Journal of Asian Concrete Federation

journal homepage: https://jacf.sfulib3.publicknowledgeproject.org/index.php/jacf

Autogenous shrinkage mitigation in UHPC: mechanisms, multiscale regulation, and future perspectives

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A B S T R A C T

Autogenous shrinkage remains a critical obstacle to the dimensional stability and crack resistance of ultra-high-performance concrete (UHPC), owing to its low water-to-binder ratio, dense pore structure, and rapid early-age self-desiccation. This review critically examines the mechanisms governing autogenous shrinkage in UHPC and establishes a mechanism-based framework for shrinkage mitigation. The evolution of hydration, chemical shrinkage, internal relative humidity, capillary pressure, stiffness development, and restrained stress is first discussed. Mitigation approaches are then classified into four functional categories: moisture regulation through internal curing, hydration regulation, internal restraint enhancement, and direct shrinkage mitigation using shrinkage-reducing admixtures and expansive agents. Their effectiveness is compared by considering shrinkage-control mechanisms, action timing, performance trade-offs, and application conditions. The review emphasizes that shrinkage reduction should not be treated as an isolated index, because mitigation strategies may simultaneously influence hydration kinetics, pore structure, workability, strength, durability, and cracking resistance. Finally, a future-oriented design framework is proposed, highlighting time-matched, performance-coupled, and sustainability-aware shrinkage regulation for durable UHPC structures.

Keywords: Ultra-high-performance concrete; Autogenous shrinkage; Self-desiccation; Shrinkage mitigation strategies; Volume stability

1. Introduction

1.1 UHPC: exceptional performance and sustainability challenges

Ultra-high-performance concrete (UHPC) has emerged as one of the most advanced cement-based materials owing to its exceptional mechanical performance, superior durability, and long-term serviceability [1-3]. Compared with conventional concrete, UHPC generally exhibits compressive strengths higher than 120 MPa, ultra-low permeability, and remarkable resistance to chloride penetration, freeze–thaw cycles, and chemical attack [4-6]. These superior properties have promoted the increasing application of UHPC in bridges, high-rise buildings, precast components, and other critical infrastructures requiring high durability and structural reliability [7].

The unique performance of UHPC originates from its highly densified matrix design, which is achieved through optimized particle packing, extremely low water-to-binder ratios, high binder contents, and the incorporation of supplementary cementitious materials and fibers [8, 9]. Such design strategies significantly enhance matrix compactness, interfacial bonding, and mechanical performance [10]. In addition, the dense microstructure of UHPC contributes to its excellent durability and extended service life compared with conventional cement-based materials [11, 12].

Nevertheless, the highly densified nature of UHPC also brings challenges related to sustainability and dimensional stability. The high binder content and very low water-to-binder ratio (w/b) commonly adopted in UHPC may increase carbon emissions, early-age hydration heat, and internal water demand [13]. These characteristics make volume stability a critical concern in UHPC, particularly at early ages when hydration proceeds rapidly and the matrix becomes increasingly dense [14, 15]. Therefore, balancing exceptional

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DOI http://dx.doi.org/10.18702/acf.2026.12.4.1

Received: 24-Jun-2026; Revised: 19-Aug-2026; Accepted: 03-Sep-2026; Published online: 12-October-2026

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performance with sustainability and dimensional stability has become an important issue in the development of advanced UHPC systems.

1.2 Autogenous shrinkage as a critical challenge in UHPC

Autogenous shrinkage is widely recognized as one of the most critical volume stability issues in UHPC. Due to the extremely low w/b and highly dense pore structure, significant shrinkage deformation can occur even under sealed curing conditions, primarily as a result of internal water consumption during hydration [16-18]. Moreover, the rapid reduction in further intensifies self-desiccation and capillary stress development, thereby aggravating autogenous shrinkage at early ages [19].

When autogenous shrinkage is restrained, tensile stress may develop before sufficient tensile strength is established, thereby increasing the risk of early-age microcracking [20-22]. Such cracking may create preferential pathways for the ingress of moisture and aggressive ions, ultimately compromising the long-term durability and service performance of UHPC structures [23-26]. Therefore, effective mitigation of autogenous shrinkage is essential for achieving both the exceptional mechanical performance and long-term durability expected from UHPC systems.

1.3 Scope and structure of this review

In recent years, autogenous shrinkage in UHPC has attracted considerable research attention. To visualize the research landscape of shrinkage-related studies in UHPC, 382 bibliographic records were retrieved from the Clarivate Web of Science platform. The principal search terms included material-related terms, such as “ultra-high-performance concrete” and “UHPC” , and shrinkage-related terms, such as “autogenous shrinkage” and “shrinkage” . The retrieved records were analyzed using VOSviewer to construct the keyword co-occurrence network shown in Figure 1. Existing reviews and related studies have provided valuable overviews of UHPC composition, hydration, microstructure, mechanical properties, and specific shrinkage-mitigation approaches. However, previous reviews have generally emphasized either the fundamental mechanisms of UHPC shrinkage, the behavior of individual mitigation materials, or specific aspects such as mechanical performance and durability, rather than systematically integrating these aspects into a unified shrinkage-control framework. In contrast, the present review establishes a mechanism-based and performance-oriented framework that links the evolution of hydration, chemical shrinkage, self-desiccation, internal RH, capillary pressure, stiffness, and restrained stress with four functional mitigation pathways: moisture regulation, hydration regulation, internal restraint enhancement, and direct shrinkage mitigation. The mitigation strategies are further compared in terms of their dominant action stages, condition-dependent quantitative responses, inherent performance trade-offs, and applicable engineering scenarios. This integrated perspective is intended to move beyond material-specific shrinkage reduction toward time-matched and performance-coupled UHPC shrinkage control.

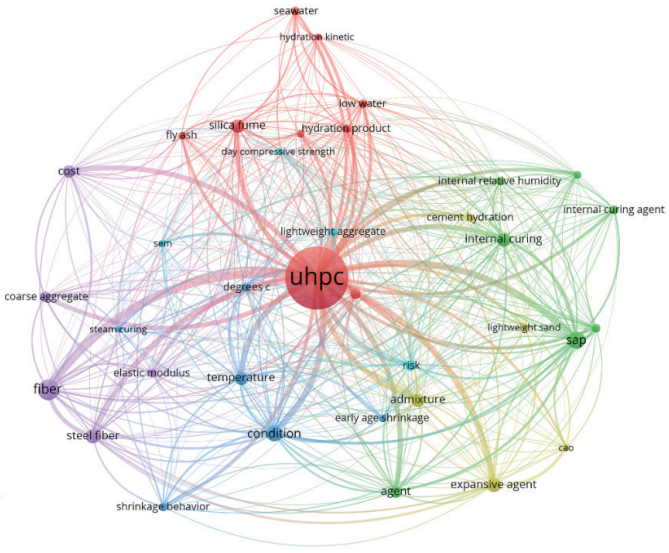


Figure 1. Keyword co-occurrence network of publications related to autogenous shrinkage in UHPC based on the Web of Science database and visualized using VOS viewer.

Therefore, this review provides a comprehensive overview of the mechanisms, mitigation strategies, and future perspectives of autogenous shrinkage in UHPC. First, the fundamental mechanisms governing autogenous shrinkage development are discussed, including self-desiccation, internal relative humidity reduction, capillary pressure evolution, and microcrack formation. Subsequently, current mitigation strategies are systematically reviewed, with emphasis on internal curing, hydration regulation, fiber reinforcement, and microstructure modification approaches. In addition, the advantages, limitations, and sustainability implications of different mitigation strategies are comparatively discussed. Finally, future perspectives for achieving sustainable and crack-resistant UHPC systems are presented.

2. Mechanisms of autogenous shrinkage in UHPC

Autogenous shrinkage in UHPC results from a sequence of strongly coupled physicochemical and mechanical processes rather than from several independent mechanisms. Hydration produces chemical shrinkage and continuously consumes internal water. After the formation of a load-bearing solid skeleton, the resulting water deficit promotes self-desiccation and internal RH reduction, followed by capillary-pressure development within partially saturated pores. As the matrix progressively stiffens, autogenous deformation is increasingly converted into tensile stress under internal or external restraint. When the accumulated stress exceeds the developing tensile resistance of the matrix, microcracking may occur. The following subsections organize these coupled processes into three interconnected modules.

2.1 Hydration evolution, self-desiccation, and internal RH reduction

Cement hydration is the initiating process of autogenous shrinkage in UHPC, and the associated chemical shrinkage creates the internal volume deficit that promotes self-desiccation. Chemical shrinkage occurs because the absolute volume of the hydration products is smaller than the combined volume of the reacting cement and water. Before the formation of a continuous load-bearing skeleton, a considerable portion of this volume deficit may be accommodated by plastic or bulk deformation and therefore does not translate directly into shrinkage stress within the hardening matrix. After setting, continued hydration, through the associated chemical shrinkage, creates empty capillary volume. Under sealed conditions, this volume cannot be replenished by external water, causing progressive desaturation of the capillary pores and a reduction in internal RH. This self-desiccation promotes the formation of liquid–vapor menisci and capillary tension, which, together with the increasing stiffness of the matrix, produces measurable autogenous shrinkage.

Self-desiccation is widely recognized as one of the fundamental mechanisms governing autogenous shrinkage in UHPC [27]. During cement hydration, water is continuously consumed through chemical reactions and hydration product formation. In UHPC systems with extremely low water-to-binder ratios, the available internal water is insufficient to maintain full saturation within the pore structure [28, 29]. Consequently, internal RH decreases rapidly as hydration proceeds, even under sealed curing conditions [30, 31].

The continuous reduction in internal RH promotes self-desiccation within the cementitious matrix. As hydration progresses, the consumption of capillary water leads to the formation of partially saturated pores within the cementitious matrix, as schematically illustrated in Figure 2 [32]. Due to the highly refined pore structure and limited moisture transport capacity of UHPC, the loss of internal moisture occurs rapidly at early ages, thereby intensifying self-desiccation and autogenous deformation development [33, 34]. Therefore, self-desiccation and internal RH reduction provide the fundamental basis for subsequent capillary pressure generation and autogenous shrinkage development in UHPC systems.

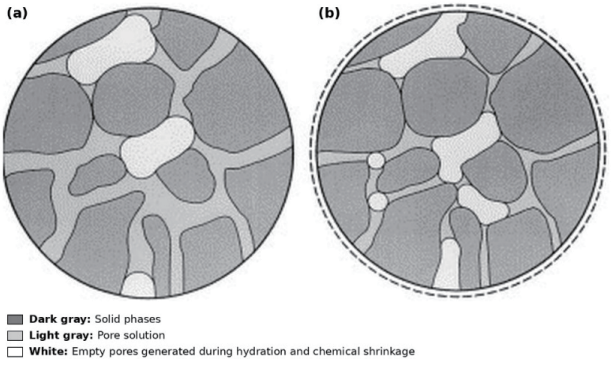


Figure 2. Schematic illustration of self-desiccation development in UHPC during hydration: (a) low degree of hydration; (b) high degree of hydration [32].

2.2 Capillary pressure development

As internal relative humidity decreases during self-desiccation, liquid–vapor menisci gradually form within partially saturated capillary pores in the cementitious matrix. The formation of these menisci generates capillary pressure inside the pore structure, which is widely considered one of the primary driving forces of autogenous shrinkage in low w/b cement-based systems [35]. A schematic illustration of capillary pressure development during hydration is shown in Figure 3.

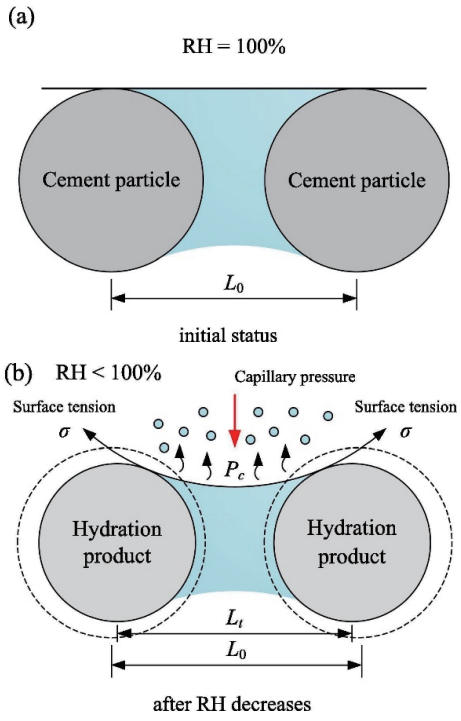


Figure 3. Schematic illustration of capillary pressure development during self-desiccation in UHPC [35].

According to the Young–Laplace equation [36], capillary pressure is inversely proportional to pore radius and can be expressed as Eq. (1):

$$P_c = \frac{2\gamma\cos\theta}{r} \quad (1)$$

where P_c is the magnitude of capillary pressure (Pa), γ is the surface tension of the pore solution ($N \cdot m^{-1}$), θ is the liquid–solid contact angle, and r is the positive radius of the concave liquid meniscus (m).

As hydration proceeds and internal RH continuously decreases, the radius of the liquid meniscus becomes smaller, resulting in higher capillary stress within the pore structure [37].

The relationship between internal RH and capillary pressure can be further described by the Kelvin equation (Eq. (2)) [38]:

$$\ln(RH_k) = -\frac{2\gamma V_w \cos\theta}{rRT} \quad (2)$$

where RH_k is the equilibrium relative humidity associated

with the Kelvin meniscus and is expressed as a dimensionless fraction, V_w is the molar volume of water ($m^3 \cdot mol$), R is the universal gas constant ($8.314 \cdot J\ mol^{-1} \cdot K^{-1}$), and T is the absolute temperature (K).

These relationships indicate that internal RH reduction during hydration directly contributes to capillary pressure development within the pore network. Due to the highly refined pore structure of UHPC, capillary stress can increase significantly at early ages, thereby promoting autogenous shrinkage and internal tensile stress development [39].

2.3 Pore structure evolution, stiffness development, restrained stress, and microcracking

As hydration proceeds, hydration products progressively fill the pore space, resulting in pore refinement and reduced pore connectivity. As self-desiccation progresses, the refined pore network supports the formation of liquid–vapor menisci with smaller radii of curvature, thereby increasing capillary pressure within the cementitious matrix.

The mechanical consequences of capillary-pressure-induced deformation depend strongly on the age-dependent stiffness of the UHPC matrix. Before a continuous load-bearing skeleton forms, the low stiffness of the fresh matrix allows a considerable portion of the deformation to occur with limited stress accumulation. As the load-bearing skeleton develops during setting, the elastic modulus increases, and continued autogenous shrinkage is progressively converted into tensile stress under internal or external restraint. The magnitude of the restrained tensile stress is governed by free autogenous shrinkage, stiffness evolution, creep and stress relaxation, and the degree of restraint, whereas the developing tensile strength determines whether cracking occurs.

When the accumulated tensile stress exceeds the developing tensile strength of the matrix, microcracks may initiate and propagate, particularly at weak regions of the microstructure [40]. Although often microscopic in size, these cracks represent shrinkage-induced damage and may provide preferential pathways for the ingress of aggressive agents, thereby negatively affecting the long-term durability of UHPC [41]. Therefore, pore structure evolution and microcracking can be regarded as the primary microstructural manifestations of autogenous shrinkage in UHPC.

From a measurement perspective, because the transition from plastic deformation to stress-bearing shrinkage occurs progressively during setting, the reported magnitude of autogenous shrinkage is sensitive to the reference time used to zero the deformation curve, commonly referred to as the time-zero (t0). The start of data acquisition should be distinguished from t0, because deformation may be continuously recorded soon after casting but subsequently re-referenced to a selected stage of hardening. Selecting initial setting, final setting, or a physically based criterion such as the onset of internal RH reduction as t0 determines how much very-early-age deformation is included in the reported autogenous shrinkage [39]. Consequently, different time-zero definitions may alter the reported early-age shrinkage and the apparent effectiveness of mitigation measures. For meaningful comparison among studies, the measurement start, setting-time determination method, initial and final setting times, time-zero criterion, temperature-correction procedure, curing temperature, and test age should therefore be clearly reported.

Overall, pore refinement and self-desiccation amplify the capillary driving force, while stiffness development and restraint convert autogenous deformation into tensile stress and possible cracking. The selected time-zero does not alter these underlying mechanisms but determines which portion of the early-age deformation is represented in the reported test result.

3. Mitigation strategies for autogenous shrinkage in UHPC

3.1 Moisture regulation through internal curing

3.1.1 Superabsorbent polymers (SAPs)

SAPs are among the most widely studied internal curing materials for mitigating autogenous shrinkage in UHPC. During hydration, SAPs gradually release previously absorbed water, thereby compensating for self-desiccation, maintaining internal relative humidity, and delaying capillary pressure development (As illustrated in Figure 4(a-b)) [42]. Internal RH measurements confirm that SAP addition effectively delays self-desiccation, maintaining humidity above 89% in UHPC mixtures with increasing SAP content [43]. In addition to moisture compensation, SAPs delay the main hydration peak but subsequently promote the degree of hydration in a manner similar to increasing the water-to-cement ratio [44]. As a result, SAP-based internal curing has been shown to effectively reduce autogenous shrinkage while promoting a higher degree of cement hydration.

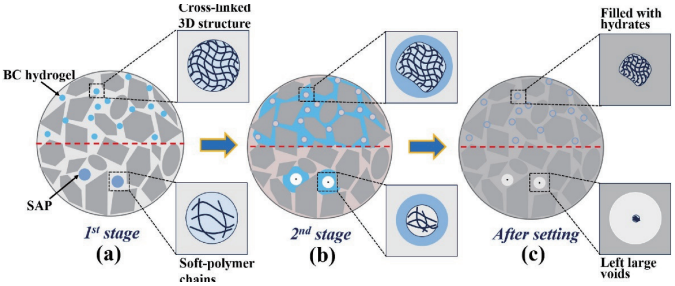


Figure 4. Schematic illustration of the internal curing mechanism of superabsorbent polymers (SAPs) in UHPC during hydration [47].

The effectiveness of SAP depends on its absorption capacity, particle size, dosage, water-release behavior, and pre-treatment method [45]. Among these factors, particle size plays a critical role in determining internal curing efficiency. Smaller SAP particles generally provide a larger number of water reservoirs and a wider curing zone within the dense UHPC matrix, whereas larger particles typically possess higher water-storage capacity. However, the influence of particle size remains complex because it is also closely related to the absorption and desorption characteristics of SAP. Temperature can further influence SAP water-release behavior and internal

curing efficiency [46]. Despite their effectiveness in shrinkage mitigation, SAPs may introduce residual voids after water release, potentially affecting mechanical performance (As illustrated in Figure 4(c)) [47-49]. Therefore, the overall effectiveness of SAP is governed by the balance between hydration enhancement and pore generation, making the optimization of SAP characteristics and water-release kinetics a key research focus.

3.1.2 Porous water reservoirs

Porous materials can absorb and store water prior to mixing and release it gradually during hydration, thereby compensating for internal water consumption, maintaining internal relative humidity, and alleviating self-desiccation [50]. Depending on particle size and pore characteristics, they can be classified into porous aggregates and porous powders, which differ in water-storage capacity, pore scale, and compatibility with the dense particle-packing system of UHPC.

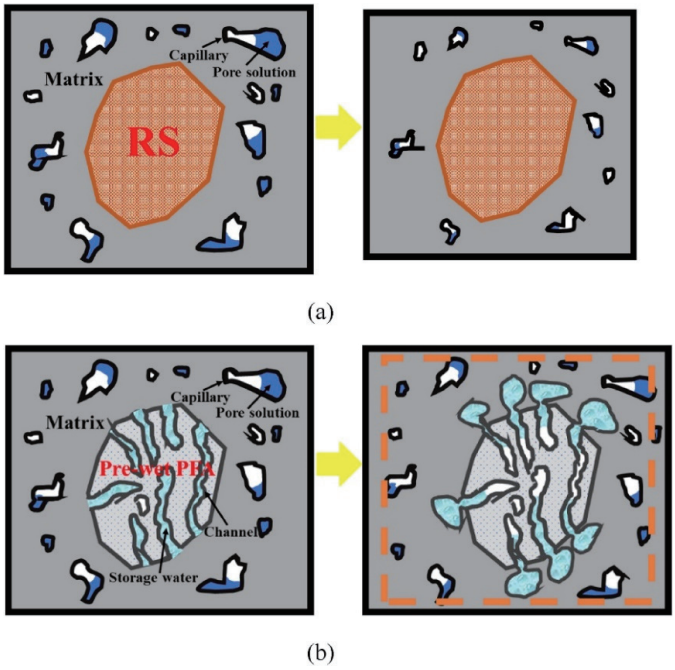


Figure 5. Schematic illustration of water release behavior in porous aggregates during hydration: (a) conventional aggregate (RS) without water release capacity; (b) pre-wetted porous fine aggregate (PFA) providing internal curing through gradual water desorption via interconnected pore channels [61].

Porous aggregates, including lightweight aggregates (LWAs) [51, 52], pumice [51], expanded shale [53], zeolite [54], and recycled aggregates [55], typically absorb 10%–30% of their own mass in water via physical capillary forces [56, 57], as schematically illustrated in Figure 5. Appropriately dosed porous aggregates can effectively mitigate autogenous shrinkage while maintaining or slightly improving compressive strength; however, excessive incorporation may introduce additional porosity and compromise mechanical performance [58]. For example, replacing 40% of aggregates with pre-saturated lightweight sand resulted in 75% less autogenous shrinkage at 56 days and a 10% higher internal relative humidity compared to the reference mixture [59]. Furthermore, the pretreatment method significantly influences curing efficiency, with vacuum-saturated porous aggregates demonstrating superior internal curing performance compared to conventionally soaked or untreated aggregates [58]. Their curing efficiency depends critically on pore size and connectivity, making quantitative characterization of pore structure essential for optimization [60].

In contrast, porous powders, such as rice husk ash and bottom ash [62, 63], generally exhibit lower water-storage capacities but offer better compatibility with the dense particle-packing system of UHPC. Besides serving as internal water reservoirs, they may further enhance microstructural refinement through filler effects and, in some cases, pozzolanic reactions [62]. As shown in Figure 6, porous aggregates can develop relatively dense interfacial transition zones (ITZs), whereas porous powders such as rice husk ash may become tightly integrated with the surrounding cement matrix, further contributing to microstructural integrity [58, 62].

Overall, porous materials cause relatively limited disruption to the UHPC matrix, but their shrinkage mitigation efficiency is sensitive to pre-wetting degree, pore size distribution, and water migration distance, necessitating careful optimization for specific UHPC mix designs.

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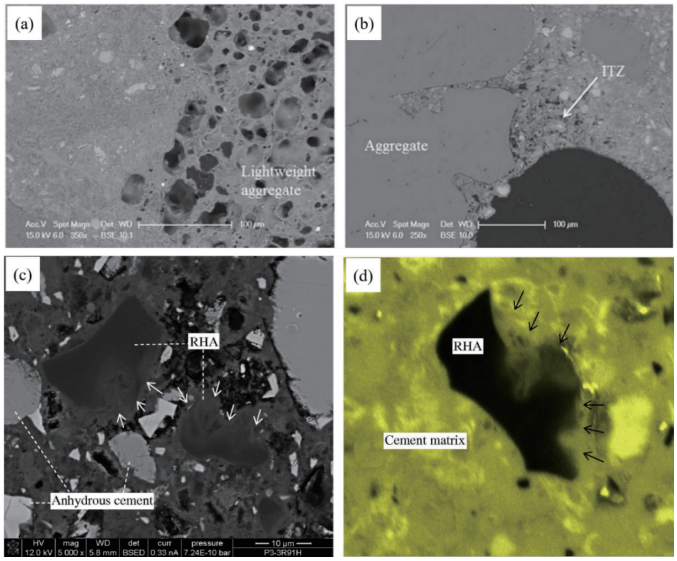


Figure 6. Representative interfacial characteristics of porous aggregates and porous powders in cementitious matrices: (a, b) lightweight aggregate (LWA) and its interfacial transition zone (ITZ); (c, d) rice husk ash (RHA) particles embedded within the cementitious matrix [58, 62].

3.1.3 Emerging internal curing carriers

Beyond SAPs and porous water reservoirs, a number of emerging internal curing materials have been proposed to further improve the efficiency of internal curing in UHPC. Among them, cellulose fibers have attracted particular interest because their hollow lumen structure enables water absorption

and storage, allowing them to function as internal water reservoirs during hydration [64, 65]. In addition to mitigating self-desiccation, cellulose fibers can improve crack resistance and toughness, providing simultaneous benefits in shrinkage control and mechanical performance [66]. More recently, cellulose nanofibers (CNFs) have attracted increasing attention because of their superior water-retention capacity and ability to modify the microstructure of cementitious materials [67]. Compared with conventional cellulose fibers, CNFs possess a much larger specific surface area, resulting in enhanced water-retention capacity and greater potential for microstructural refinement in cementitious composites [68].

In addition, microcapsule-based systems have been proposed to encapsulate water within a protective shell and release it in a controlled manner during hydration, thereby improving water-use efficiency and reducing premature water loss [69, 70]. Although these approaches remain at an early stage of development, they highlight the growing trend toward multifunctional internal curing systems capable of simultaneously regulating hydration, shrinkage, and microstructural evolution.

3.2 Hydration regulation strategies

Since cement hydration is the fundamental driving force behind autogenous shrinkage in UHPC, regulating hydration kinetics provides an alternative route to shrinkage mitigation. Unlike internal curing, which compensates for water consumption by supplying additional water, hydration regulation aims to reduce or delay early-age hydration, thereby slowing the development of autogenous shrinkage. Various approaches have been proposed to achieve this objective, including binder modification and curing-condition control.

A common approach to hydration regulation is to partially replace highly reactive constituents, particularly cement and silica fume, with supplementary cementitious materials (SCMs), inert fillers, or low-reactivity binders. In general, reducing the overall reactivity of the binder system slows early-age hydration, thereby decreasing water consumption and mitigating autogenous shrinkage. However, the influence of SCMs is often complex because their effectiveness depends on material characteristics and dosage, which can simultaneously affect hydration kinetics and pore structure evolution. For example, Ghafari, Ehsan, et al. [27] reported that replacing silica fume with fly ash or ground-granulated blast-furnace slag (GGBS) effectively reduced the autogenous shrinkage of UHPC, with the greatest reduction observed at a silica-fume replacement level of 100%. Furthermore, similar reductions in autogenous shrinkage have also been reported for other SCMs, including rice husk ash and metakaolin [71, 72]. These findings indicate that shrinkage mitigation is governed not only by changes in hydration kinetics but also by the resulting microstructural evolution.

In addition to SCM replacement, hydration kinetics can also be regulated through the use of low-reactivity cement systems. For instance, belite-rich cement, owing to its lower early-age reactivity than ordinary Portland cement, has been shown to reduce hydration heat release and autogenous shrinkage while maintaining satisfactory later-age mechanical performance [73, 74].

Beyond binder modification, hydration kinetics can also be regulated through temperature control. Xuan et al. [75] demonstrated that the incorporation of dry ice (solid CO_2) delayed early-age hydration and significantly mitigated autogenous shrinkage by reducing the early-age temperature rise associated with cement hydration.

3.3 Internal restraint enhancement strategies

In addition to internal curing and hydration regulation, enhancing the internal restraint capacity of UHPC represents another effective strategy for mitigating autogenous shrinkage. By incorporating reinforcing phases capable of redistributing internal stresses and providing mechanical restraint, the susceptibility of UHPC to shrinkage-induced deformation and cracking can be significantly reduced.

Fiber reinforcement is one of the most widely adopted approaches for enhancing internal restraint in UHPC. Owing to their high stiffness and crack-bridging capability, fibers can effectively redistribute shrinkage-induced stresses and restrain deformation development. As schematically illustrated in Figure 7, compared with the plain matrix where shrinkage-induced tensile stress is more likely to localize and develop into cracks, fiber-reinforced concrete can bridge microcracks, distribute tensile stress more uniformly, and limit crack opening. Steel fibers, which are commonly incorporated in UHPC, have been shown to reduce autogenous shrinkage and improve crack resistance by providing mechanical restraint within the cementitious matrix. For example, Wu et al. [76] demonstrated that increasing the steel-fiber content from 0% to 3% progressively reduced the autogenous shrinkage of UHPC, whereas variations in fiber geometry had a comparatively smaller effect, as shown in Figure 8. Similar benefits have also been reported for other fiber systems, including basalt, polypropylene, and glass fibers, which can enhance the ductility and crack resistance of UHPC [77].
system of UHPC.

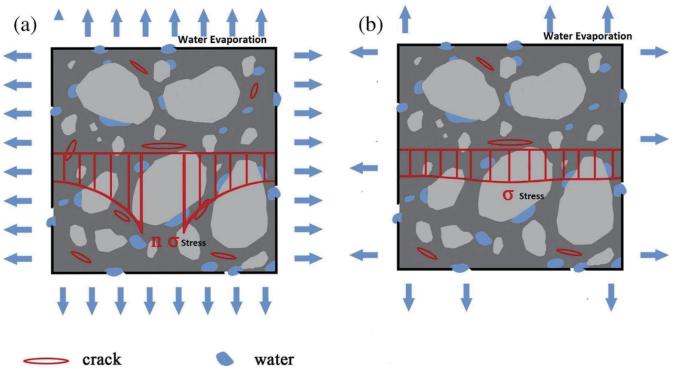


Figure 7. Schematic illustration of fiber-bridging and stress-redistribution mechanisms for controlling shrinkage-induced cracking: (a) plain matrix and (b) fiber-reinforced matrix. Adapted from [78].

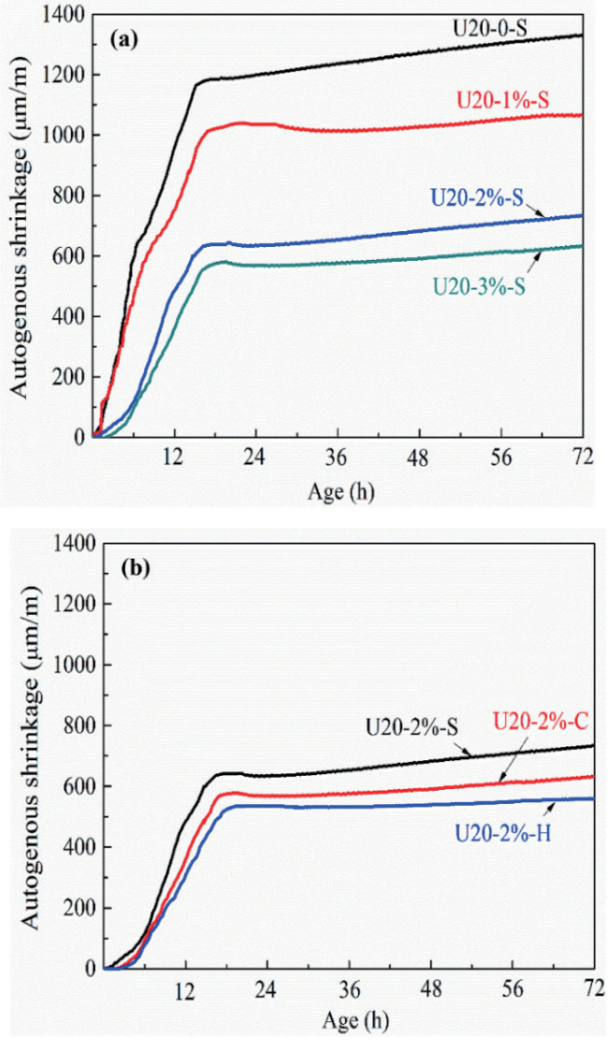


Figure 8. Influence of steel-fiber content and geometry on the development of autogenous shrinkage in UHPC. (a) Different steel-fiber volume fractions; (b) Different fiber geometries [76].

At the nanoscale, CNFs have recently attracted increasing attention as multifunctional additives for shrinkage mitigation. In addition to their water-retention capability, CNFs can enhance internal restraint through their high aspect ratio and crack-bridging ability within the cementitious matrix. By bridging nano- and micro-scale cracks, CNFs improve the resistance of the matrix to shrinkage-induced deformation [68]. Xuan et al. [67] demonstrated that the incorporation of CNFs effectively reduced autogenous shrinkage while simultaneously improving the mechanical performance of UHPC, highlighting the dual benefits of internal curing and nanoscale reinforcement.

At the microscale, micro-reinforcing materials with fibrous or needle-like morphologies can also contribute to shrinkage mitigation. Wollastonite is a representative example that has attracted considerable interest in UHPC. Owing to its acicular particle shape, wollastonite can act as a micro-reinforcement phase, promoting stress redistribution and providing internal restraint through microcrack bridging, thereby reducing shrinkage-induced deformation and cracking [79, 80].

Overall, although fibers, CNFs, and wollastonite differ significantly in composition, size, and reinforcing mechanism, they share a common function of enhancing the internal restraint capacity of UHPC. By enhancing the ability of UHPC to redistribute and resist shrinkage-induced stresses, these approaches complement internal curing and hydration regulation strategies and provide an additional pathway for mitigating autogenous shrinkage.

3.4 Direct shrinkage mitigation strategies

In addition to moisture regulation, hydration control, and internal restraint enhancement, direct shrinkage mitigation strategies provide another important pathway for reducing autogenous shrinkage in UHPC. These strategies directly target either the driving force of shrinkage or the resulting deformation. Shrinkage-reducing admixtures (SRAs) and expansive agents (EAs) are the most representative approaches. SRAs mainly reduce capillary pressure by lowering the surface tension of the pore solution [81, 82], whereas expansive agents compensate shrinkage through controlled volume expansion during hydration [83]. Therefore, these strategies are closely associated with the fundamental mechanisms of autogenous shrinkage, particularly capillary pressure development and early-age deformation evolution.

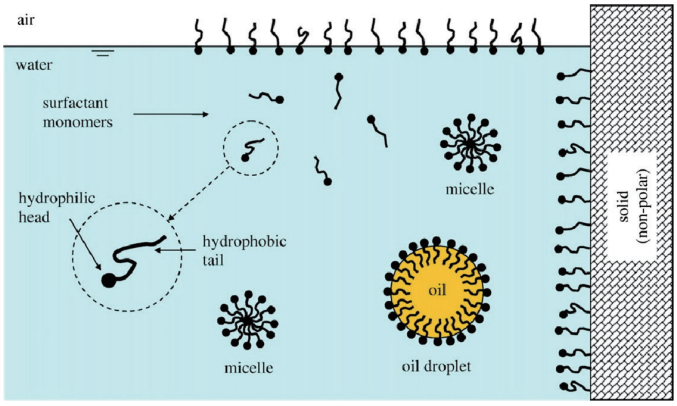


Figure 9. Schematic illustration of the existing forms and interfacial adsorption behavior of SRA molecules in pore solution [84].

SRAs mitigate autogenous shrinkage mainly by regulating the interfacial properties of the pore solution. As amphiphilic surfactant-like molecules, SRAs can adsorb at the liquid–gas interface and reduce the surface tension of the pore solution [84]. As schematically shown in Figure 9, SRA molecules may exist as dissolved monomers, interfacially adsorbed molecules, or micelles; among these forms, adsorption at the liquid–gas interface plays the dominant role in reducing pore solution surface tension. According to the Young–Laplace equation, the reduced surface tension directly lowers the capillary pressure generated by curved menisci during self-desiccation [85]. This mechanism is particularly important for UHPC because it' s very low w/b and refined pore structure accelerate internal RH reduction and amplify capillary stress. In addition to surface tension reduction, SRAs may also influence self-desiccation, internal RH evolution, hydration kinetics, and the

surface free energy of hydration products [86]. Experimental studies have confirmed that properly designed SRAs can effectively reduce shrinkage deformation in cementitious materials, demonstrating that interfacial regulation can improve volume stability [87]. Moreover, the efficiency of SRAs is temperature-dependent; temperature can alter hydration rate, water consumption, pore solution characteristics, and capillary stress development, thereby changing the autogenous volume response of SRA-modified cementitious systems [88]. Nevertheless, excessive SRA dosage may lead to micelle formation, reduce the efficiency of surface tension reduction, retard hydration, or compromise early-age mechanical performance [84]. Therefore, SRA application in UHPC should be optimized to balance shrinkage reduction, hydration development, workability, and mechanical performance.

Expansive agents provide another direct approach by generating controlled chemical expansion within the cementitious matrix to compensate shrinkage deformation. Unlike SRAs, which reduce capillary stress, expansive agents mainly offset contraction through expansive hydration products (Figure 10(a)). Common systems include calcium sulfoaluminate-based [89], CaO-based [90], and MgO-based [90] expansive agents. Calcium sulfoaluminate (CSA)-based agents expand mainly through ettringite formation [91], whereas CaO- and MgO-based agents generate expansion through the hydration of CaO to $Ca(OH)_2$ and MgO to $Mg(OH)_2$, respectively [92]. These systems differ in their water demand, thermal stability, and expansion timing: CSA-based agents may be limited in UHPC by the water-consuming and heat-sensitive formation of ettringite [93], MgO-based agents require less water but may react slowly and cause delayed expansion [94], whereas CaO-based agents are generally more compatible with UHPC because of their relatively low water demand and early expansion. For example, Shen et al. [83] reported that increasing the dosage of CaO-based expansive agent to 5% eliminated the 7-day autogenous shrinkage of cement paste with a w/b of 0.18. However, their efficiency in UHPC is limited by insufficient free water, dense microstructure, and rapid stiffness development, which may restrict both expansive-agent hydration and effective expansion space (Figure 10(b)) [83]. Excessive dosage or poorly timed expansion may further generate internal stress and increase the risk of microcracking. Therefore, the type, reactivity, dosage, and curing condition of expansive agents should be coordinated with the hydration kinetics and shrinkage evolution of UHPC.

In addition, based on previous studies, the combined use of SRA and EA appears to be a promising direction for direct shrinkage mitigation in UHPC. SRA can reduce the capillary stress generated during self-desiccation, while EA can compensate the remaining shrinkage deformation through controlled expansion. Therefore, the SRA–EA system may provide a complementary effect by acting on both the driving force and the deformation outcome of autogenous shrinkage. Recent studies on UHPC containing SRA and EA have further indicated that this combined effect is closely related to curing temperature, hydration development, and expansion timing [95, 96]. However, such synergy is not a simple superposition of the two mechanisms, because SRA may influence hydration kinetics and EA reaction efficiency. Therefore, the dosage ratio and curing condition of SRA–EA systems should be carefully optimized to reduce residual shrinkage and associated cracking risks in restrained UHPC applications.

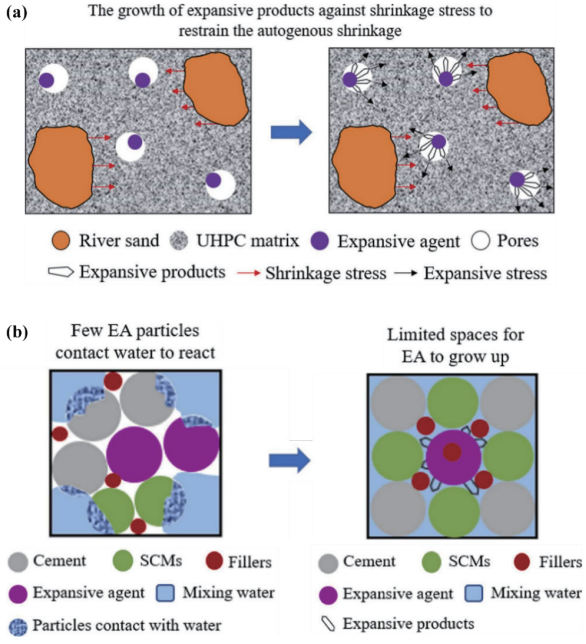


Figure 10. Schematic illustration of the compensatory expansion mechanism of expansive agents and their limitations in UHPC: (a) shrinkage compensation by expansive products; (b) restricted hydration and expansion space in dense UHPC matrix. Adapted from [90].

4. Comparison and integrated assessment of different mitigation strategies

4.1 Shrinkage mitigation efficiency

The shrinkage mitigation efficiency of different strategies in UHPC should be interpreted in relation to the shrinkage-development process rather than being evaluated only by the maximum reported reduction percentage. Autogenous shrinkage in UHPC is governed by coupled processes, including rapid water consumption, internal RH reduction, capillary pressure development, matrix stiffening, and stress accumulation under restraint [97, 98] . Therefore, an efficient mitigation strategy should match the dominant shrinkage-driving mechanism and the critical time window of the target UHPC system. A comparative assessment of the representative mechanism-based strategies is presented in Table 1. Rather than establishing a universal ranking, the comparison highlights the dominant action stage, typical shrinkage-control effect, and major limitations of each strategy.

SRAs mitigate autogenous shrinkage mainly by regulating the interfacial properties of the pore solution. As amphiphilic surfactant-like molecules, SRAs can adsorb at the liquid–gas interface and reduce the surface tensi

Within this framework, moisture regulation through internal curing is generally effective for early-age autogenous

Table 1(a). Comparative assessment of mechanism-based shrinkage mitigation strategies in UHPC.

Mechanism-based category	Representative strategies	Typical action period	Typical shrinkage-control effect	Main limitations	References
Moisture regulation through internal curing	SAPs; pre-saturated LWA; zeolite; pumice; porous powders	Mainly early-age shrinkage development, with effects potentially extending to later ages depending on water-release behavior	Effectively mitigates self-desiccation-driven shrinkage by maintaining internal RH and supplying additional curing water	Efficiency depends on water-release behavior and may introduce additional pores	[20, 42, 45]
Hydration regulation strategies	SCMs; low-reactivity binders; optimized binder systems	Early to long-term shrinkage development, depending on hydration kinetics and SCM reactivity	Reduces shrinkage by moderating hydration rate and pore refinement	Strongly dependent on material reactivity and replacement level	[27, 71, 72, 74]
Internal restraint enhancement strategies	Steel fibers; CNFs; wollastonite; micro/nano-reinforcements	Throughout shrinkage development, particularly under restrained conditions	Reduces shrinkage-induced deformation and improves crack resistance through internal restraint	Limited influence on self-desiccation and capillary pressure	[76, 77, 79, 80]
Direct shrinkage mitigation strategies	SRAs; expansive agents; SRA–EA systems	Mainly early-age shrinkage development, although the effective period depends on the timing of capillary stress reduction or expansion	Reduces capillary stress and/or compensates shrinkage deformation directly	Sensitive to dosage, reaction timing, and admixture compatibility	[16, 87, 95]

shrinkage because it directly alleviates self-desiccation and delays internal RH reduction [99-101]. This strategy is particularly suitable for UHPC mixtures in which shrinkage is mainly driven by rapid water consumption and limited internal water availability. Direct shrinkage mitigation strategies act closer to the origin or manifestation of shrinkage. SRAs reduce the surface tension of the pore solution and thus weaken capillary pressure, whereas expansive agents compensate shrinkage deformation through controlled chemical expansion [87, 102]. Their efficiency can be high when the action period of the admixture coincides with the main stage of capillary stress development or shrinkage deformation. Hydration regulation strategies, by contrast, usually provide a more indirect and material-dependent effect by moderating hydration rate, water demand, and pore refinement [103, 104]. Internal restraint enhancement strategies are different from the above methods because they may not substantially reduce free autogenous shrinkage, but they are highly relevant for restrained shrinkage conditions by redistributing tensile stress and suppressing crack development [105].

However, quantitative comparisons among studies should be interpreted with caution because the reported shrinkage response depends strongly on mixture composition, mitigation-material dosage, and the definition of the measurement reference state. To complement the mechanism-based comparison in Table 1(a), Table 1(b) provides condition-resolved quantitative evidence from representative studies. The values are intended to illustrate condition-dependent responses rather than establish a universal ranking among mitigation strategies.

These representative cases demonstrate that the magnitude of shrinkage mitigation is strongly condition-dependent and should be evaluated together with the associated changes in pore structure, strength, internal humidity, workability, or expansion behavior rather than by the reduction percentage alone.

Therefore, the selection of shrinkage mitigation strategies should be based on the dominant shrinkage-control target rather than on a single reduction value. For self-desiccation-dominated UHPC, internal curing or SRA may be more efficient. For systems requiring deformation compensation, expansive agents or SRA–EA combined systems may provide additional benefits. For restrained applications, such as repair layers, bridge deck overlays, wet joints, or UHPC–normal concrete interfaces, the ability to reduce shrinkage-induced stress and cracking risk can be as important as the reduction of free autogenous deformation.

Table 1(b). Condition-resolved quantitative comparison of representative autogenous-shrinkage mitigation studies in UHPC.

Mechanism-based category	Representative study	Mixture / binder characteristics	Mitigation parameters	Test conditions	Autogenous shrinkage response	Performance trade-offs
Moisture regulation through internal curing	Al Moman et al. (2025) [20]	w/b = 0.147; Portland cement 770 kg/m^3, SF 236 kg/m^3, limestone powder 311 kg/m^3	Pre-saturated LWS; 10–40 vol.% replacement of natural sand; 40% LWS = 201 kg/m^3	Time-zero: final setting; test age: 56 d	40% LWS reduced 56-d autogenous shrinkage by 75% (− 1155 → − 295 με).	Maintained strength while increasing IRH and reducing self-desiccation.
Hydration regulation	Ghafari et al. (2016) [27]	w/b ≈ 0.22; Portland cement; reference mixture with 24% SF	FA/GGBS replacing SF at 50% and 100%	Time-zero: NR; test age: 28 d	Autogenous shrinkage decreased progressively with SF replacement, with 100% FA/GGBS replacement showing the lowest values.	Lower shrinkage was associated with reduced fine-pore volume, with a trade-off in compressive strength depending on SCM and curing condition.
Internal restraint enhancement	Wu et al. (2019) [76]	w/b = 0.18; 80% Portland cement + 20% SF	Steel fibers, 0–3 vol.%; 0.2 mm × 13 mm; straight/corrugated/hooked	Time-zero: first measurement after casting; test age: 72 h	1%, 2%, and 3% straight fibers reduced autogenous shrinkage by 17%, 50%, and 53%, respectively, at 16 h.	Fiber addition increased compressive/flexural strength while reducing shrinkage, although high fiber contents may impair workability.
Direct shrinkage mitigation	Zhang et al. (2024) [95]	w/b = 0.18; cement–SF–quartz powder–microbeads–mineral powder–FA binder	1% SRA; 1% SRA + 7.5% EA	Time-zero: onset of shrinkage-stress generation; test age: 150 d	1% SRA reduced 150-d autogenous shrinkage by 24.4% and 22.8% under standard and natural curing, respectively; SRA+EA produced strong expansion compensation.	SRA/EA improved shrinkage control but excessive EA caused delayed expansion and potential strength/durability deterioration.

4.2 Performance trade-offs: hydration, microstructure, strength, and durability

Although the strategies discussed above can mitigate autogenous shrinkage in UHPC, their overall effectiveness should not be assessed only by shrinkage reduction. UHPC is a highly optimized cementitious system in which hydration kinetics, particle packing, pore structure, interfacial bonding, mechanical strength, and durability are strongly coupled [1, 9]. Therefore, a strategy that reduces autogenous shrinkage may also modify the hydration process, alter the pore structure, or affect the compactness and load-bearing capacity of the matrix. From this perspective, shrinkage mitigation should be regarded as a multi-objective optimization problem rather than a single-index improvement.

Moisture regulation through internal curing illustrates this trade-off clearly. SAPs and porous water reservoirs can release stored water during hydration, thereby maintaining internal RH, promoting further hydration, and reducing self-desiccation-induced shrinkage [43, 45, 106]. However, the additional water reservoirs introduced into the UHPC matrix may also become residual voids or weak zones after

water release. For SAPs, excessive dosage, inappropriate particle size, or excessive additional water may increase macroporosity and reduce strength, even though internal curing can effectively mitigate autogenous shrinkage [107, 108]. This strength–shrinkage balance is consistent with the general concept of water-entrained cementitious materials, where internally stored water improves hydration but may leave designed pores after water release [109]. For porous aggregates, the lower stiffness of the aggregate and the quality of the interfacial transition zone may influence strength and transport properties, although optimized pre-treatment and pore structure can improve internal curing efficiency [58, 60]. In contrast, some porous powders, such as rice husk ash, may provide both internal curing and microstructural refinement through filler effects or pozzolanic reactions [62]. Therefore, the key challenge for internal curing is to achieve sufficient water release while minimizing the negative influence of additional pores on matrix compactness.

Hydration regulation strategies involve a different balance between shrinkage reduction and performance development. Replacing cement, silica fume, or other highly reactive constituents with SCMs, low-reactivity binders, or inert fillers can reduce early water consumption and slow the development of self-desiccation, thereby mitigating autogenous shrinkage [72, 73]. However, excessive replacement may dilute the binder system, reduce the amount of early hydration products, and delay stiffness and strength development. The final performance depends on the competition among dilution effect, filler effect, particle packing, and later-age pozzolanic reaction. For example, fly ash, GGBS, rice husk ash, metakaolin, limestone powder, calcined clay, and belite-rich cement may reduce autogenous shrinkage through different mechanisms, but their effects on early strength, later-age densification, and durability are not identical [27, 71, 72, 103]. Similar performance-based UHPC mixture design studies have also shown that efficient use of cement and mineral admixtures requires balancing packing density, binder reactivity, mechanical performance, and environmental impact [110]. Thus, hydration regulation should not simply aim to suppress early hydration; it should maintain sufficient early-age stiffness while enabling long-term pore refinement and durability improvement.

Internal restraint enhancement strategies, especially fiber and micro/nano-reinforcement, mainly influence the mechanical response of UHPC rather than the origin of self-desiccation. Steel fibers, cellulose nanofibers, wollastonite microfibers, and other reinforcing phases can restrain shrinkage deformation, redistribute tensile stress, and bridge microcracks, thereby improving cracking resistance and post-cracking behavior [67, 76, 77, 79, 80]. These effects are particularly valuable for restrained UHPC applications, where shrinkage-induced tensile stress may be more critical than free autogenous deformation. However, the incorporation of reinforcing phases may also affect fresh and hardened properties. High fiber volume fractions can reduce flowability, disturb particle packing, and cause fiber clustering or weak interfacial zones if dispersion is not well controlled. Previous studies on UHPFRC have shown that the improvement in strength and ductility depends strongly on fiber content, fiber geometry, orientation, and matrix compatibility [111, 112]. Similarly, micro/nano-reinforcements may improve microstructural integrity at appropriate dosages, but agglomeration can reduce their reinforcing efficiency and create local defects. Therefore, internal restraint strategies require careful control of reinforcement type, dosage, dispersion, and interfacial bonding.

Direct shrinkage mitigation strategies also present important performance trade-offs. SRAs directly reduce capillary pressure by lowering the surface tension of the pore solution, but they may influence hydration kinetics, setting behavior, air-void characteristics, and early-age mechanical performance [86-88]. Excessive SRA dosage may reduce the efficiency of surface tension reduction due to molecular aggregation and may retard cement hydration. In addition to autogenous shrinkage mitigation, SRA-related studies have also reported its influence on shrinkage cracking behavior, indicating that its benefits should be evaluated together with fresh-state and early-age performance [113]. Expansive agents compensate shrinkage through expansive hydration products, but their performance depends strongly on water availability, reaction rate, and expansion timing. Insufficient expansion may fail to compensate shrinkage, whereas excessive or delayed expansion after matrix stiffening may generate internal stress and microcracking [83, 90, 91, 95, 96]. In SRA–EA combined systems, the interaction becomes more complex because SRA may influence hydration and EA reaction efficiency, while EA expansion must be synchronized with shrinkage development [82,83]. Therefore, direct mitigation strategies should be optimized not only for shrinkage reduction but also for hydration compatibility and microstructural stability.

Overall, the performance trade-offs of different mitigation strategies arise from the same fundamental issue: reducing autogenous shrinkage often requires altering water distribution, hydration kinetics, pore structure, or internal stress transfer in UHPC. Internal curing improves moisture availability but may introduce additional pores; hydration regulation lowers shrinkage by moderating early reactions but may delay strength development; internal restraint enhances crack resistance but may affect workability and homogeneity; and direct mitigation strategies reduce capillary stress or compensate deformation but may disturb hydration or generate internal damage if improperly designed. Accordingly, no mitigation strategy should be regarded as optimal solely because it achieves the largest reported shrinkage reduction. Its suitability should instead be evaluated through a multi-criteria assessment of hydration and setting development, pore structure and residual void formation, workability and constructability, strength retention, durability-related transport properties, and resistance to restrained shrinkage cracking under the intended curing and restraint conditions. The optimal strategy is therefore application-dependent and should achieve an acceptable balance between shrinkage control and the other required fresh-state, mechanical, and durability properties of UHPC. This multi-performance

balance provides the basis for the synergistic and application-oriented design discussed in the following section.

4.3 Synergistic strategies and application-oriented selection

Synergistic shrinkage mitigation should be regarded as mechanism-complementary regulation rather than the simple addition of multiple admixtures. Since autogenous shrinkage in UHPC results from coupled hydration, self-desiccation, capillary pressure development, matrix stiffening, and restrained stress accumulation, a single strategy often addresses only part of the shrinkage-development process. Therefore, more effective control can be achieved by combining strategies with different but compatible functions. For example, internal curing can alleviate self-desiccation by supplying additional water, while hydration regulation can reduce early water consumption and moderate pore refinement [114, 115]. Similarly, SRA–EA systems can act on both the driving force and the deformation outcome of shrinkage: SRA reduces capillary stress by lowering pore solution surface tension, whereas EA compensates residual deformation through controlled expansion. Fiber reinforcement can further improve cracking resistance in restrained systems, although its role is mainly related to stress redistribution and crack control rather than direct suppression of self-desiccation [116, 117]. Thus, the key to synergy lies in matching water release, hydration rate, capillary stress reduction, expansion timing, and restraint capacity.

Application-oriented selection is equally important because different UHPC structures do not face the same shrinkage risk. For mixtures with extremely low water-to-binder ratios and rapid internal RH reduction, internal curing and SRA are more suitable as primary measures. For systems where residual shrinkage deformation remains significant, expansive agents or SRA–EA combinations may provide additional compensation, provided that expansion occurs within the effective shrinkage-development period. For repair layers, wet joints, bridge deck overlays, and UHPC–normal concrete interfaces, restrained shrinkage and interfacial cracking are often more critical than free autogenous deformation; therefore, shrinkage-reducing measures should be combined with sufficient tensile reinforcement or fiber bridging capacity [64, 118]. Overall, the selection of mitigation strategies should shift from material-based trial-and-error toward performance-oriented design, in which the dominant shrinkage mechanism, curing condition, structural restraint, and required durability are considered simultaneously.

4.4 Sustainability and future-oriented design framework

Future shrinkage mitigation of UHPC should be developed within the broader context of sustainable and crack-resistant cementitious materials. Due to its high binder content, low water-to-binder ratio, and frequent use of steel fibers, UHPC may have a relatively high material-level environmental burden. However, its dense microstructure, high strength, and superior durability can also extend service life and reduce maintenance demand [110, 119]. Therefore, sustainability-oriented shrinkage mitigation should not simply aim at reducing cement content or adding low-carbon materials; it should ensure that clinker reduction, autogenous shrinkage control, strength development, and durability are achieved simultaneously. Low-carbon binders incorporating SCMs, limestone powder, calcined clay, slag, fly ash, rice husk ash, recycled powders, or belite-rich cement are promising, but their effects on hydration kinetics, internal RH evolution, pore refinement, and early-age stiffness must be systematically evaluated [27, 71, 74]. Otherwise, a mixture with reduced carbon footprint may still exhibit high shrinkage-induced cracking risk if its early-age volume stability is not properly controlled.

A future-oriented strategy should also shift from single-measure shrinkage reduction to time-matched and mechanism-integrated regulation. Internal curing, SRA, expansive agents, hydration regulation, and fiber reinforcement act through different pathways, but their effectiveness depends on whether their action periods are synchronized with UHPC shrinkage development. For example, water release from internal curing agents should match the period of rapid self-desiccation; SRA should be effective during capillary stress development; expansive reactions should occur after sufficient skeleton formation but before excessive shrinkage stress accumulation; and fibers should provide restraint and crack-bridging capacity when residual tensile stress develops [16, 43, 76, 87]. Therefore, future research should focus on the compatibility and synchronization among water release, hydration rate, capillary pressure reduction, compensatory expansion, stiffness development, and restrained stress evolution, rather than optimizing each material independently.

Based on the above considerations, future UHPC shrinkage mitigation should move toward a multi-criteria design framework that integrates mechanism-based shrinkage regulation, performance trade-off control, application-specific crack-risk assessment, and sustainability evaluation. For precast UHPC, early-age volume stability and curing compatibility may be the priority; for repair layers, wet joints, bridge deck overlays, and UHPC–normal concrete interfaces, restrained shrinkage and interfacial cracking should receive greater attention [118, 120]; for long-life infrastructure, crack resistance, chloride resistance, mechanical retention, and carbon footprint should be assessed together. In this framework, the success of a mitigation strategy should no longer be judged only by the reduction of free autogenous shrinkage, but by its ability to deliver stable hydration, dense microstructure, sufficient strength, low cracking risk, durable service performance, and reduced environmental impact. This transition from single-index shrinkage reduction to shrinkage-aware performance design represents a key direction for future UHPC research.

5. Conclusions

This review synthesized autogenous shrinkage mitigation in UHPC from a mechanism-based and performance-oriented

perspective. Instead of treating mitigation strategies as isolated material solutions, this review linked shrinkage mechanisms, mitigation pathways, mechanical performance, durability, and sustainability to establish a more integrated understanding of shrinkage control in UHPC. The main conclusions are as follows:

(1) Autogenous shrinkage in UHPC results from the coupled evolution of hydration, chemical shrinkage, self-desiccation, internal RH reduction, capillary pressure, and matrix stiffening. Effective mitigation therefore depends on matching the intervention to the dominant shrinkage-driving stage rather than applying a single strategy throughout the entire process.

(2) The four mitigation pathways differ in their dominant functional stages: internal curing acts primarily at early ages by alleviating self-desiccation; SRAs act mainly during active capillary-stress development; expansive agents compensate deformation over the expansion reaction period; and fibers or micro/nano-reinforcements contribute mainly after stiffness develops, particularly under restraint. Their effectiveness is therefore highly time- and condition-dependent.

(3) The principal trade-offs are strategy-specific: internal curing may introduce additional porosity, hydration regulation may alter strength development, high fiber contents may reduce workability, and excessive expansive-agent dosage may cause delayed expansion and cracking. Shrinkage reduction should therefore be evaluated together with strength, workability, durability, and cracking resistance.

(4) Strategy selection should be application-oriented. Internal curing is most suitable for UHPC dominated by early-age self-desiccation, SRA or SRA–EA systems for direct shrinkage control or deformation compensation, hydration regulation where binder modification can be tolerated, and fiber or micro/nano-reinforcement for restrained applications requiring stress redistribution and crack control.

CRediT authorship contribution statement

Meiyu Xuan: Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. Juhyuk Moon: Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no knowncompeting financial interests or personal relationshipsthat could have appeared to influence the work reportedin this paper.

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