Since this study does not consider continued sulfate ingress during the drying phase, nor the surface salt efflorescence, crystal deposition, or the associated mass loss, a zero-flux boundary condition is imposed for sulfate at the exposed surface during the drying phase:

$$-\phi s D_{eff}^r \frac{\partial c}{\partial x} - \phi s c D_H(s) \frac{\partial s}{\partial x} = 0 \quad (36)$$

For the non-exposed surface, it is assumed that this boundary does not directly exchange sulfate or moisture with the external environment. Zero-flux boundary conditions are therefore adopted:

$$\frac{\partial s}{\partial x} = 0, \frac{\partial c}{\partial x} = 0 \quad (x = L) \quad (37)$$

Sulfate ingress is controlled by the external concentration boundary during the wetting phase, while the moisture exchange boundary during the drying phase establishes a saturation gradient that drives convective transport. The non-exposed surface is treated with zero-flux boundary conditions throughout. Axial static loads and fatigue loads are not imposed as direct boundary conditions; their effects are instead incorporated into the effective diffusion coefficient D_{eff}^* through the modification coefficients H_L^* and H_F^* , thereby influencing the sulfate diffusion-convection transport process.

3. Numerical Implementation

The coupled load–damage–diffusion apparent transport model developed in this study is numerically implemented in MATLAB. The verification strategy and case configuration draw on the work of Zhang et al., who employed a one-dimensional model to validate sulfate transport under drying–wetting cycles, axial static loading, and fatigue loading within their hydro-chemo-mechanical coupled framework. In contrast to full coupling models that explicitly resolve chemical reactions, physical crystallization, crystallization pressure, and expansion strain, the present model does not simulate the formation of gypsum, ettringite, or sodium sulfate crystals, nor their associated expansion-induced damage. It instead focuses on the apparent sulfate transport behavior under drying–wetting cycles and on the modification of the effective diffusion coefficient induced by axial static loads and fatigue loads.

In the numerical implementation, the concrete domain is simplified to a one-dimensional computational region along the direction normal to the exposed surface, with the erosion depth x and exposure time t serving as the primary independent variables. A MATLAB program is developed to simulate the spatiotemporal variation in sulfate content under various loading scenarios. Within the theoretical framework, sulfate migration is governed jointly by a diffusion term and a convection term driven by moisture migration.

The effects of axial static loads are incorporated into the effective diffusion coefficient through the pore-structure modification coefficient H_L^* , while the effects of fatigue loads are incorporated through the crack-channel amplification coefficient H_F^* . The model parameters are primarily determined from two published experimental studies: the sustained flexural loading and drying–wetting sulfate attack tests conducted by Gao et al. [32], and the fatigue loading and drying–wetting sulfate attack tests conducted by Liu et al. [33]. Gao et al. employed concrete prism specimens of 100 mm × 100 mm × 400 mm under sustained four-point bending at 20%, 40%, and 60% of the ultimate flexural load. The drying–wetting regime consisted of 15 days of immersion in Na₂SO₄ solution (mass fraction 6.9%) and 15 days of natural drying, with sulfate content measured at 30, 90, 180, 270, and 360 days. Liu et al. used specimens of the same dimensions under flexural fatigue loading at maximum stress levels of 20%, 35%, and 50% of the static flexural strength, with 480 cycles per day over 180 days. Sulfate content was measured by layered powder grinding and chemical analysis at the end of exposure. The static load levels of 0%, 20%, 40%, and 60% are adopted from Gao et al., where they correspond to 0%, 20%, 40%, and 60% of the ultimate flexural load of the concrete specimens. The fatigue load levels of 0%, 20%, 35%, and 50% follow Liu et al., where they represent the ratio of the applied maximum fatigue stress to the static flexural strength of the specimens. Specifically, the apparent diffusion coefficient, apparent content amplitude, near-surface correction coefficients, and fatigue damage related parameters are inverted using the MATLAB optimization toolbox. Two simulation durations are adopted in this study, each corresponding to the timeframe of the experimental study it draws upon. For the static loading and drying–wetting cycle scenario, which is parameterized against the experiments of Gao et al., the simulation duration is set to 360 days to match the full exposure period reported in that study. For

the fatigue loading coupled scenarios, which are based on the fatigue tests of Liu et al., the simulation duration is set to 180 days. This 180-day limit reflects not only the experimental protocol of Liu et al. but also the fact that specimens under the highest fatigue stress level of 50% experienced structural failure before 180 days, beyond which no reliable sulfate transport data could be obtained. These two simulation durations are adopted to ensure consistency between the numerical model and the respective experimental benchmarks.

The parameters required for the numerical simulations encompass the initial conditions, external environmental parameters, drying–wetting cycle regime, axial static load levels, fatigue load levels, and the key parameters of the load–damage–diffusion coupled model. The initial conditions and external environmental parameters are summarized in Table 1, and the key model parameters are listed in Table 2.

Table 1. Initial conditions and external environmental parameters.

Parameter	Symbol	Value	Unit
Computation depth	L	13	mm
Simulation duration	t_{end}	180	d
Time step	Δt	0.5	d
Initial pore saturation	s_0	0.95	-
Surface saturation	s_w	1	-
Surface equilibrium saturation	s_a	0.55	-
Initial pore solution sulfate	c_0	0	mol/m ³
Initial apparent sulfate content	C_0	0.7	%
External sulfate solution concentration	c_{ext}	483	mol/m ³
Drying–wetting cycle regime	-	15 d wetting + 15 d drying	d
Static tensile stress level	L_{sT}	0, 20, 40, 60	%
Static compressive stress level	L_{sC}	0, 20, 40, 60	%
Fatigue stress ratio	S_{min}/S_{max}	0.1	-
Single fatigue cycle duration	-	3	min/cycle
Number of fatigue cycles per day	N_d	480	cycles/d
Total number of cycles at 180 d	N_{180}	86,400	cycles

Table 2. Key parameters of the load–damage–diffusion coupled model.

Parameter	Symbol	Value	Unit
Water-cement ratio	w/c	0.44	-
Degree of hydration	α	0.87	-
Initial porosity	ϕ_0	0.167	-
Poisson ratio	μ	0.2	-
Drying transport coefficient	D_d	11.23	mm ² /d
Wetting reference transport coefficient	D_{w0}	3.46	mm ² /d
Empirical saturation parameter	n	2	-
Reference sulfate diffusion coefficient	D_0	2.33	mm ² /d
Pore tortuosity influence coefficient	H_τ	1	-
Minimum diffusion ratio	α_p	0.001	-
Pore shape parameter	β_p	4	-
Bulk modulus of equivalent solid matrix	K_m	18,300	MPa
Shear modulus of equivalent solid matrix	G_m	9600	MPa
Matrix diffusion coefficient	D_m	2.33	mm ² /d
Crack-matrix diffusion ratio	D_c/D_m	30	-
Crack channel diffusion coefficient	D_c	69.9	mm ² /d
Initial crack density	C_{d0}	0.005	-
Fatigue life parameter	a	1	-

Table 2. Cont.

Parameter	Symbol	Value	Unit
Fatigue life parameter	b	0.07	-
Upper bound of fatigue damage	d_{max}	0.95	-
Tensile fatigue sensitivity coefficient	χ_T	1	-
Compressive fatigue sensitivity coefficient	χ_C	0.72	-
Pore-to-mass conversion factor	K_c	1	-
Characteristic depth of surface correction	x_{loss}	1.25	mm

For the bulk modulus and shear modulus of the equivalent solid matrix in the static load pore-structure modification model, the values adopted in existing multi-field coupled models are followed: $K_m = 18.3$ GPa and $G_m = 9.6$ GPa.

To quantitatively evaluate the agreement between the model predictions and the experimental data, three statistical metrics are employed: the mean absolute error (MAE), the root mean square error (RMSE), and the coefficient of determination (R^2), defined as:

$$MAE = \frac{1}{n} \sum_{i=1}^n |C_{sim,i} - C_{exp,i}| \quad (38)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (C_{sim,i} - C_{exp,i})^2} \quad (39)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (C_{exp,i} - C_{sim,i})^2}{\sum_{i=1}^n (C_{exp,i} - C'_{exp})^2} \quad (40)$$

where n is the number of data points, $C_{sim,i}$ and $C_{exp,i}$ are the simulated and experimentally measured sulfate contents at data point i , respectively, and C'_{exp} is the mean of the experimental measurements. The metrics are computed separately for the tensile and compressive zones using all available measurement points from Gao et al., including both the time-series data at the convection peak (30, 90, 180, 270, and 360 days) and the depth profile data at 360 days.

4. Results and Discussion

4.1. Sulfate Transport Under Static Loading and Drying–Wetting Cycles

4.1.1. Temporal Evolution at the Convection Peak

Figures 1 and 2 presents the simulated temporal evolution of sulfate content at the convection peak depth of 2 mm for both the tensile and compressive zones under static load levels of 0%, 20%, 40%, and 60%, over a 360 days exposure period. Since the convection peak resides within the convection-dominated zone governed by drying–wetting cycles, the sulfate content at this depth serves as a direct indicator of the cumulative rate of near-surface ingress and the extent of damage development.

In the tensile zone, sulfate content increases monotonically with exposure time for all load levels, while the accumulation rate gradually decreases. The rapid accumulation during the early stage is driven by the coupled convection-diffusion effect under large external concentration and moisture migration gradients. As sulfate accumulates internally, the concentration gradient declines and the transport process progressively decelerates. The 60% load curve consistently occupies the uppermost position, followed by the curves for 40%, 20%, and the unloaded case, demonstrating a clear load-level-dependent enhancement of sulfate ingress. At 360 days, the convection peak content under the 60% load level is

approximately 50% higher than that of the unloaded case. This result indicates that high tensile stress levels, such as 60% of the ultimate load, promote the initiation and propagation of internal microcracks and significantly increase the connectivity of the pore network. The convective and diffusive transport coefficients are consequently amplified, enhancing the ingress capacity of sulfate ions.

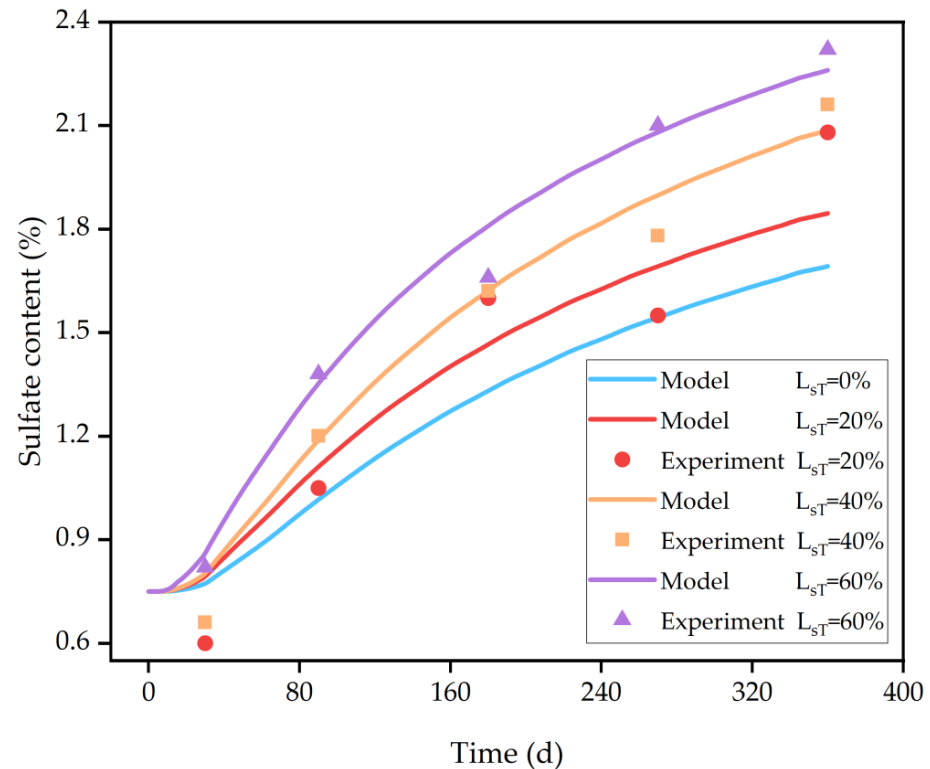


Figure 1. Temporal evolution of sulfate content at the convection peak in the tensile zone.

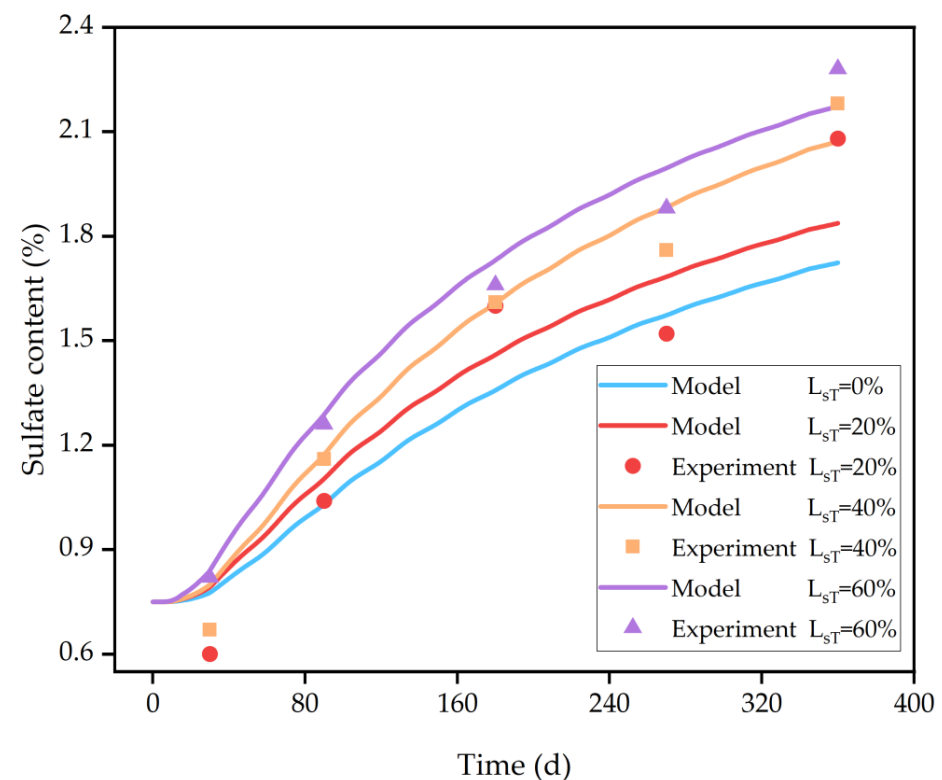


Figure 2. Temporal evolution of sulfate content at the convection peak in the compressive zone.

The compressive zone displays qualitatively similar temporal trends, yet the spacing among the curves is substantially compressed. The curves for the 20%, 40%, and 60% compression levels lie in close proximity to one another, with differences of less than 15% at 360 days. This behavior is consistent with the experimental finding of Gao et al. that compressive stress exerts no pronounced influence on ionic transport properties [32]. The quantitative agreement between the simulated and measured sulfate contents at the convection peak is evaluated in Section 4.1.2 and summarized in Table 3.

Table 3. Quantitative agreement between model predictions and experimental data.

Zone	Data Points	MAE (%)	RMSE (%)	R ²
Tensile	30	0.097	0.115	0.957
Compressive	30	0.220	0.280	0.834

4.1.2. Depth Profiles and the Convection Peak

Figures 3 and 4 displays the simulated sulfate content depth profiles at 360 days for both the tensile and compressive zones. In the tensile zone, the most salient feature is the non-monotonic depth distribution, in which sulfate content rises from the exposed surface to a maximum at approximately 1 to 3 mm depth and then decays monotonically into the interior. This maximum constitutes the convection peak. Such a distribution is a hallmark of drying–wetting sulfate transport and cannot be reproduced by purely diffusive models based on Fick’s law, which predict a monotonic decrease from the surface.

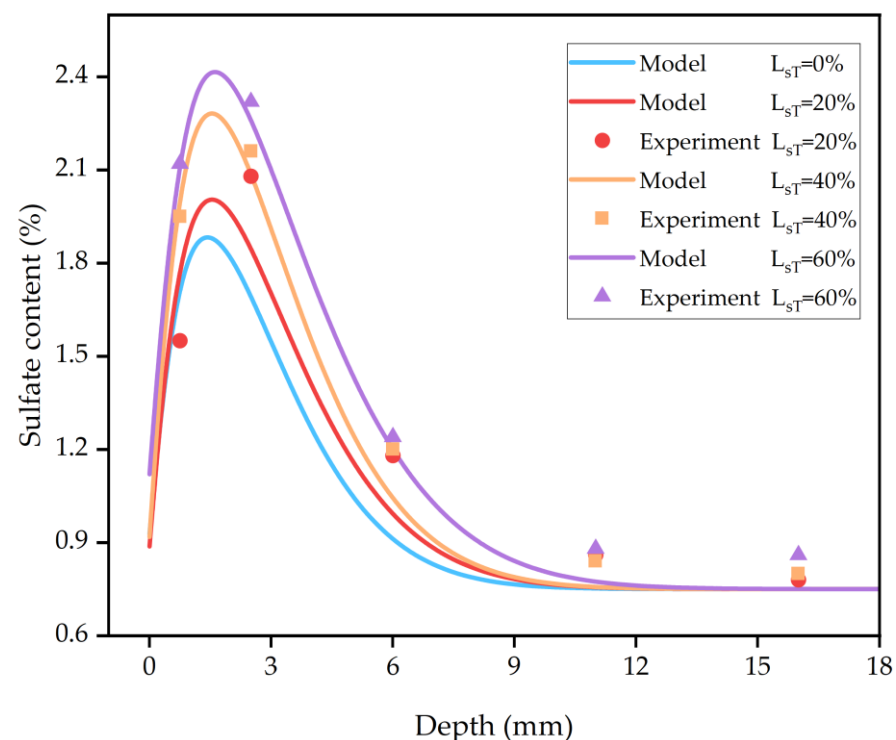


Figure 3. Sulfate content depth profiles at 360 days in the tensile zone.

The physical origin of the convection peak lies in the coupled moisture-solute dynamics during drying–wetting cycles. During the wetting phase, external sulfate solution penetrates the pore network through capillary suction and diffusion, transporting sulfate inward. During the drying phase, pore water evaporates from the surface, creating an outward moisture flux that carries dissolved sulfate toward the surface through convection. The counterplay of inward diffusion during wetting and outward convection during drying

leads to sulfate enrichment and accumulation at a shallow depth where the two fluxes approximately balance.

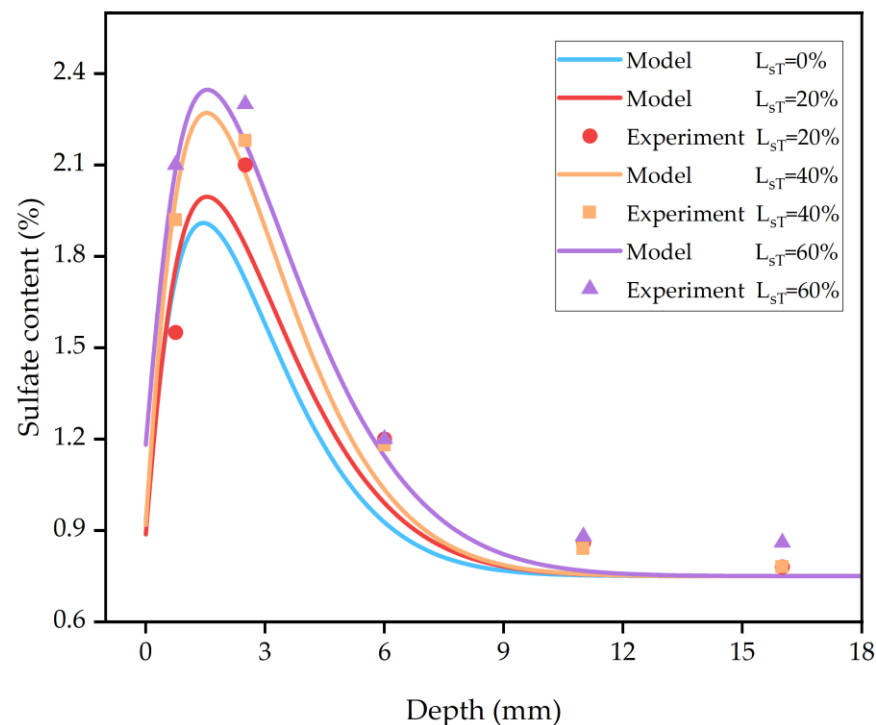


Figure 4. Sulfate content depth profiles at 360 days in the compressive zone.

The 60% tensile load curve exhibits both an elevated convection peak and a shallower decay gradient in the interior diffusion zone compared to the unloaded case. This indicates that tension-induced pore dilation and microcrack development not only intensify near-surface enrichment but also create more efficient transport pathways to greater depths, an effect with significant implications for long-term reinforcement corrosion risk [36].

The compressive zone depth profiles at 360 days similarly exhibit a distinct convection peak and subsequent attenuation with depth, albeit with a much smaller dispersion among the different load levels. This further confirms that under compressive stress states below the failure threshold, microcrack propagation is suppressed and changes in the pore structure remain insignificant. Consequently, sulfate transport in this zone predominantly relies on the baseline convection and diffusion mechanisms driven by drying–wetting cycles, with the load-induced strain exerting a limited amplification effect on the transport process.

Table 3 summarizes the statistical evaluation of the model predictions against the experimental data of Gao et al. For the tensile zone, the MAE and RMSE are 0.097% and 0.115%, respectively, and the R^2 reaches 0.957, indicating that the model captures the time-dependent accumulation at the convection peak and the depthwise decay with high accuracy. For the compressive zone, the corresponding MAE and RMSE are 0.220% and 0.280%, and the R^2 is 0.834. The lower R^2 in the compressive zone reflects the inherently weaker load-level dependence of sulfate transport under compression: the differences among the 20%, 40%, and 60% load curves are small (see Figure 4), and experimental scatter accounts for a larger proportion of the total variation. Taken together, these metrics confirm that the model provides a quantitatively satisfactory description of sulfate transport under static loading and drying–wetting cycles in both the tensile and compressive zones.

4.1.3. Tension–Compression Asymmetry

Figure 5 directly compares the tensile-zone and compressive-zone sulfate depth profiles at 360 days for all static load levels, with solid lines representing the tensile zone and dashed lines the compressive zone. The tension–compression asymmetry is quantitatively evident across all load levels. At the 60% load level, the convection peak sulfate content in the tensile zone exceeds that in the compressive zone by approximately 35%, and the penetration depth, taken as the depth at which the sulfate content falls to 0.1% above background, is roughly 25% greater. This asymmetry arises from the signed volumetric strain mechanism: tensile volumetric strain increases porosity and enhances transport, whereas compressive volumetric strain reduces porosity and inhibits transport. The magnitude of the asymmetry is load-level-dependent, with the 20% load case showing a difference of only approximately 10% and the 60% case yielding a difference approaching 40%.

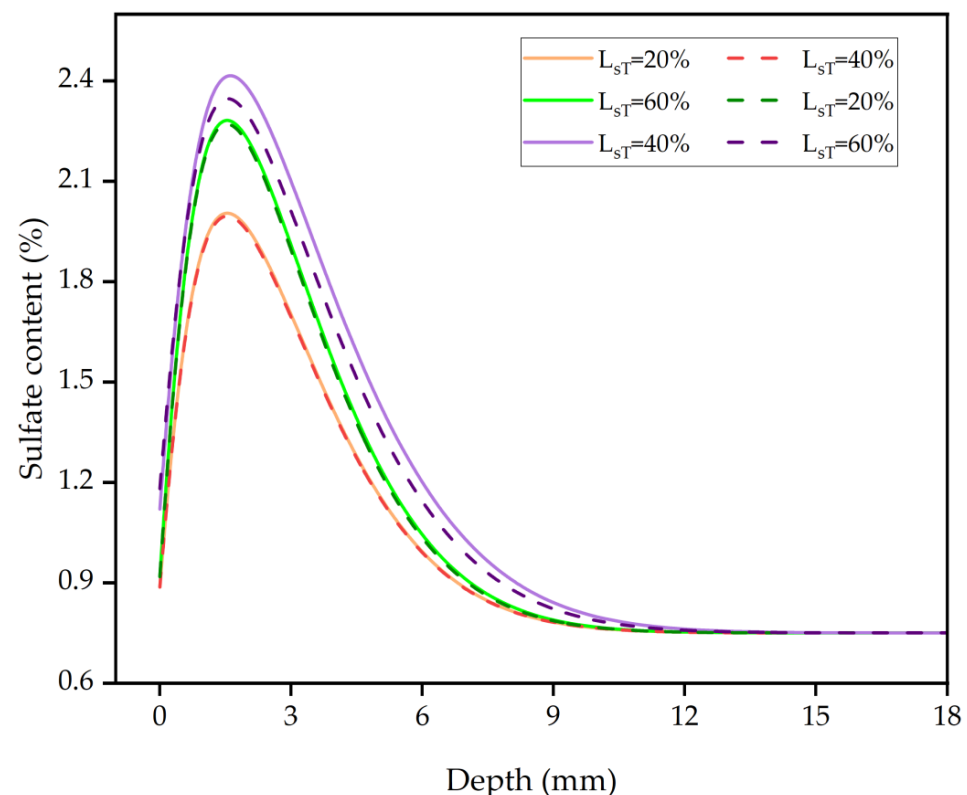


Figure 5. Comparison of simulated sulfate distributions between the tensile and compressive zones at 360 days.

From a mechanistic perspective, the documented tension–compression asymmetry has a clear physical basis. Under tensile stress, existing microcracks at aggregate–paste interfaces open and new microcracks initiate, creating interconnected preferential transport pathways. Under compressive stress at levels well below the compressive strength, pore closure dominates over microcrack initiation and the net effect is transport inhibition. Although the absolute concentration differences between the two zones may not span orders of magnitude over a single cycle or a short exposure period, the long-term accumulation of this structural divergence driven by opposing strains will cause the tensile zone to cross the damage threshold considerably earlier, leading to a significantly higher degradation risk. This finding also underscores the inadequacy of single-amplification-factor load corrections and supports the separate treatment of tensile and compressive zones in sulfate transport models.

These numerical findings are consistent with experimental observations reported in the literature. Gao et al. conducted SEM observations and thermal analysis (TG/DSC) on concrete specimens subjected to sustained flexural loading and drying–wetting sulfate attack for 360 days. Their results showed that the ettringite and gypsum contents in the tensile zone were generally higher than those in the compressive zone, and visible macrocracks had formed in the tensile surface at the 60% load level, providing direct pathways for sulfate ingress. Liu et al. employed XRD phase analysis and confirmed that, under combined flexural fatigue loading and drying–wetting cycles, ettringite and gypsum diffraction peaks appeared in the near-surface layers of specimens subjected to 35% fatigue stress at 180 days. The specimen at the 50% fatigue stress level experienced structural failure before 180 days. These experimental findings confirm the tension–compression asymmetry and the fatigue-induced amplification of sulfate transport that the present model captures.

4.2. Sulfate Transport Under Static-Fatigue Loading and Drying–Wetting Cycles

4.2.1. Sulfate Transport Under Coupled Static Tensile and Compressive Loading with Fatigue

Figure 6 presents the simulated sulfate content depth profiles under the coupled action of static tensile stress, fatigue loading, and drying–wetting cycles at 180 days. The most prominent feature is the pronounced fatigue-level sensitivity of the sulfate transport behavior. At any given static load level, the sulfate content distribution curves shift upward nonlinearly as the fatigue load level increases from 0% to 20%, to 35%, and to 50%. Despite this substantial increase in cumulative sulfate ingress, the convection peak position remains consistently within the near-surface region at approximately 1 to 3 mm from the exposed surface. This stability of the peak position is consistent with the model framework, in which fatigue loading does not alter the moisture migration depth or the convection mechanism governed by the drying–wetting cycles. Instead, the repeated loading–unloading cycles drive the continuous accumulation of the equivalent fatigue damage variable, which in turn amplifies the effective diffusion coefficient through the crack-channel modification coefficient. Under the highest fatigue level of 50%, the convection peak concentration increases sharply and the tail of the distribution curve extends markedly deeper into the interior. This behavior indicates that fatigue loading effectively promotes microcrack initiation and interconnection, significantly amplifying the transport flux through the pore network toward greater depths.

Figure 7 displays the corresponding results for the compressive zone. In contrast to the pronounced response observed in the tensile zone, sulfate transport under static compressive stress coupled with fatigue loading exhibits a clear pattern of suppression and delayed accumulation. The sulfate content at any given fatigue level follows the same basic trend observed in the tensile zone, namely that higher fatigue levels produce greater transport enhancement, with the 50% fatigue curve occupying the uppermost position and the 0% curve the lowermost. However, the spacing among the fatigue-level curves is substantially narrower than that in the tensile zone, and the curves as a group converge toward the baseline unloaded state. From the perspective of the model formulation, the pore-structure modification coefficient in the compressive zone remains at a low level. The compressive stress constrains the dynamic opening of fatigue-induced microcracks, so that even when localized matrix damage occurs through fatigue cycling, its conversion into effective macroscopic transport pathways is considerably less efficient. This numerical result reproduces the enhanced sulfate resistance observed in engineering practice for compression-dominated structural elements, such as the compression sides of bridge piers or the lower layers of heavy-duty pavements under vehicular loading.

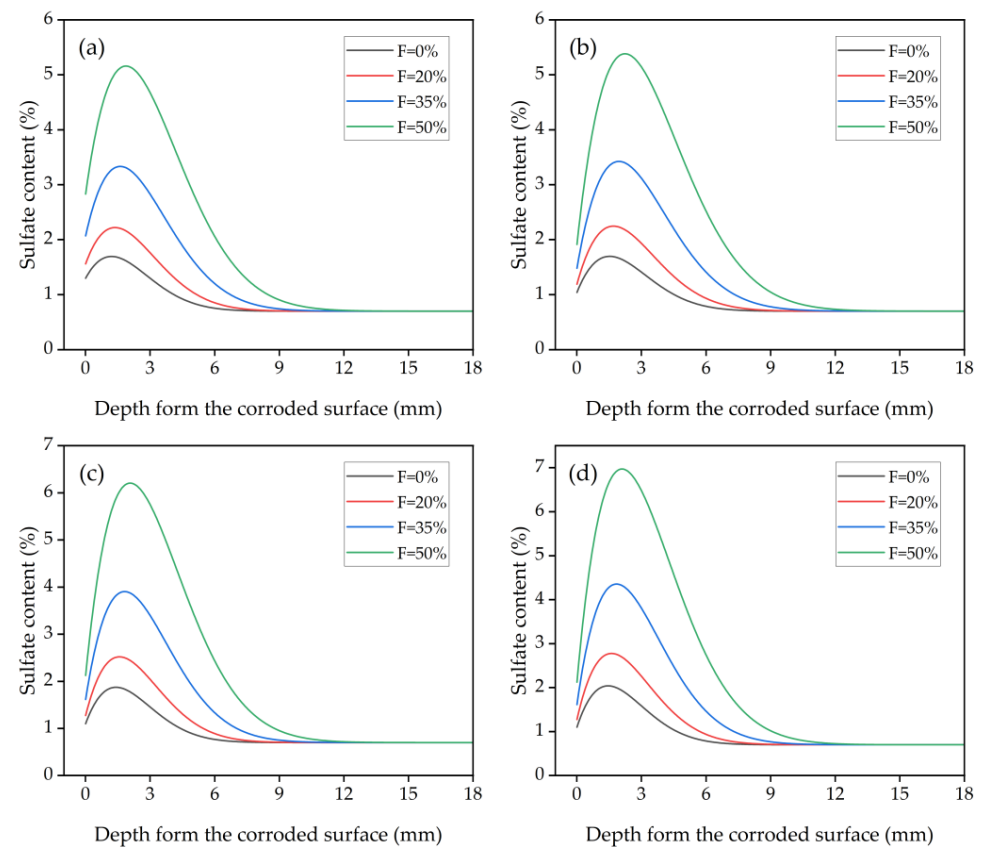


Figure 6. Sulfate depth profiles at 180 d under static tensile-fatigue loading and drying-wetting cycles: (a) 0%, (b) 20%, (c) 40%, (d) 60%.

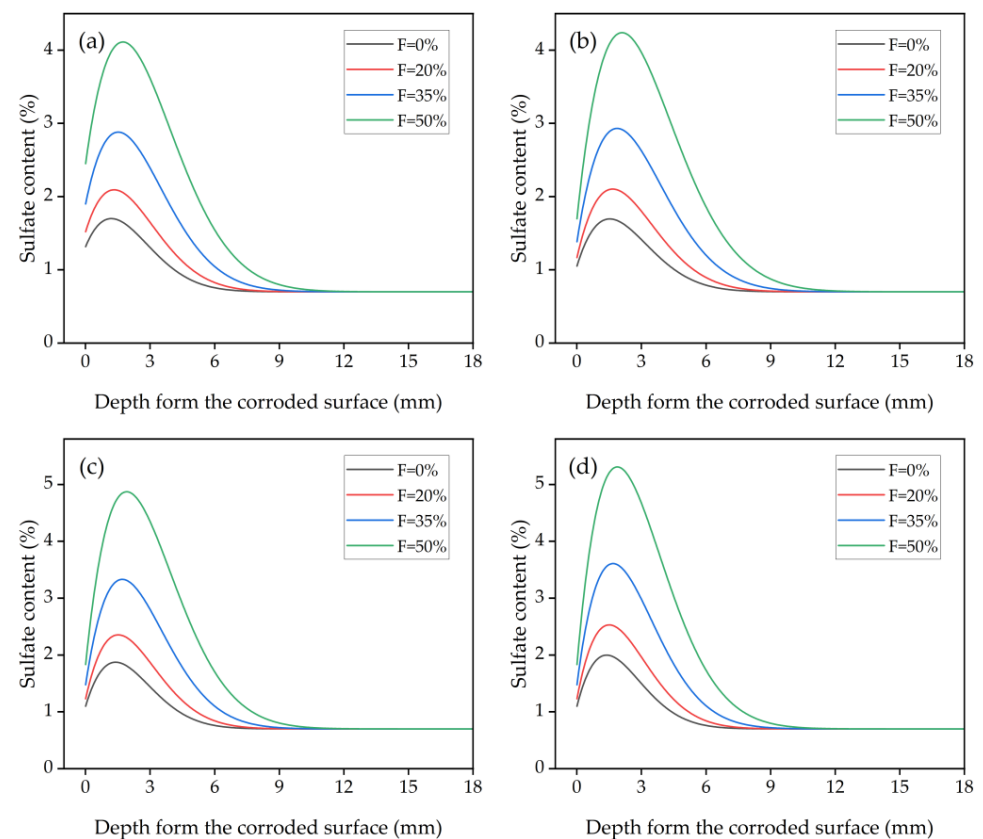


Figure 7. Sulfate depth profiles at 180 d under static compression-fatigue loading and fi cycles: (a) 0%, (b) 20%, (c) 40%, (d) 60%.

4.2.2. Tension–Compression Asymmetry Under Superimposed Fatigue Loading

Figure 8 directly compares the sulfate content depth profiles in the tensile and compressive zones at a static load level of 40%, each under fatigue load levels of 0% and 35%. The results clearly demonstrate a nonlinear amplification of the tension–compression asymmetry when fatigue loading is introduced. With the same 35% fatigue load superimposed, the sulfate content in the tensile zone rises to a far greater extent than that in the compressive zone. This behavior reflects the core coupling logic of the model, in which the static load establishes the baseline damage state and the fatigue load governs the cumulative amplification. Static tensile stress introduces a higher initial level of damage and leaves micro-defects in a critically open state, rendering the concrete highly sensitive to subsequent fatigue stress cycles. The crack propagation driven by fatigue loading then interacts with this pre-existing tensile damage, forming a strong positive feedback loop that accelerates deterioration. The two effects act jointly on the effective diffusion coefficient and make the tensile zone the most vulnerable region for durability degradation under extreme service conditions.

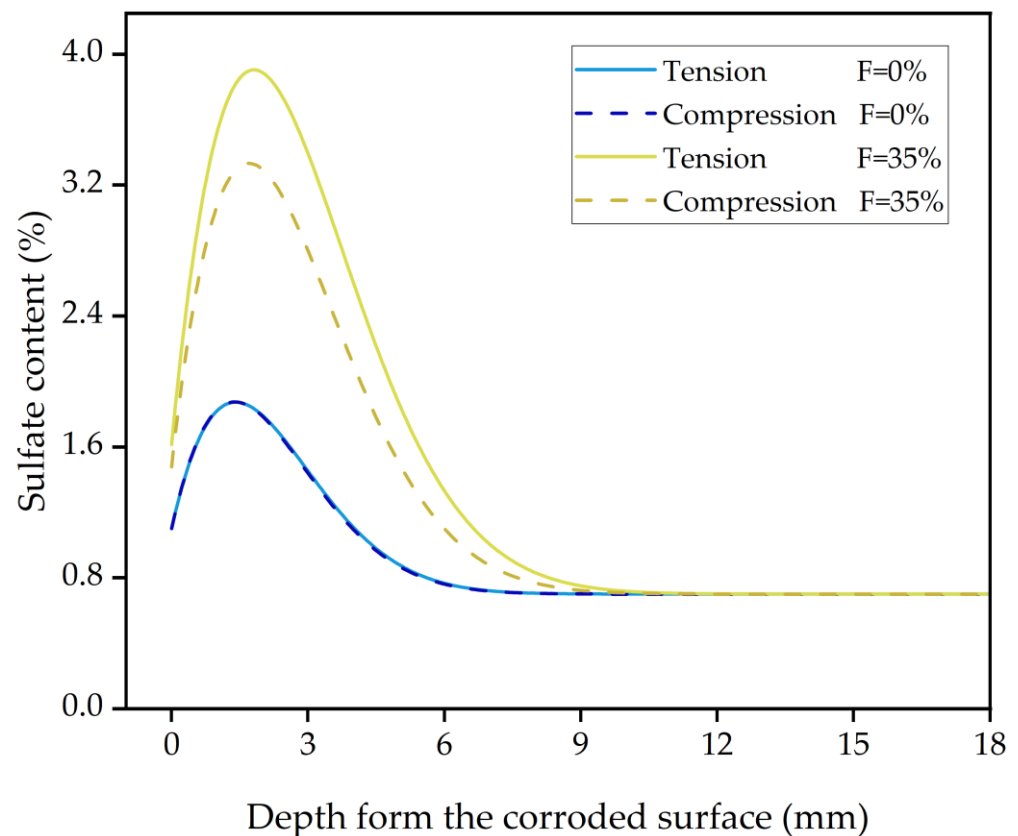


Figure 8. Comparison of sulfate content depth profiles between the tensile and compressive zones at a static load level of 40% under superimposed fatigue load levels of 0% and 35% at 180 days.

Figure 9 presents the temporal evolution of sulfate content at the convection peak, taken at a depth of 2 mm, over the full 180-day exposure period. The curves reveal two defining characteristics of the fatigue damage effect, namely time-dependent accumulation and nonlinear acceleration. In both the tensile and compressive zones, the sulfate content increases continuously throughout the entire exposure period. During the early stage, up to approximately 60 days, the differences among the fatigue load levels remain relatively small, indicating that the fatigue damage variable is still in a slow incubation phase. As the number of loading cycles accumulates, however, the curve for the highest fatigue level of 50% undergoes a marked acceleration in the middle-to-late period and ultimately

diverges substantially from the lower fatigue level curves by 180 days. This temporal pattern suggests that fatigue-induced pore degradation and ionic transport enhancement do not proceed at a uniform rate. Once the cumulative number of fatigue cycles exceeds a certain threshold, the microcrack network undergoes a connectivity transition that triggers an accelerated regime of sulfate ingress.

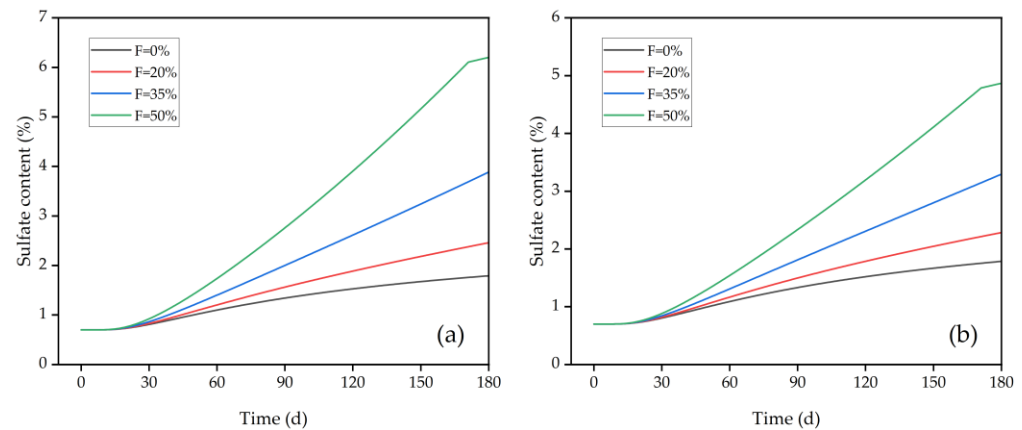


Figure 9. Temporal evolution of sulfate content at the convection peak under a static load level of 40%: (a) static tensile stress; (b) static compressive stress.

Figure 10 isolates the role of the initial static stress state in governing the transport mechanism under a fixed dynamic loading input. With the fatigue load level held constant at 35%, the sulfate concentration curves exhibit systematic differences across the three static tensile stress levels of 20%, 40%, and 60%. Both the peak sulfate concentration and the penetration depth increase as the static tensile stress level rises. This result clarifies the respective roles of static loading and fatigue loading in the coupled mechanism. Although fatigue loading provides the cyclic driving force for crack propagation, it is the static tensile stress that determines the baseline crack opening width and governs whether effective large-scale transport channels can form. Under identical fatigue damage conditions, a higher static tensile stress substantially reduces the resistance to ionic diffusion, further confirming the complex synergistic interaction inherent in the load–damage–diffusion coupled system.

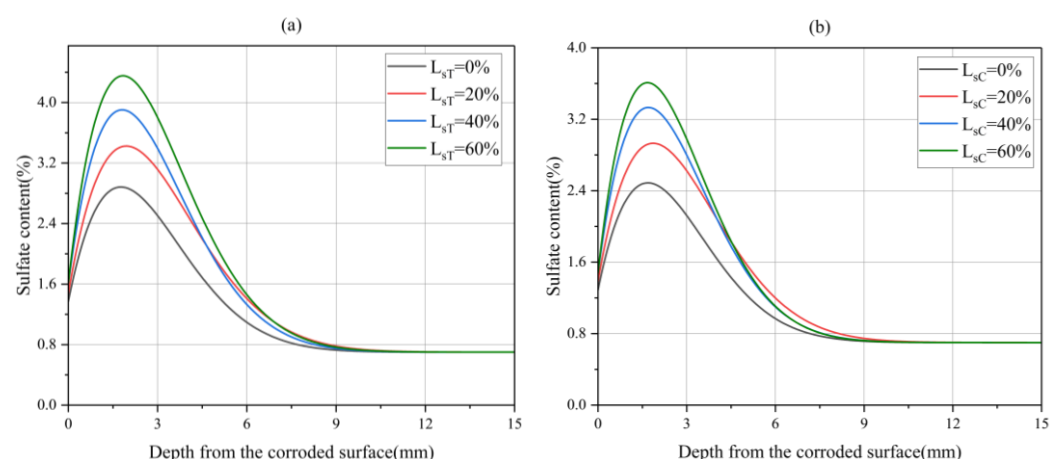


Figure 10. Comparison of sulfate content depth profiles at 180 days under different static stress levels at a fixed fatigue load level of 35%: (a) tensile zone; (b) compressive zone.

4.2.3. Fatigue Damage Evolution and Transport Amplification

Figure 11 presents the evolution of the equivalent fatigue damage variable D_f and the transport amplification coefficient H_f under different fatigue load levels. These mesoscale

parameter trajectories provide a direct interpretation of the macroscopic transport behavior described in the preceding sections. At the fatigue load level of 0%, D_f remains zero throughout the exposure period and H_f stays at the baseline value of 1.0, corresponding to the absence of any fatigue-induced amplification. At the lower fatigue load levels of 20% and 35%, D_f increases steadily with the cumulative number of loading cycles and drives a gradual rise in H_f that remains close to linear. At the highest fatigue load level of 50%, however, the stress level approaches the critical range of the material fatigue strength. The cracks enter a stage of rapid propagation, and both D_f and H_f undergo a sharp surge of exponential character in the middle-to-late period of exposure. This mesoscale parameter evolution confirms that the fatigue crack-channel modification model developed in this study captures the dynamic coupling among mechanical loading, damage accumulation, and sulfate transport.

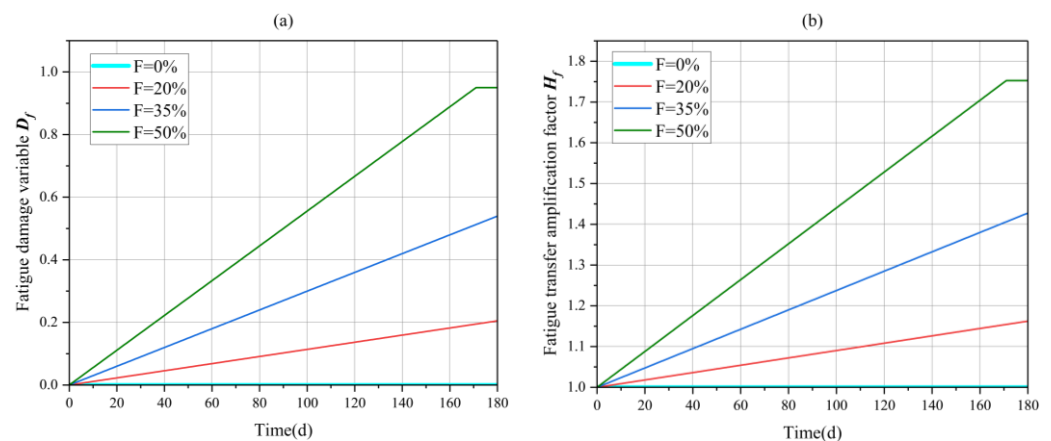


Figure 11. Evolution of the fatigue damage variable and the transport amplification coefficient under different fatigue load levels: (a) damage evolution under each load level; (b) corresponding amplification of the apparent transport capacity.

5. Sensitivity Analysis

5.1. Methodology

The preceding sections have examined the influence of individual factors on sulfate transport behavior through comparisons of sulfate content distribution curves across different loading scenarios. These case-by-case comparisons, however, cannot readily separate the relative contributions of multiple input parameters to the output response. To quantitatively identify the parameters that dominate the load–damage–diffusion coupled model behavior, this section undertakes a parameter sensitivity analysis using the numerical simulation results obtained in Sections 3 and 4. The aim is to rank, at the model parameter level, the contribution of each influencing factor to three aspects of the transport response: the degree of near-surface sulfate enrichment, the migration of the convection peak position, and the total sulfate ingress.

In accordance with the model structure, four core input variables are selected: the apparent diffusion coefficient D_{app} , the convection intensity coefficient s_c , the axial static load level L_s , and the fatigue load level L_f . The coefficient D_{app} governs the rate of sulfate diffusion through the concrete pore network. The coefficient s_c equivalently represents the intensity of convective input induced by moisture migration under drying–wetting cycles. The level L_s reflects the degree to which axial static loads modify the pore structure and the initial crack state. The level L_f quantifies the cumulative damage and crack-channel amplification caused by cyclic loading. These four variables correspond directly to the four core components of the theoretical framework of this study: the convective input driven

by drying–wetting cycles, the diffusive transport controlled by concentration gradients, the pore-structure modification induced by axial static loads, and the transport pathway amplification produced by fatigue damage.

The sensitivity analysis adopts a one-factor-at-a-time (OAT) perturbation method. Each input variable is varied individually while the remaining variables are held at their baseline values, and the resulting change in the model output is computed. To comprehensively characterize the sulfate transport response, three output indicators are selected: the sulfate content at the convection peak C_{peak} , which reflects the degree of near-surface enrichment, the convection peak position x_{peak} , which captures the depthwise migration of the enrichment zone, and the total sulfate ingress C_{sum} , which measures the overall accumulation of sulfate within the computational domain. The total sulfate ingress is defined as:

$$C_{sum} = \int_0^L C(x, t) dx \quad (41)$$

Let the set of input variables be denoted by $x_1, x_2, \dots, x_l$ and the output indicator by y . The input-output relationship can be abstractly written as:

$$y = f(x_1, x_2, \dots, x_l) \quad (42)$$

To eliminate the influence of differing dimensions and perturbation magnitudes among the input variables on the sensitivity evaluation, the normalized effective variance method is employed [37]. The total effective variance V_{te} is:

$$V_{te} = \sum_{i=1}^n V_{ei} = \sum_{i=1}^n \sum_{j=1}^l V_{eij} \quad (43)$$

where V_{eij} represents the effective variance of the i -th input variable across the j -th perturbation dimension, which is defined as:

$$V_{eij} = \frac{1}{N} \sum_{k=1}^N \frac{(y_{jk} - y_{mk})^2}{\alpha_{ij}} \quad (44)$$

The normalized increment coefficient α_{ij} is defined as:

$$\alpha_{ij} = \frac{x_{ij} - x_{im}}{x_{im}} \quad (45)$$

Ultimately, the sensitivity coefficient S_i corresponding to the i -th input variable is formulated as:

$$S_i = \frac{V_{ei}}{V_{te}}, 0 \leq S_i \leq 1 \quad (46)$$

where N denotes the number of output data points, y_{jk} represents the k -th output value under the corresponding perturbed condition, y_{mk} is the k -th output value under the baseline or median condition, x_{ij} is the perturbed value of the variable, and x_{im} signifies the baseline or median value of the respective variable. The value of S_i ranges from 0 to 1, with a higher value indicating a more pronounced influence of the given input variable on the corresponding output metric. By comparing the sensitivity coefficients of the four input variables with respect to C_{peak} , x_{peak} , and C_{sum} , the relative importance of each factor across different dimensions of sulfate transport behavior can be quantitatively ranked.

It should be noted that the OAT method employed here cannot capture interactions among the input variables, which are likely to be physically meaningful given the coupled

nature of the load–damage–diffusion system. The quantification of such interactions using global sensitivity algorithms represents a direction for future work.

5.2. Sensitivity of the Tensile Zone

Figure 12 presents the sensitivity coefficients of the four input variables with respect to the three output indicators in the tensile zone. Distinct differences emerge in the influence of each input variable across the three dimensions of the transport response. For the convection peak sulfate content C_{peak} , the fatigue load level L_f yields the highest sensitivity coefficient, substantially exceeding those of the other three variables. The convection intensity coefficient s_c ranks second, while the apparent diffusion coefficient D_{app} and the axial static load level L_s exhibit comparatively low sensitivity. This ranking indicates that near-surface sulfate enrichment in the tensile zone is governed primarily by fatigue-induced cumulative damage. Under repeated loading cycles, microcracks within the concrete undergo continuous opening, closure, and extension, and their number, width, and interconnectivity all grow progressively. These interconnected crack pathways provide increasingly efficient transport channels for sulfate ions and thereby drive the marked elevation of the convection peak concentration.

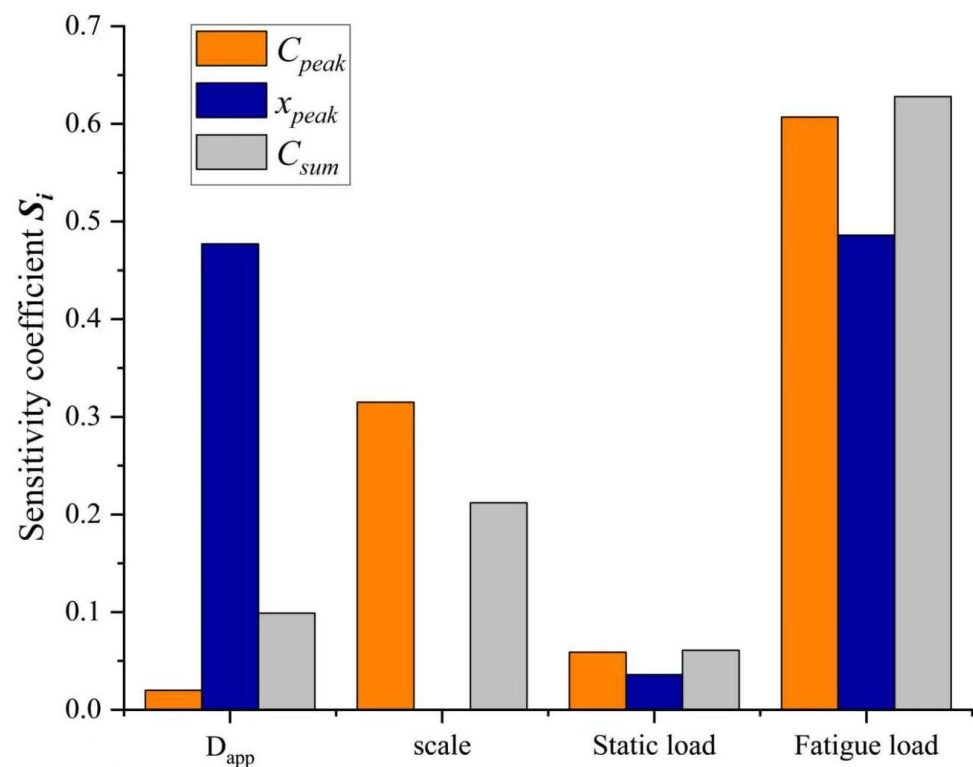


Figure 12. Sensitivity coefficients of the input variables with respect to the sulfate transport indicators in the tensile zone.

For the convection peak position x_{peak} , D_{app} displays the highest sensitivity. The fatigue load level L_f also exerts a considerable influence, whereas s_c and L_s have relatively limited effects. This pattern indicates that the depth to which the enrichment peak migrates into the concrete interior is determined predominantly by the apparent diffusion capacity of sulfate ions. A larger D_{app} enhances sulfate migration through the interior diffusion zone and shifts the peak position further inward. By contrast, s_c mainly controls the intensity of near-surface convective input and enrichment, and its direct influence on the peak position remains relatively weak.

For the total sulfate ingress C_{sum} , L_f again ranks as the most sensitive parameter, followed by s_c , with L_s and D_{app} contributing relatively modest shares. This result demonstrates that the total sulfate accumulation in the tensile zone depends not only on the baseline diffusion capacity but also, and more decisively, on the transport pathway amplification produced by cumulative crack damage. The interconnected crack network that develops in the tensile zone under fatigue loading is therefore the primary driver of the enhanced sulfate ingress and the extended penetration depth.

5.3. Sensitivity of the Compressive Zone

Figure 13 presents the sensitivity coefficients of the four input variables with respect to the three output indicators in the compressive zone. The overall pattern of sensitivity shares broad qualitative similarities with that obtained for the tensile zone, yet meaningful differences arise in both the magnitude of the response and the relative ranking of the controlling factors. For the convection peak sulfate content C_{peak} , the fatigue load level L_f again yields the highest sensitivity coefficient. This result indicates that fatigue-induced cumulative damage continues to drive near-surface sulfate enrichment even under the constraining influence of compressive stress. Compared with the tensile zone, however, the sensitivity of C_{peak} to L_f is moderately lower. The reduction reflects the capacity of compressive stress to restrain microcrack opening and interconnection, thereby limiting the efficiency with which fatigue damage is converted into enhanced transport pathways.

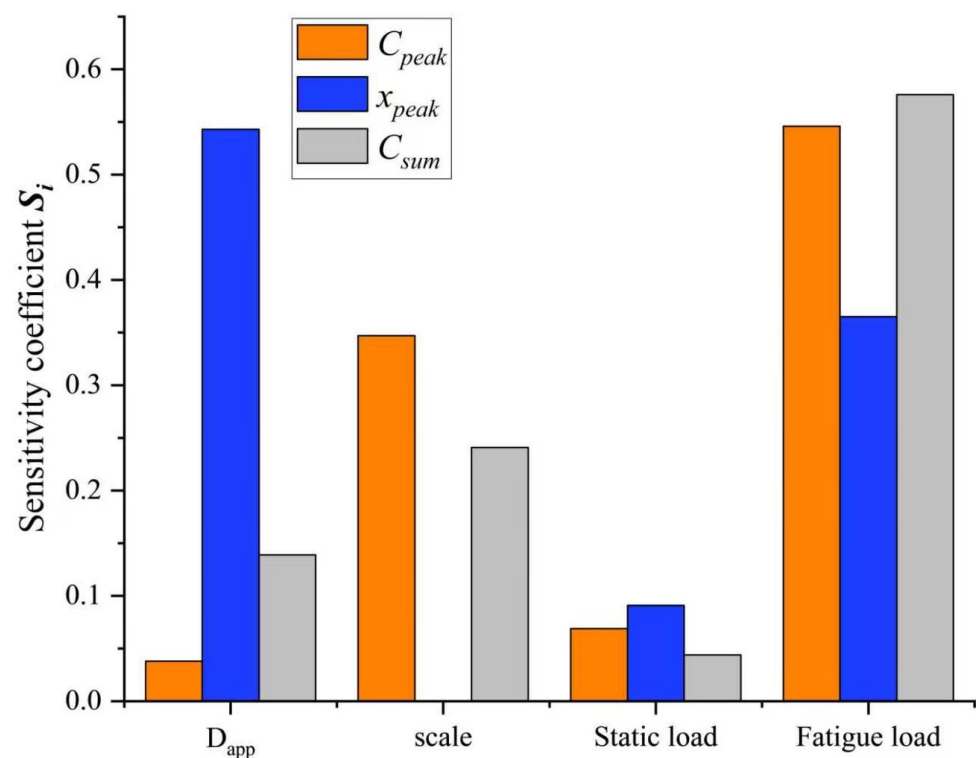


Figure 13. Sensitivity coefficients of the input variables with respect to the sulfate transport indicators in the compressive zone.

For the convection peak position x_{peak} , D_{app} exhibits the highest sensitivity coefficient, confirming that the peak position in the compressive zone is also controlled primarily by the apparent diffusion capacity. Under compressive stress, crack propagation is suppressed, and sulfate migration toward the interior consequently depends to a greater extent on diffusion through the matrix pore network than on preferential transport along crack

channels. The governing role of D_{app} over the peak position is therefore expressed more distinctly in the compressive zone than in the tensile zone.

For the total sulfate ingress C_{sum} , L_f remains the dominant factor. Its amplification effect, however, is weaker than that observed in the tensile zone. This attenuation stems from the partial closure of pores and microcracks induced by compressive stress, which reduces the efficiency with which fatigue damage translates into effective macroscopic transport. The response of C_{sum} to fatigue loading is thus less pronounced in the compressive zone than in the tensile zone, a clear and consistent manifestation of the tension–compression asymmetry that characterizes the coupled transport behavior throughout this study.

The present sensitivity analysis is limited to first-order effects because of the OAT perturbation framework. Given the strongly coupled nature of the modeled system, parameter interactions are expected to be physically relevant. For instance, the amplification of sulfate transport by fatigue loading may depend on the existing static load level, since the baseline crack state under tension provides a different initial condition for fatigue-induced crack propagation than that under compression. The application of global sensitivity analysis algorithms, such as variance-based Sobol' indices or the Morris elementary effects method, would allow systematic quantification of both main effects and interaction effects, and is identified as a methodologically valuable extension for future studies.

6. Conclusions

This study developed a coupled load–damage–diffusion apparent transport model for sulfate ingress in concrete under combined static loading, fatigue loading, and drying–wetting cycles. Mechanical load effects are embedded into the effective diffusion coefficient through physically motivated correction factors, without explicitly resolving chemical reactions or physical crystallization. The main findings are as follows.

- (1) Drying–wetting cycles generate alternating moisture gradients that drive concurrent diffusion and convection, producing a stable convection peak at approximately 1 to 3 mm from the exposed surface. This peak persists across all load levels, confirming that the moisture regime governs the basic morphology of the sulfate distribution profile.
- (2) Axial static loads exert a pronounced tension–compression asymmetry. Static tensile stress amplifies the effective diffusion coefficient by promoting microcrack opening and pore dilation, whereas static compressive stress tends to close pores and restrain crack propagation, resulting in a substantially weaker transport inhibition effect.
- (3) Fatigue loading introduces time-dependent accumulation and nonlinear acceleration of sulfate ingress. As the cumulative number of loading cycles exceeds a critical threshold, the equivalent fatigue damage variable undergoes a rapid increase that triggers a sharp surge in the transport amplification coefficient.
- (4) The tensile zone exhibits disproportionately high sensitivity to fatigue damage. Static tensile stress establishes an elevated baseline of damage, and superimposed fatigue cycling drives further crack extension through a positive-feedback synergy, making the tensile zone the most vulnerable region for durability degradation under multi-factor coupling.

The proposed framework enables explicit distinction between the transport behavior in tensile and compressive zones, a feature absent from most simplified models. The effective diffusion coefficient incorporates closed-form correction factors that are functions of measurable load and material parameters, and the fatigue damage variable is linked to the S–N relationship. The sensitivity coefficients provide quantitative guidance for prioritizing input parameters in durability assessment. Its limitations include the omission of chemical reactions, expansion-induced cracking, and mesoscale heterogeneity. Future work should extend the framework toward multi-ionic transport, chemical-mechanical feed-

back, mesoscale structural detail, and the development of an explicit service-life prediction formula under coupled static and fatigue loading.

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