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Technical Paper

Ultra–high performance lightweight concrete (UHPLC) for sustainable infrastructure: materials design, performance, and outlook

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Abstract: Ultra-high-performance lightweight concrete (UHPLC) integrates the high strength and durability of UHPC with reduced self-weight through the use of lightweight fillers and aggregates. This review synthesizes recent advances in UHPLC mixture design, workability, mechanical properties, volume stability, shrinkage, thermal/fire performance, and environmental impact. Strategies to mitigate strength loss, shrinkage, and segregation are critically discussed. Key engineering applications are highlighted. Current limitations and future research directions are identified to guide the development of next-generation UHPLC systems with enhanced performance and sustainability.

Keywords: Ultra-high performance lightweight concrete (UHPLC); Workability; Shrinkage and volume stability; Thermal insulation and fire resistance; Sustainable concrete materials.

1. Introduction

1.1 UHPC: Evolution and key features

The evolution of cement-based materials from normal concrete (NC) to ultra-high performance concrete (UHPC) represents a significant milestone in structural engineering. Traditional NC, with a typical compressive strength of approximately 30 MPa, primarily relies on coarse and fine aggregates for structural integrity. However, it is often characterized by relatively high permeability and a strong propensity for cracking under environmental and mechanical stress. The emergence of high-performance concrete (HPC), with strengths up to 80 MPa, has been driven by a combination of factors. HPC is a multifaceted material system, characterized by optimized aggregate selection, the synergistic use of mineral admixtures (e.g., silica fume and fly ash), tailored water-to-binder ratios, and advanced mix design strategies aimed at enhancing strength, durability, workability, and long-term performance [1]. These developments collectively contributed to significant improvements in mechanical and durability properties, paving the way for the subsequent evolution of UHPC.

Building upon these innovations, UHPC further pushes the boundaries by integrating the principles of densified particle packing, nano-scale reactive fillers, and fiber-reinforced systems [2, 3]. As a result, UHPC achieves compressive strengths exceeding 150 MPa, tensile strengths in the range of 5–15 MPa, and exhibits exceptional toughness and ductility [4]. In addition to its outstanding mechanical performance, UHPC demonstrates superior durability characteristics, including ultra-low permeability (< 10^{-12} m/s), and high resistance to chloride penetration, carbonation, sulfate

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attack, and freeze–thaw cycles [5]. These attributes have led to its widespread application in critical infrastructure, such as long-span bridges, nuclear power facilities, prefabricated structural components, and marine and offshore structures [6].

1.2 Need for UHPLC

Despite the superior mechanical and durability properties of ultra-high performance concrete (UHPC), its high density remains a major limitation in certain structural and functional applications. Conventional UHPC formulations typically rely on dense mineral aggregates such as quartz sand or basalt sand, resulting in unit weights ranging from 2400 to 2600 kg/m^3 [7]. While such density is beneficial for strength development, it introduces challenges in applications where self-weight, transportability, or energy efficiency is a concern.

The high density of UHPC can lead to increased structural dead loads, particularly problematic in long-span bridges and high-rise buildings, where reduced mass can significantly improve load efficiency and seismic performance. Moreover, the heavy weight of UHPC elements increases construction complexity and cost, especially in prefabricated and modular systems where transport and on-site assembly are critical factors. In emerging applications such as 3D printing, UHPC's flowability and pumping behavior are further constrained by its weight and high solid content [8].

The development of UHPLC has evolved from two parallel approaches aimed at reducing the density of cement-based materials: the introduction of air voids and the use of lightweight aggregates (LWAs). While the former, achieved through chemical or physical foaming, is limited to non-structural applications due to poor mechanical integrity, the latter has gained traction for structural use. Early combinations of UHPC and LWA faced challenges due to the low strength and high water absorption of typical LWAs. However, advances in engineered LWAs, such as sintered ceramics, expanded glass, and nano/micro-sized light fillers, along with improvements in concrete densification and internal curing strategies, have enabled the successful formulation of UHPLC. These developments mark key technological milestones, positioning UHPLC as a viable solution for lightweight, high-strength structural applications.

In response to the demands of modern construction, there is a growing demand for the development of UHPLC. In bridge engineering, UHPLC can reduce deck and girder weight, enhancing both load-carrying capacity and design flexibility [2, 9]. In tall buildings, lowering the overall mass of structural components contributes to better seismic resilience and foundation efficiency [10-12]. In the context of prefabrication, UHPLC facilitates easier transport, lifting, and installation of components, reducing overall construction time and cost. From a sustainability perspective, replacing conventional dense aggregates with low-carbon, recycled lightweight materials not only lowers the material's embodied energy but also aligns with the objectives of green building and carbon reduction strategies [13, 14].

As a result, the pursuit of UHPLC represents a key evolution in UHPC technology—bridging the gap between performance and practicality, and opening new opportunities for sustainable, lightweight, and multifunctional infrastructure solutions.

Bibliometric analysis based on the keyword "Ultra-high performance lightweight concrete & Lightweight UHPC" was conducted using data retrieved from Web of Science and Scopus (Elsevier) databases as of March 25, 2025. As shown in Fig. 1, a significant increase in publications has been observed since 2015, with a sharp rise between 2020 and 2025, indicating growing global interest in UHPLC research. Prior to 2015, only a limited number of studies referenced UHPLC, suggesting that this field is relatively new but rapidly developing. In terms of geographic distribution, the top five contributing countries are China, the United States, Germany, Australia, and South Korea. Notably, China accounts for approximately 56% of the total publications, highlighting its leading role in UHPLC research worldwide.

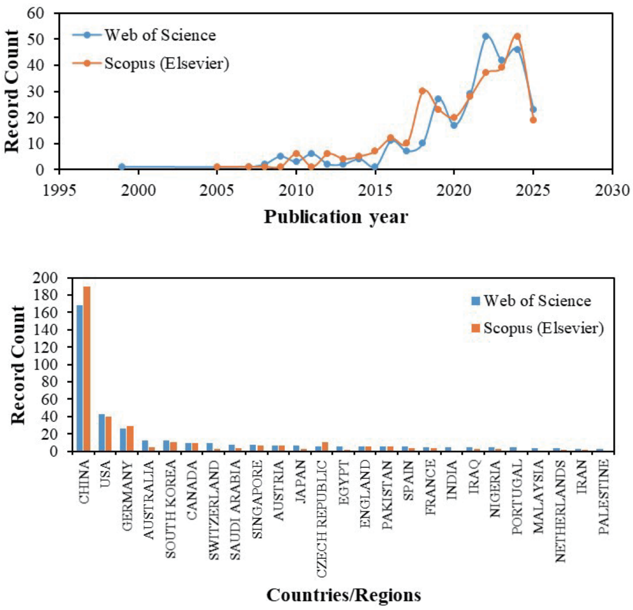

Fig. 1 Bibliometric analysis of publications on lightweight UHPC retrieved from Web of Science and Scopus.

1.3 Scope of the review

This review focuses on the material design, property evaluation, and application potential of UHPLC. It covers:

(1) Selection and classification of lightweight fillers and aggregates;

(2) Fresh and hardened properties, including workability, strength, modulus, and shrinkage;

(3) Thermal and fire performance, fiber integration, and microstructural behavior;

(4) Life cycle environmental performance and carbon footprint analysis;

(5) Engineering applications in bridges, high-rise buildings, prefabricated components, and marine structures.

The review aims to serve as a resource for researchers and practitioners seeking to design and apply UHPLC in performance-critical and sustainability-driven infrastructures.

2. Design philosophy of UHPLC

The development of UHPLC focuses on achieving an optimal balance between reduced density and superior mechanical, durability, and multifunctional properties. To realize this, a variety of strategies have been employed that involve the use of lightweight components, composite optimization, and interface enhancement techniques. Central to this approach is the substitution or partial replacement of traditional dense aggregates and fillers with lightweight alternatives, accompanied by careful matrix refinement and curing design [13].

Lightweight fillers, such as hollow glass microspheres [15] and fly ash cenospheres [16], are frequently used to reduce the matrix density and improve rheological and insulation properties. Their spherical geometry and low specific gravity make them particularly suitable for integration in dense cementitious systems. These materials are typically incorporated at moderate volumes and are often combined with matrix densifiers such as silica fume, nano-silica, or graphene oxide (GO) to ensure particle packing efficiency and mitigate strength reduction. These high-quality supplementary cementitious materials (SCMs) enhance UHPLC performance through both chemical and physical mechanisms. Chemically, pozzolanic reactions contribute to continued hydration and matrix densification. Physically, the ultra-fine particle size of materials such as silica fume and nano-silica improves packing density and reduces porosity via the micro-filler effect. Collectively, these effects contribute to reduced matrix density, increased strength, and improved durability against chloride penetration and freeze–thaw cycling.

A broad range of LWAs have also been introduced into UHPLC formulations. These include recycled expanded glass [17], artificial aggregates such as shale ceramsite [18] and lightweight expanded clay [19], and naturally occurring materials like pumice and volcanic ash-based granules [20]. In some cases, thermally expanded minerals such as perlite and vermiculite are used due to their ultra-low density and thermal insulation capacity [21]. The choice of LWA depends on availability, target density, and compatibility with other mix components.

In addition to solid-phase lightweight materials, foaming techniques have been applied to further reduce concrete density. Chemical foaming involves the introduction of gas-generating agents [22], while physical foaming uses mechanical methods to introduce air into the mix. Although these techniques allow flexible density control, their application in UHPLC is typically limited to non-structural or layered systems due to concerns regarding pore stability and strength retention.

Another critical component of UHPLC design is fiber reinforcement [23]. The use of steel fibers, polyethylene fibers, or hybrid fiber systems enables the enhancement of tensile strength, toughness, and cracking resistance, particularly important given the reduced stiffness associated with many lightweight matrices. Fiber-matrix compatibility and dispersion are essential to achieve these benefits effectively.

In the current development of UHPLC, mixture design predominantly builds upon the particle packing theory that underpins UHPC, where the granular composition of all dry components is carefully tailored to achieve maximum density and minimal porosity. Among the most widely adopted mathematical models is the modified Andreasen and Andersen (MAA) model, which provides a continuous particle size distribution framework to optimize packing density and flow behavior [24].

In recent years, concrete mix design has increasingly integrated mathematical and statistical tools to enhance prediction accuracy and reduce trial-and-error. Representative approaches include the response surface methodology (RSM) for multi-factor optimization, and artificial neural networks (ANN) for nonlinear prediction based on experimental datasets [8]. These data-driven techniques help establish predictive relationships between mixture parameters and performance indicators. The design of UHPLC is expected to transition from empiricism to a science-driven paradigm. This includes coupling theoretical prediction, numerical simulation, and experimental validation into a full-chain optimization framework. The integration of computational materials science and machine learning algorithms holds significant potential to improve efficiency, reproducibility, and material performance consistency in UHPLC design.

Finally, internal and external curing strategies [25, 26] play a pivotal role in ensuring early-age dimensional stability and long-term durability. Pre-saturated LWAs are often used as internal curing agents, helping to regulate internal humidity and reduce autogenous shrinkage. When combined with external methods such as steam curing or dry heat treatment, the matrix can achieve improved hydration, reduced porosity, and enhanced interfacial bonding.

In conclusion, the design of UHPLC is an exercise in multi-objective optimization. By carefully selecting and combining lightweight fillers, aggregates, reinforcement systems, and curing regimes, it is possible to create materials that are not only structurally efficient but also energy-efficient and environmentally sustainable. These strategies collectively underpin the next generation of lightweight concrete technologies, advancing the performance frontier of cement-based materials for modern construction.

3. Physical properties of UHPLC

3.1 Workability

Workability is a critical parameter in evaluating the performance of fresh cementitious mixtures. It reflects the material's ability to fill formworks uniformly under self-weight or external vibration and directly affects pumping efficiency, compaction quality, and surface finish. In the context of UHPLC, achieving adequate workability is essential for ensuring construction efficiency, structural compactness, and uniform performance. However, due to the inherently high content of cementitious materials (typically exceeding 800 kg/m^3), low water-to-binder ratios (<0.25) [27], and significant dosages of high-range water-reducing admixtures, UHPLC often exhibits limited flowability compared to traditional concretes. Moreover, the use of various LWA and fibers adds further complexity to rheological behavior.

The workability of lightweight concrete is strongly influenced by the properties of LWA, including density, shape, surface roughness, and water absorption capacity [28]. Because of the significant density difference between LWA and cement paste, lightweight concrete is particularly sensitive to component volume proportions. Issues such as floating, segregation, and bleeding are more pronounced in low-viscosity systems. Fortunately, the high cohesiveness of UHPC matrices mitigates some of these concerns. When excessive vibration is avoided during casting, LWA flotation can generally be suppressed.

A major rheological challenge arises from the water absorption behavior of porous LWA. If dry aggregates are directly mixed into the UHPC matrix, they rapidly absorb water from the paste, thereby increasing the yield stress and reducing the overall fluidity. Zhang et al. [29] found that compared to dense quartz sand, porous shale ceramsite has a rougher surface and more open pores, increasing internal friction and thickening the mixture. Pre-wetting of LWA has therefore become a widely adopted strategy to moderate this behavior. Pre-saturated aggregates slowly release moisture into the paste, reducing the water gradient and enabling better hydration compatibility [30]. However, the effectiveness of pre-wetting depends on both time and technique. Guo et al. [31] reported that extended pre-soaking time allows water to penetrate finer capillaries in the LWA, further increasing internal water content. This implies that, under a constant total water-to-binder ratio, a higher water absorption capacity of LWA results in less free water remaining in the paste, thereby increasing the mixture's viscosity and reducing flowability.

Vacuum saturation, which allows water to enter smaller pores, often results in higher internal curing capacity, but also leads to a notable increase in paste viscosity. In contrast, simple immersion for 24 hours strikes a balance between sufficient internal water and manageable rheology. Golias et al. [32] demonstrated that dry LWA not only absorbs water, but also sequesters fine cement particles, clogging its pore system and reducing its in-situ water absorption capacity. For aggregates with smaller pores, pre-wetting or prolonged mixing is essential to minimize segregation or bleeding [33].

The effect of LWA type and morphology on flowability has also been well documented. Rafieizonooz et al. [34] showed that artificial lightweight fine aggregates with irregular shape and rough surface increased internal friction and reduced UHPLC fluidity. Conversely, smooth and spherical aggregates such as quartz sand facilitated paste flow [35, 36]. Interestingly, pumice has been found to improve flowability due to its relatively rounded geometry and lower specific gravity [37]. Zeyad et al. [20] and Abadel et al. [38] both reported that substituting pumice for fine aggregates significantly increased slump flow, attributed to the lubricating effect of increased paste volume and smoother LWA surfaces. Similarly, hollow fillers such as fly ash microspheres and hollow glass microspheres—due to their amorphous structure, spherical morphology, and low density—improve workability via the “ball bearing effect,” reducing interparticle friction and enhancing matrix flow [31].

The particle size distribution (grading) of LWAs also plays an important role in the workability of UHPLC [39]. As discussed in Section 2, UHPLC relies on densified particle packing theory to achieve high flowability and physical durability. Prior to mixing, the particle size distribution of LWAs should be analyzed in combination with other solid constituents, and iteratively adjusted to approach the target optimal grading curve. This process improves packing density and reduces the need for excessive water or admixture adjustments during mixing or casting [22, 40]. Moreover, because LWAs typically exhibit high water absorption, it is advisable to use modified packing models that incorporate film thickness theory to better account for water distribution and interparticle lubrication [41]. Such approaches can greatly enhance the predictive accuracy of mixture flowability and reduce the reliance on empirical adjustments.

Fibers also exert a strong influence on the rheology of UHPLC. Steel fibers are most commonly used and tend to reduce workability as their dosage increases [42]. This is primarily due to the formation of a random network within the matrix, which obstructs particle mobility and increases shear resistance [43]. Moreover, increasing fiber content raises the overall specific surface area, requiring more paste to coat each fiber, thus elevating mixture viscosity [44]. Low-density fibers, such as polyethylene or polypropylene, can further aggravate workability loss due to their large surface area and low settling stability [45].

In addition to fibers, chemical additives also modulate UHPLC fluidity. Jiang et al. [18] found that GO reduces slump flow due to its large surface area and capacity to absorb free water [46, 47]. Moreover, GO’s functional groups (e.g., carboxyl, hydroxyl, epoxy) accelerate cement hydration, thereby shortening setting time and stiffening the paste [48]. Similarly, Chen et al. [49] showed that increasing the dosage of expansive agents reduces workability by increasing water demand and shortening setting time [50]. The incorporation of expansive agents accelerates the formation of $Ca(OH)_2$ and promotes earlier cement network development [51]. Furthermore, rupture of LWAs can increase water demand during mixing and decrease interparticle spacing, accelerating matrix stiffening and further reducing workability [45, 52].

In summary, the workability of UHPLC is governed by a complex interplay of factors including LWA absorption behavior, particle shape, internal curing effects, fiber reinforcement, and chemical admixtures. Achieving optimal flowability requires tailored strategies such as aggregate pre-saturation, particle packing optimization, and the careful balancing of admixture dosages. As UHPLC moves toward broader practical application, especially in precast or 3D-printed components, ensuring reliable and consistent workability will remain a key technical challenge and design priority.

3.2 Density and strength

Mechanical performance, particularly compressive strength, remains the most direct and fundamental indicator for evaluating UHPLC [53]. While ultra-high strength and lightweight design are seemingly contradictory objectives, UHPLC seeks to achieve a favorable balance between these two through careful material design and processing optimization. The density and strength of UHPLC are intricately linked to a variety of factors, including mixture compactness, water-to-binder ratio, the type and volume of LWA, cementitious content, SCMs, fiber addition, casting method, and curing regime [54].

The mechanical strength of UHPLC incorporating LWA is predominantly governed by the intrinsic strength, morphology, and porosity of the aggregates, which are in turn influenced by raw materials and production methods. In general, the lower the density of the LWA, the lower the resultant concrete strength. Therefore, the primary challenge in UHPLC design is to maximize structural efficiency (strength-to-weight ratio) while minimizing performance trade-offs.

Shale ceramsite is among the most widely used LWAs in UHPLC. Yang et al. [55] achieved compressive and flexural strengths exceeding 110 MPa and 15 MPa, respectively, with a density below 2100 kg/m³ by replacing quartz sand with shale ceramsite. Similarly, Zhang et al. [29] studied replacement ratios from 0% to 100% and observed that as the replacement increased, both density and strength declined. Nevertheless, even at 100% replacement, compressive and flexural strengths remained above 100 MPa and 15 MPa, respectively, with a density below 2000 kg/m³. This performance is attributed to the rough surface of ceramsite, which improves mechanical bonding with the cement matrix despite its lower inherent strength and irregular particle shape.

The improvement in interfacial transition zone (ITZ) quality has been highlighted as a critical factor in maintaining mechanical performance [56]. μCT and SEM analyses show that quartz sand creates a distinct wall effect in the ITZ (Fig.2), whereas rough-surfaced LWAs like ceramsite lead to a denser and more gradual transition with stronger bonding [57]. Meng et al. [58] combined coal ash ceramsite and shale ceramsite to produce UHPLC with densities ranging from 1995 to 2114 kg/m³ and compressive strengths from 102.4 to 114.5 MPa. The specific strength surpassed 50 MPa·m³/t, exceeding that of typical lightweight concrete. Lu et al. [15, 59] employed expanded clay and expanded shale, achieving structural efficiency values over 65 kN·m/kg and compressive strength of 123 MPa at 1929 kg/m³ density. Pumice stone has also been adopted, with Abadel [38] and Zeyad et al. [20] reporting compressive strengths of ~100–127 MPa and densities around 2000 kg/m³.

More recently, hollow microspheres (HGM) have been integrated into UHPC matrices to develop high-strength, ultra-light concretes. With their spherical morphology, hard shell, and enclosed voids, HGMs offer high strength-to-density ratios, low thermal conductivity, and pozzolanic reactivity under thermal activation [53]. Dahal et al. [26] demonstrated that incorporating HGM allowed for the preparation of UHPLC with a compressive strength of 160 MPa and a drying density of 1862 kg/m³. Lu et al. [60] reported similar results with compressive strengths over 120 MPa and densities as low as ~1800 kg/m³, accompanied by improvements in thermal insulation, water resistance, and electrical resistivity.

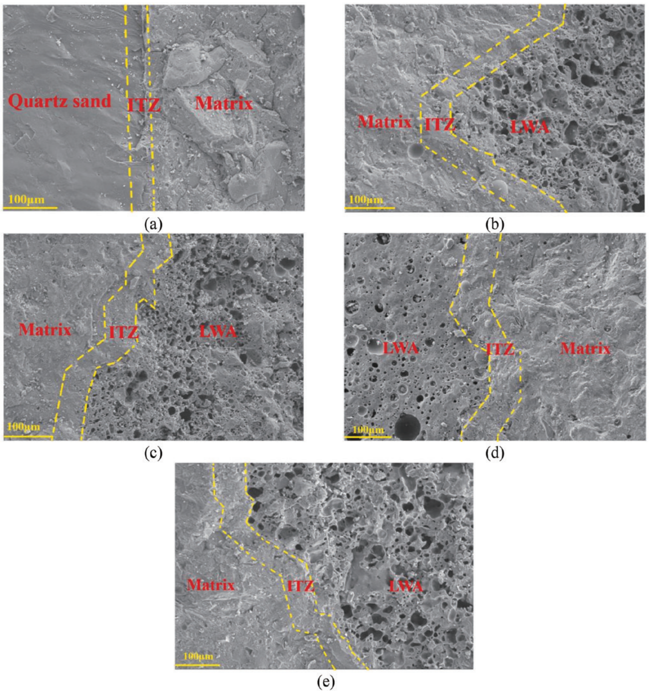

Fig. 2 SEM images of the UHPLC with different LWA contents: (a) 0%; (b) 25%; (c) 50%; (d) 75%; (e) 100% [29].

However, not all LWAs are beneficial to mechanical properties. Artificial lightweight fine aggregates often reduce strength due to their higher porosity, lower mechanical integrity, and weaker ITZ bonding [61]. Rafieizonooz et al. [34] observed reduced compressive and tensile strengths with increasing replacement of traditional sand by artificial LWA, reinforcing the need for aggregate optimization.

The synergistic effect of fibers and SCMs further enhances UHPLC performance. Meng et al. [62] prepared UHPLC with fly ash microbeads and different types of steel fibers, achieving a compressive strength above 120 MPa and a density of ~2080 kg/m³. UHPLC exhibited higher strain-rate sensitivity and greater energy absorption capacity than conventional UHPC, largely due to the crack-deflecting role of LWA. While fiber shape had limited effect on static strength, increasing fiber length or aspect ratio improved dynamic toughness. Steel fibers significantly enhanced splitting and flexural strength through their bridging effect [58]. Fig. 3 illustrates the increase in crack-bridging fibers with increasing fiber volume, leading to better post-peak toughness. The inclusion of polyethylene fibers [45] further enhanced ductility while simultaneously reducing density and carbon footprint [63]. Although steel fibers play a critical role in enhancing strength and toughness, their relatively high density can lead to an increase in the overall density of UHPLC when used in large quantities. Current literature suggests that the density reduction achieved by incorporating LWAs often offsets the density increase caused by steel fiber addition. In successfully designed UHPLC systems, the dosage of steel fibers typically ranges from 0.5% to 2.5% by volume [58, 64, 65], which is consistent with conventional UHPC formulations [66]. To balance strength and density, it is recommended that the fiber content in UHPLC remain within this range. Furthermore, some studies have employed polyethylene fibers as substitutes for steel fibers to further reduce composite density [63]. The optimization of fiber type, geometry (e.g., straight vs. hooked), and content in conjunction with specific LWAs warrants further research to achieve the best trade-off between mechanical performance and weight reduction.

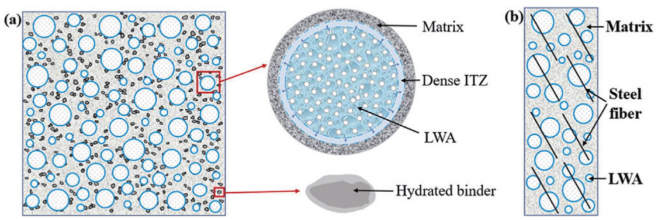

Fig. 3 Schematic diagram of UHPLC prepared with LWA: (a)Without fiber; (b)With fiber [58].

In addition to fibers, SCMs such as nano-silica and silica fume densify the matrix and mitigate strength reductions caused by porous aggregates [59]. The use of air-entraining or expansive agents can also lower concrete density, but often at the expense of strength [49]. Therefore, these admixtures are best used in tandem with optimized LWA systems to balance overall performance [20].

Curing conditions exert a decisive influence on strength development. Internal curing, enabled by pre-wetted LWA, provides sustained moisture release to promote hydration and suppress shrinkage-induced cracking. External curing strategies, such as steam curing, hot water immersion, and autoclaving, can accelerate strength gain and reduce porosity. Zhang et al. [67] reported that clay-based spherical ceramsite combined with steam curing enhanced hydration and produced compressive strength above 120 MPa with a density <2100 kg/m³. Molecular dynamics simulations indicated improved mechanical performance of the C-A-S-H phase under steam or autoclave curing [68]. Similarly, Lu et al. [69] achieved compressive strengths >150 MPa and densities <1800 kg/m³ by combining LWA with dry-heat curing. Teng et al. [70] found that using pre-saturated fine LWA enabled compressive and flexural strengths of 139 MPa and 19 MPa, respectively, through enhanced hydration and pozzolanic activity.

Furthermore, internal curing was shown to refine the pore structure and strengthen ITZs [71]. Guo et al. [31] demonstrated that a 24-hour pre-soak of fly ash microbeads enhanced ITZ hydration and resulted in compressive and flexural strengths exceeding 155 MPa and 20 MPa, respectively, with densities below 2100 kg/m³. Dry heat curing (180°C for 10 h) and autoclaving (180°C, 1 MPa, 10 h) both yielded denser matrices and stronger ITZs. As shown in Fig. 4, all curing regimes led to flexural hardening behavior, but dry heat curing showed the highest fiber-matrix bond strength and residual toughness [72].

Structural efficiency, commonly defined as the ratio of compressive strength to material density, serves as a key indicator for evaluating performance per unit weight. Reported structural efficiency values for UHPLC typically range from 50 to 65 kN·m/kg [20, 38, 59, 63], while conventional lightweight concretes generally fall between 10 and 40 kN·m/kg [58]. Standard UHPC mixes, with designed compressive strengths of 120–150 MPa—and in some cases easily exceeding 200 MPa [73]—combined with densities of 2400–2600 kg/m^3, usually exhibit structural efficiencies between 50 and 80 kN·m/kg. Notably, some studies have demonstrated that UHPLC subjected to high-temperature curing can achieve structural efficiencies over 85 kN·m/kg [69], approaching or even matching that of UHPC. Therefore, although current UHPLC systems already demonstrate commendable structural efficiency, there remains considerable potential for further enhancement through material optimization.

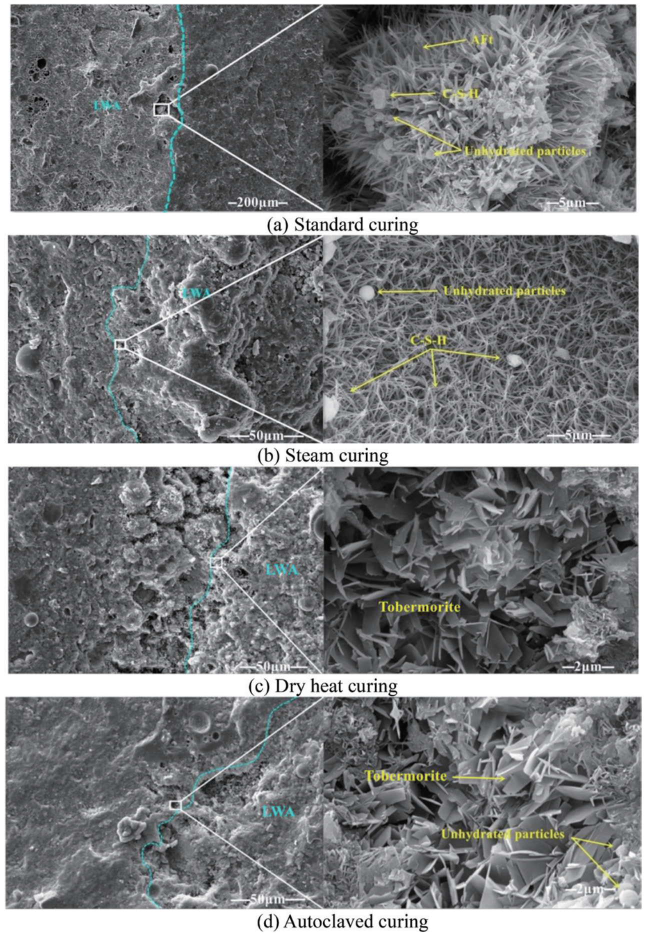

Fig. 4 Microscopic morphology of hydration products under (a) Standard curing; (b) Steam curing; (c) Dry heat curing; (d) Autoclaved curing [31].

In summary, the development of UHPLC with high strength and low density relies on a multi-faceted strategy that integrates aggregate selection and pre-treatment, fiber reinforcement, SCM optimization, and tailored curing protocols. The structural efficiency of UHPLC can now rival or exceed that of conventional UHPC, paving the way for its use in load-bearing yet weight-sensitive applications such as prefabricated bridge decks, tall structures, and energy-efficient enclosures.

3.3 Modulus of elasticity

As a key indicator reflecting a material's elastic deformation capacity, the elastic modulus plays a critical role in the structural design and engineering application of UHPLC. It governs stiffness, deformation coordination, and dynamic response of structural components—particularly in long-span bridges, high-rise buildings, and other load-sensitive and deflection-critical scenarios. Compared with conventional concrete containing natural aggregates, UHPLC often exhibits higher brittleness under the same strength class, resulting in relatively lower elastic modulus values [74, 75]. This trade-off limits its application in load-bearing systems where both strength and deformation control are required.

The dominant factor controlling the elastic modulus in UHPLC is the physical characteristics of LWA, including their density, pore structure, and water absorption behavior [76]. Aggregates with high apparent density and uniform pore distributions provide a more continuous and effective stress transfer path, thereby increasing the overall stiffness of the composite [77]. For instance, Teng et al. [70] reported that increasing the content of pre-saturated lightweight sand from 0% to 25% enhanced compressive and flexural strength due to internal curing effects. However, the elastic modulus decreased from 50 GPa to 44 GPa, indicating that internal curing improves strength but may lead to a reduction in stiffness. The use of lightweight fillers such as fly ash cenospheres or hollow glass microspheres has also been shown to reduce the elastic modulus, mainly due to their low stiffness and the introduction of additional pores into the matrix [45]. Interestingly, the particle size of these fillers matters: smaller fly ash microspheres yielded higher compressive strength and elastic modulus compared to larger ones, likely due to better particle packing and less void formation [78].

Fiber reinforcement is a well-established approach to compensate for the reduced stiffness and to enhance ductility in UHPLC. The type, volume fraction, and geometry of fibers all have notable effects on the elastic modulus [79]. Incorporating steel fibers, which possess a modulus of approximately 200 GPa, significantly improves the overall stiffness of the composite. Studies have shown that introducing just 1 vol% of hooked-end steel fibers can raise the modulus above 30 GPa [80]. The random three-dimensional network formed by these fibers facilitates load transfer, inhibits microcrack propagation, and increases both elastic and post-peak performance. In contrast, low-modulus fibers such as polyolefin (typically <10 GPa) or polyethylene offer limited improvements in stiffness and may even reduce the elastic modulus due to interfacial debonding during shrinkage and thermal mismatch [74].

Despite their limited effect on stiffness, synthetic fibers can substantially transform the failure mode of UHPLC from brittle to ductile. Polyethylene fibers, in particular, help promote fine crack distribution and improve strain capacity, making them valuable for toughness enhancement without significantly increasing weight or environmental impact [81].

The role of SCMs such as silica fume and fly ash in modulating elastic modulus is nuanced. While they enhance compressive strength and reduce porosity, their effect on stiffness is often marginal [82, 83]. Jiang et al. [18] prepared UHPLC using optimized gradation of shale ceramics and found that incorporating GO significantly improved both compressive and flexural strengths. This improvement was attributed to the increased hydration degree and densification of the cement matrix facilitated by GO's large specific surface area and functional groups (e.g., carboxyl, hydroxyl, epoxy) [84, 85]. The elastic modulus of UHPLC containing GO reached up to 46.4 GPa, higher than that of the control mixture [84]. GO enhances ITZ densification, improves interfacial bonding, and promotes the formation of high-polymerized C-S-H gel, thereby boosting both strength and stiffness [86].

In contrast, the inclusion of air-entraining agents or expansive agents often leads to reduced density but at the cost of stiffness degradation. These admixtures increase porosity and disturb the matrix continuity, resulting in lower elastic moduli even though they may improve freeze-thaw resistance or volume stability.

Curing regimes also significantly influence the development of the elastic modulus. Pre-wetted LWA can promote internal curing by forming a localized water-release network, enhancing hydration and reducing shrinkage-related microcracks. Fig.4 showed that the ITZ near LWA could form a high-modulus zone with a thickness of 5–35 μm, attributed to enhanced hydration from internal curing [31]. External thermal curing methods, including steam curing and dry-heat curing, further improve the matrix by refining pore structure, increasing hydration product density, and strengthening interfacial zones [87]. Guo et al.

[31] confirmed that combining internal and external curing strategies significantly increased both the elastic modulus and toughness of UHPLC, while also compensating for defects caused by porous LWAs. As illustrated in Fig. 5, these coupled effects lead to a denser ITZ and higher modulus, enhancing the structural resilience of UHPLC under elastic loading.

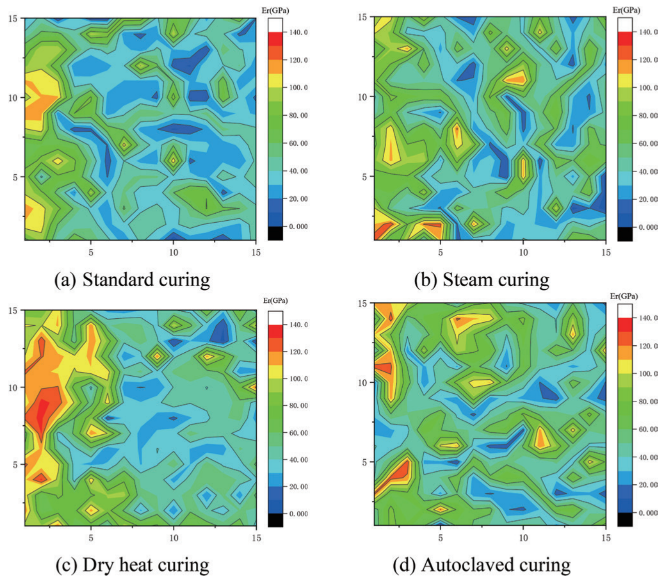

Fig. 5 The elastic modulus of ITZ under (a) Standard curing; (b) Steam curing; (c) Dry heat curing; (d) Autoclaved curing [31].

Creep is defined as the time-dependent deformation of concrete under sustained loading. In general, UHPC exhibits significantly lower creep than conventional concrete due to its dense microstructure and high early-age elastic modulus. However, the incorporation of LWA, which typically possess lower elastic modulus, can alter this behavior [88]. For instance, it has been reported that at 1 year, lightweight and normal concrete with a compressive strength of 50 MPa showed specific creep values of 95 με/MPa and 76 με/MPa, respectively, indicating a 25% increase in creep for lightweight concrete [89]. Liu et al. [39] compared the influence of different aggregate types on UHPC, including porous calcined bauxite, expanded shale LWA, and basalt. The UHPC incorporating high-elastic modulus porous calcined bauxite exhibited specific creep values 11.2% and 22.6% lower than those of UHPC with basalt and LWA, respectively. These findings suggest that at the macro scale, higher LWA elastic modulus leads to lower creep deformation in UHPLC. At the microscale, internal curing water stored within the LWA promotes continued hydration, densifying the cementitious matrix. Furthermore, the moisture-retention capability of LWA helps reduce water migration within C-S-H gel under long-term loading, thereby limiting creep strain [90]. Therefore, the use of high-quality, structurally sound LWA is essential to achieving low-creep performance in UHPLC systems.

In conclusion, the elastic modulus of UHPLC is the outcome of a delicate interplay between material composition, microstructure, and curing process. Achieving a desirable modulus without sacrificing lightweight or toughness requires a multi-scale, multi-material strategy, integrating optimized LWAs, high-modulus fibers, targeted nanomaterial modification, and advanced curing technologies. Future work should focus on developing predictive models that relate elastic modulus to pore structure, ITZ behavior, and composite gradation, thereby guiding the rational design of UHPLC for demanding structural applications.

3.4 Volume stability

Cracking is a common and critical durability issue in cement-based materials, fundamentally caused by the generation of tensile stresses that exceed the intrinsic tensile strength due to volume deformations such as chemical shrinkage, autogenous shrinkage, and drying shrinkage. In UHPLC, the challenge of volume stability becomes more pronounced due to its unique material characteristics: a very low water-to-binder ratio (typically < 0.20), high cementitious content (800–1000 kg/m^3), and vigorous pozzolanic activity from ultrafine admixtures (e.g., silica fume, nano-silica). These features lead to rapid hydration in the early stage and a sharp drop in internal relative humidity—often below 70% within the first 24 hours—causing autogenous shrinkage to contribute up to 80% of total shrinkage, compared to 20–50% in conventional concrete [91]. This substantial volume instability not only increases the risk of through-cracking and stiffness loss but also accelerates deterioration mechanisms such as reinforcement corrosion and freeze–thaw damage, ultimately undermining long-term structural performance.

The shrinkage process in concrete typically occurs in two distinct phases: an early rapid development stage (1–28 days), followed by a steady stabilization stage (28–91 days) [92]. Factors influencing volume stability can be broadly categorized into environmental factors (e.g., temperature, humidity, wind speed) and material-related parameters, such as aggregate type, binder content, admixture dosage, and fiber reinforcement [93].

Among these, the role of LWA in improving volume stability is particularly notable. Properly designed LWA systems can offer internal curing, mitigating shrinkage, while also avoiding the detrimental effects of weak ITZs or poor mechanical strength. Numerous studies have shown that porous aggregates such as pumice, sintered shale, or coral-based materials significantly reduce autogenous shrinkage in UHPLC [19, 92, 94-96]. This is primarily because LWA absorbs water during mixing and gradually releases it into the matrix as hydration progresses [38], thereby maintaining internal humidity and suppressing self-drying-induced tensile stress [97]. Additionally, substituting a portion of the fine aggregate with LWA reduces the overall cement paste content and capillary stress [98], contributing to shrinkage reduction [99]. Guo et al. [63] reported a 47% shrinkage reduction (from 809 μm/m to 507 μm/m) when replacing natural sand with expanded glass aggregate, due to moisture release from LWA enhancing C–S–H gel formation and densifying the ITZ (see Fig. 6) [100]. These findings highlight the dual benefit of LWA: enhancing hydration through internal curing and reinforcing the microstructure surrounding the aggregate–matrix interface.

The particle size distribution and internal pore structure of LWA have a significant impact on their internal curing efficiency in UHPLC. To ensure effective internal curing without compromising matrix performance, both parameters must be carefully controlled. Jensen et al. [101] reported that when the capillary meniscus diameter in a pore is approximately 100 nm, the equilibrium relative humidity of pure water inside that pore reaches ~99%. This implies that pores smaller than 100 nm tend to retain water, while those larger than 100 nm are more effective in releasing it for internal curing. Given that the dominant pore sizes in UHPC binders are typically between 2 and 3 nm, it is essential that internal curing water be readily available at this scale. If LWA particles are too large or have oversized pores, they tend to release water too rapidly at early stages, leading to inefficient internal curing [31, 102, 103]. Therefore, UHPLC systems generally favor LWA with smaller particle sizes and finely tuned pore structures, which better match the absorption–release kinetics needed for controlled water delivery during hydration.

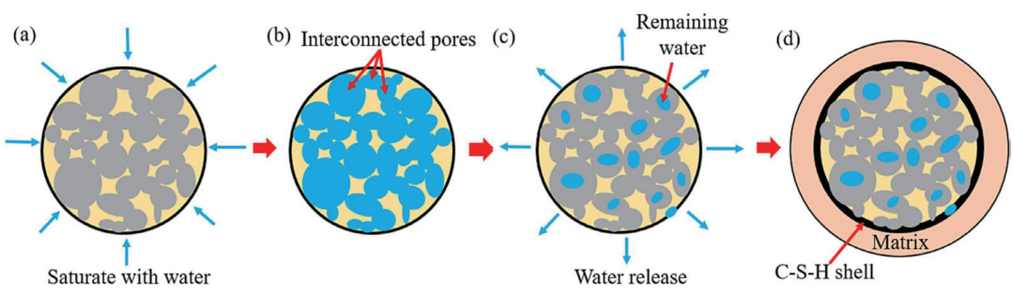

Fig. 6 Internal curing effect of the expanded glass: (a) Pre-saturation of the expanded glass (particles soaked in water for 24 h); (b) Internal pores occupied by water; (c) Release of internal curing water in the hardening process; (d) Promotion of the hydration of the unreacted cementitious materials to produce C–S–H gel [63].

Fiber reinforcement represents another key approach to control volume instability. The bridging effect of fibers and their ability to redistribute internal stresses can effectively delay crack initiation and propagation during shrinkage. As the cement matrix contracts, fibers convert shrinkage strain energy into elastic deformation via interfacial bonding, thus suppressing stress concentration [25]. Steel fibers have been shown to reduce early shrinkage by 15% at moderate dosages (~0.5 vol%) [23]. Increasing the steel fiber content generally improves crack resistance, owing to stronger mechanical interlocking [104]. However, low-density synthetic fibers such as polyethylene can outperform steel fibers in shrinkage suppression due to their fine diameter and uniform dispersion, which provides more continuous restraint across the matrix [45]. These fibers are particularly effective against early plastic shrinkage and localized stress buildup [105].

Admixtures also play a vital role in improving volume stability. Expansion agents can compensate for internal tensile stress by generating expansive hydration products (e.g., ettringite), while shrinkage-reducing agents reduce capillary tension by lowering water surface tension. Chen et al. [49] observed that with 4% expansion agent, UHPLC exhibited negligible early shrinkage, suggesting that internal expansion effectively offsets autogenous shrinkage. When combined with LWA, the synergistic interaction between internal curing and expansion pressure enhances dimensional stability. Studies have shown that replacing 25% of the sand with LWA or adding 1% expansion agent can reduce 28-day shrinkage by over 20% compared to reference UHPC [70]. Furthermore, combining both strategies yields superior performance compared to using either method alone, due to simultaneous control of humidity loss and chemical shrinkage pressure [100, 106, 107]. The coupling of internal and external curing has proven particularly effective in managing volume stability. Pre-saturated LWA acts as a water reservoir, while external curing (e.g., steam curing, heat treatment) accelerates hydration and densifies the microstructure.

In summary, the volume stability of UHPLC is a multifactorial property influenced by aggregate design, fiber bridging, admixture synergy, and curing strategies. Through intelligent mixture optimization, the risk of shrinkage-induced cracking can be effectively suppressed without compromising strength or durability. The integration of internal curing, fiber reinforcement, chemical additives, and advanced curing methods provides a comprehensive strategy for achieving both high mechanical performance and dimensional stability in UHPLC—thus facilitating its safe application in severe environments and long-life structural systems.

3.5.Segregation resistance and particle distribution

One of the critical challenges in producing high-performance lightweight concretes lies in ensuring uniform dispersion of LWA throughout the cementitious matrix. Due to their low density, LWA particles are prone to segregation—particularly floating upward—during mixing or placement. This can lead to heterogeneity in both mechanical and thermal properties of UHPLC, as local concentrations of LWA alter stiffness, porosity, and strength distribution. Therefore, the distribution and stability of LWA within the matrix are key parameters influencing the quality and reliability of UHPLC.

Recent advances in micro-computed tomography (μCT) have enabled researchers to non-destructively investigate the internal structure of UHPLC, offering detailed 3D insights into LWA dispersion, void formation, and interfacial integrity. μCT has become a widely used technique to assess the spatial arrangement of porous fillers and to distinguish between aggregate particles and entrapped air voids based on morphology and gray-scale contrast.

Yang et al. [16, 108, 109] conducted a series of studies using μCT to analyze the dispersion of various hollow microspheres (glass & ceramic) in UHPC matrices (Fig. 7). They demonstrated that both types of microspheres remained well-distributed in the matrix and provided visual evidence of HGM melting during fire exposure, revealing the evolution of vapor release channels and microcracking behavior [110, 111]. In another study, Yang et al. [112] systematically investigated segregation behavior across a range of water-to-cement (w/c) ratios from 0.25 to 0.50. A novel CT projection analysis method revealed that HGM segregation began to occur around w/c = 0.45, and became severe at w/c = 0.50, confirming that higher matrix fluidity promotes upward flotation of lightweight fillers.

The effect of matrix rheology on segregation control has also been explored. Lu et al. [15] emphasized that the high viscosity of UHPC pastes significantly improves the bonding between matrix and LWA or steel fibers, thus reducing flotation or settling during mixing.

μCT observations confirmed that both light and heavy inclusions maintained stable positions in fresh UHPC, in contrast to traditional lightweight pastes.

The successful use of μCT to study LWA distribution extends beyond microsphere systems. Dixit et al. [113] evaluated UHPC modified with expanded polystyrene (EPS) beads at replacement rates up to 45 vol%. Their μCT analysis confirmed uniform distribution and also allowed separation of EPS beads and pores based on particle size. To address the difficulty of distinguishing LWA from air voids—particularly when they are similar in size and shape—Yang et al. [16] further introduced a shape factor-based approach, using sphericity as a distinguishing metric. This technique showed promise in separating cenospheres from pores based on CT and laser diffraction data, although challenges remained in cases where material contrast or shape differences were minimal.

Ahn et al. [114] used CT scanning to assess the post-fire pore structure and confirmed that polypropylene microplastics remained evenly distributed throughout the UHPC depth, showing no signs of segregation despite their very low specific gravity (<1.0). Similarly, Umbach et al. [115] used in-situ μCT to monitor crack propagation in UHPLC. Their work demonstrates the potential of CT not only for quality control in fresh concrete but also for fracture behavior evaluation in hardened UHPLC.

Taken together, these studies indicate that uniform dispersion of LWA can be achieved in UHPLC, provided that appropriate mixture viscosity, saturation levels, and mixing protocols are maintained. μCT provides an essential tool to verify particle distribution and identify segregation risks that may not be apparent through conventional testing. However, challenges remain in real-time process monitoring and in establishing quantitative segregation thresholds linked to mechanical or durability performance. Further research integrating μCT with digital image processing and machine learning may enhance our ability to predict and control LWA dispersion across various UHPLC formulations and casting conditions.

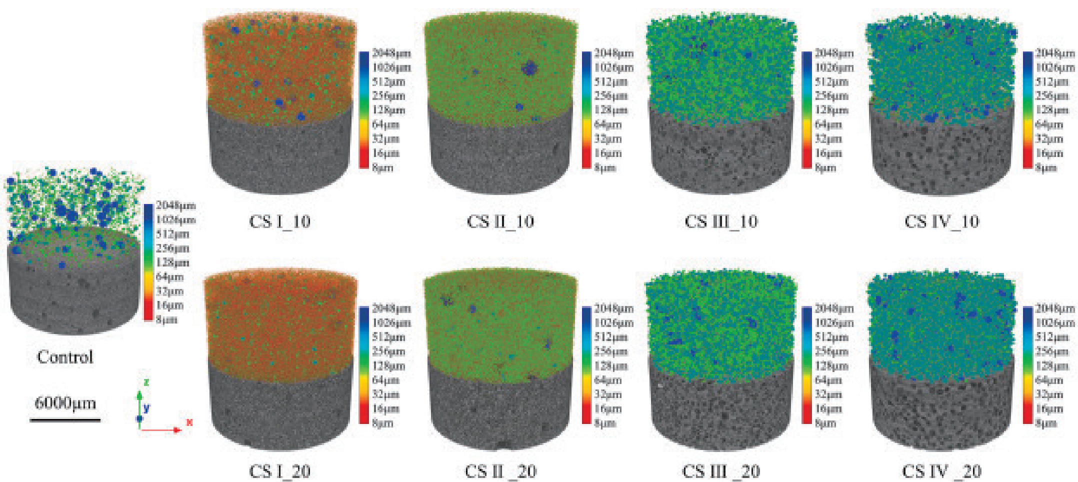

Fig. 7 Micro-CT analysis of the spatial distribution of different size hollow microspheres within the UHPC matrix [16].

4. Durability and sustainability considerations

4.1 Shrinkage behavior

Shrinkage, especially autogenous shrinkage, remains a major concern in UHPC due to its low water-to-binder ratio and dense matrix. The addition of pre-saturated LWA has been widely investigated as a strategy to provide internal curing and alleviate shrinkage. Although not all studies explicitly aimed to develop UHPLC, many employed porous lightweight materials that also contributed to reducing density, thus offering insights relevant to UHPLC design. To avoid confusion, it should be noted that shrinkage behavior represents a primary cause of volume instability but is treated separately here to allow a more focused discussion on its mechanisms and mitigation in UHPLC.

Several studies have demonstrated that internal curing through LWA significantly reduces autogenous shrinkage. For example, Meng et al. [100, 116] reported a reduction from 489 to 196 μm/m as LWA content increased from 0% to 75%, accompanied by a rise in 72 h internal relative humidity (IRH) from 85% to 97%. The relationship between IRH and shrinkage followed a parabolic trend. Huang et al. [117] similarly found that replacing 50% of sand with pre-saturated LWA decreased 28-day autogenous shrinkage from 450 to 275 μm/m, though higher LWA content increased porosity [118], offsetting some benefits. Lyu et al. [119] showed shrinkage reductions up to 84.3% using 5–20% LWA, while Guo et al. [63] achieved a 37% reduction using 100% expanded glass. Shrinkage control also depends on LWA particle characteristics and saturation treatment. Liu et al. [91] found that vacuum-saturated fine LWA provided better shrinkage reduction than conventional soaking, with optimal effects below 15% replacement. Alaskar et al. [120] confirmed that fine LWA was more effective than coarse LWA, with 20% total replacement reducing autogenous shrinkage by ~118%.

Porosity control and moisture release dynamics are also critical. Shen et al. [30] observed that over 85% of the water in expanded shale LWA was released within 40 hours, most of which supported filling in the pores created by chemical shrinkage. However, nearly half of pre-wetted water was lost before setting (6 hours), contributing to workability but not internal curing. Liu et al. [91] noted that when internal curing was too strong or excessive LWA was used, the reduced effective w/b ratio could increase shrinkage again. In some studies, LWA was combined with shrinkage-reducing admixtures (SRA), fibers, or expansive agents to improve performance. Teng et al. [121, 122] designed a UHPC overlay with 35% LWA and 5% CaO-based expansive agent [49], achieving autogenous and drying shrinkage of just 190 με and −310 με. Al Moman et al. [123] used 40% LWA and steel fibers, reducing autogenous and drying shrinkage by 75% and 26%, respectively. Tan et al. [124] reported that with LWA, SRA, and steel fibers, constrained shrinkage was reduced from 809 με to 245 με, and maximum crack width from 1.6 mm to 0.065 mm. Other porous aggregates have also shown effectiveness. Wei et al. [125, 126] used calcined bauxite and achieved shrinkage as low as 160 μm/m. Chen et al. [127] reported that combining porous coral sand and SRA reduced early-age autogenous shrinkage by 88.6% and drying shrinkage by 66.5%.

Overall, these results confirm that moderate amounts of well-saturated fine LWA can effectively mitigate shrinkage in UHPLC. However, the effects are highly dependent on pore structure, saturation degree, and dosage. Combining LWA with other shrinkage-controlling strategies provides further benefit, especially under harsh environmental conditions. Future work should focus on multi-factor coupling effects and long-term dimensional stability to better guide practical UHPLC design.

4.2 Thermal insulation performance

In building and infrastructure engineering, lowering the thermal conductivity of concrete materials is a critical pathway toward improving energy efficiency and reducing life-cycle operational energy consumption. UHPLC, by nature of its design, offers a promising balance between high mechanical performance and low thermal conductivity, potentially enabling the development of energy-efficient structural materials.

The inherent thermal conductivity (TC) of conventional UHPC typically ranges between 1.8–2.2 W/m·K, largely due to its dense matrix composed of high-modulus quartz sand and a low-porosity cementitious system. In contrast, porous aggregates such as hollow microspheres, expanded glass, and other low-density fillers contain substantial amounts of entrapped air ($\lambda \approx 0.026$ W/m·K), which drastically reduces the matrix's effective thermal conductivity. Additionally, replacing part of the cement matrix with low-TC materials such as HGM or pozzolanic ash further disrupts thermal transfer pathways, contributing to the overall reduction.

Several studies have highlighted the effectiveness of hollow fillers in reducing the thermal conductivity of UHPLC. Guo et al. [63] showed that introducing 20% glass microspheres reduced thermal conductivity to 1.3 W/m·K, significantly lower than that of reference

UHPC (~2.0 W/m·K). When expanded glass content increased to 100%, the TC further decreased to 0.65 W/m·K, indicating a strong inverse correlation with filler content. Yang et al. [16] investigated the influence of cenosphere size (10–600 μm) and content (~20%) and observed that increasing dosage reduced TC from ~1.04 to 0.83 W/m·K. Moreover, larger cenospheres exhibited a stronger insulation effect due to more trapped air and lower percolation pathways for heat conduction. In a similar strategy, Lee et al. [109] used hollow glass microspheres to formulate a high-strength, lightweight UHPC matrix with a TC as low as 0.77 W/m·K. Notably, their work also showed that elevated curing temperatures had minimal influence on thermal performance, suggesting good thermal stability of the air-entrapped structure. In contrast, Mahato et al. [108] reported slightly higher thermal conductivity in heat-treated samples containing 20% cenospheres. This effect was attributed to densification caused by secondary hydration and possibly water stored within the porous cenospheres that filled microcracks, illustrating the complex role of internal moisture on thermal behavior.

Substituting traditional high-TC components (e.g., cement, quartz sand) with materials such as glass powder, cullet, and pozzolanic ashes is another pathway to reduce thermal conductivity. Lu et al. [60, 64] reported several formulations using hollow microspheres and glass powder, achieving TC values ranging from 1.2 to 0.73 W/m·K depending on the substitution level (30–100% HGM replacing cement and glass powder). In another study [69], replacing 100% river sand with shale-expanded LWA and 40 vol% cement with HGM resulted in a TC of 1.065 W/m·K at room temperature, which further decreased to 0.8 W/m·K after curing at 250°C. Shohan et al. [128] developed UHPLC incorporating dehydrated cement powder (DCP) and aerogel, where increasing DCP content from 5% to 20% led to a reduction in thermal conductivity from 0.394 to 0.274 W/m·K. The highly porous microstructure introduced by aerogel particles are credited for this enhancement. Zaid et al. [129] demonstrated that the use of palm oil fuel ash (POFA) and Lytag as partial replacements for cement and fine aggregate, respectively, along with steel fibers, reduced thermal conductivity from 0.425 to 0.287 W/m·K. The multi-scale porosity created by Lytag and the amorphous silica in POFA helped disrupt the thermal conduction network.

In lightweight reactive powder concrete systems, several fillers have shown potential for thermal insulation. Grzeszczyk et al. [21] studied various porous aggregates including expanded clay, Pollytag, expanded perlite, and expanded polystyrene beads (30–60% by volume). The resulting thermal conductivities ranged between 0.82 and 1.35 W/m·K, depending on filler type and dosage. Expanded polystyrene beads produced the lowest TC values, consistent with its extremely low intrinsic conductivity.

Across existing literature, it is clear that thermal conductivity of UHPLC can be systematically tuned by adjusting the type, size, and dosage of low-conductivity fillers. Substituting high-density quartz sand or cement with hollow or porous materials—particularly those with low thermal conductivity and stable shell integrity—leads to predictable and scalable reductions in TC. Moreover, increasing matrix porosity (both gel and entrained air) is also correlated with thermal performance; for instance, some studies suggest that for each 1% increase in porosity, thermal conductivity drops by ~1% [130].

Nonetheless, several challenges remain. Most current UHPLC studies still fall within the 0.7–1.3 W/m·K range, and very few formulations dip below 0.7 W/m·K without compromising compressive strength. The role of moisture migration, post-curing densification, and pore connectivity is often underexamined, though these factors strongly influence thermal stability over time. Additionally, many formulations in existing literature omit steel fibers or fine sand, and therefore represent UHPLC precursors rather than structurally functional concretes. Future development should focus on achieving thermal insulation without sacrificing strength or processability.

In summary, UHPLC presents a versatile platform for combining structural and insulation performance. By leveraging composite design strategies—through particle packing, phase synergy, and pore architecture engineering—it is possible to create high-performance concretes tailored for low-energy, thermally efficient building envelopes.

4.3 Fire resistance and thermal performance

Fire resistance has become an increasingly important performance metric for UHPC in structural applications, where thermal loads, spalling risk, and residual strength are critical to long-term service. The dense microstructure and low permeability of UHPC, while advantageous for durability, make it particularly susceptible to explosive spalling under rapid heating. This challenge is further complicated in UHPLC systems due to the inclusion of lightweight fillers, which alter both thermal conductivity and internal moisture transport behavior. Also, it is important to distinguish between thermal insulation—governed by pore structure and conductivity—and fire resistance, which relates to residual strength and thermal stability under high-temperature exposure.

Incorporating thermally stable fillers such as hollow or porous microspheres has also shown great potential in improving UHPLC's fire performance. Yang et al. [110] observed that UHPC samples incorporating hollow glass microspheres and hollow ceramic microspheres retained 92% and 78% of their original compressive strength after exposure to 900°C, respectively. The microspheres were found to buffer thermal gradients and create vapor escape channels through phase transformation or inherent porosity (Fig. 8). Jin et al. [111] similarly showed that using 40 vol% glazed hollow beads maintained 47% compressive strength even after exposure to 800°C. The addition of polypropylene fibers in conjunction with these beads further improved internal vapor release, mitigating internal pressure buildup.

Other researchers focused on modifying UHPLC with porous or LWAs. For instance, Zeyad et al. [20] replaced sand with crushed pumice and added air-entraining agents, which improved residual compressive strength to 39% after 800°C exposure—compared to 28.5% in the control group. Wu et al. [131] reported that geopolymer-based UHPLC with expanded glass powder showed strong thermal-induced ductility, with flexural strength increasing by 143% to 258% after heating. Even after exposure to 800°C, compressive strength remained above 12 MPa. In contrast, Abadel et al. [38] reported that 30% pumice replacement increased mass loss at 300°C, potentially due to mismatches in thermal expansion coefficients between fine and LWAs, which induced thermal stress and microcracking.

Other innovations involved mineral admixtures and industrial by-products or structure. Zaid et al. [129] found that the formulation containing 20% POFA and Lytag exhibited minimal mass loss across a temperature range of 300–900°C, with residual strengths of 155.4 MPa, 130.8 MPa, and 97.8 MPa, respectively. The enhanced thermal stability was attributed to the pozzolanic activity of POFA, the porous structure of Lytag, and the crack-bridging ability of the steel fibers. Han et al. [9] introduced a two-layer functionally graded UHPC in which a lightweight outer layer served as a fire barrier. After 1200°C exposure for 2 hours, the structural integrity was preserved with less than 20% loss in load-bearing capacity, and the interfacial bond was significantly improved.

Recycled or synthetic lightweight fillers have also been explored. Ahn et al. [114] studied microplastics and artificial LWAs, observing combustion behavior of microplastics between 200–600°C that significantly weakened mechanical performance. Nevertheless, the inclusion of steel fibers offered partial protection against catastrophic damage by controlling spalling. Several advanced formulations have targeted thermal barrier effects. Shohan et al. [128] introduced dehydrated cement powder (DCP) and aerogels into UHPLC matrices, resulting in reduced thermal conductivity and lower high-temperature mass loss. The dual functionality of DCP as filler and cement replacement, combined with the ultra-low thermal conductivity of aerogels, helped suppress internal heat transmission and enhance thermal stability.

Current studies have shown that free water, rather than chemically bound water, is the primary factor leading to explosive spalling. High internal pore pressure generated from water vaporization under rapid heating is considered the driving force. To address this, Lu et al. [69] proposed a dry thermal curing method. Specimens cured at 150°C exhibited significantly reduced spalling, and at 250°C, spalling was completely suppressed. This outcome was attributed to the removal of free water and the enhancement of pozzolanic reactions [132], which contributed to additional C–S–H formation, improved matrix densification, and better bonding of lightweight components. Similar results were reported by Dahal et al. [26], who found that UHPLC cured at 150°C exhibited only 10% mass loss after high-temperature exposure, compared to 14% for steam-cured samples.

These findings collectively highlight that reducing free water content, enhancing vapor release paths, and managing thermal stress distribution are central to improving fire resistance in UHPLC. Dry thermal curing, hollow microsphere inclusion, and functionally graded layering have emerged as effective approaches. At the same time, the combination of porous aggregates, pozzolanic admixtures, and reinforcing fibers can further augment thermal integrity. Still, challenges remain in optimizing these systems for real-scale applications. Future work should address long-term thermal cycling, fire testing under load, and the balance between thermal insulation and mechanical resilience, particularly for structural-grade UHPLC.

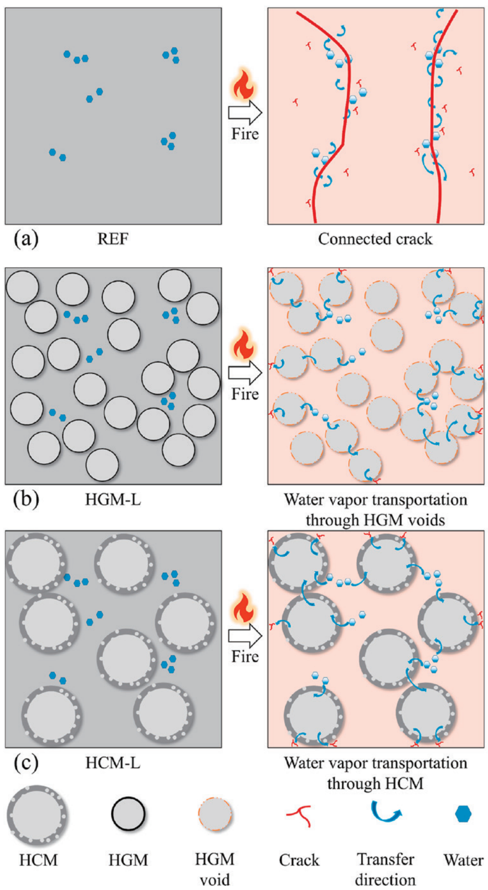

Fig. 8 Schematic illustration of the fire resistance mechanism in UHPLC modified with hollow microspheres [110].

4.4 Carbon footprint and environmental sustainability

As environmental regulations tighten and carbon neutrality goals advance globally, reducing the carbon footprint of construction materials has become an essential aspect of sustainable development. UHPLC is increasingly viewed not only as a high-strength, low-density structural material, but also as a low-carbon alternative to conventional UHPC. Compared to traditional UHPC, UHPLC offers multiple sustainability advantages, primarily due to its ability to incorporate recycled LWA and its enhanced thermal insulation, which together contribute to both lower embodied emissions and improved energy efficiency over the structure's service life.

One of the most promising strategies for reducing embodied carbon in UHPLC is the utilization of recycled or waste-derived LWAs. For instance, Guo et al. [63] demonstrated that converting waste glass—typically 60% of which is landfilled—into hollow glass microspheres and expanded glass can significantly reduce the carbon footprint of cement-based composites. These materials are not only lightweight and thermally efficient, but also recyclable and energy-saving in transportation. The life-cycle assessment (LCA) of the optimal UHPLC mix in their study revealed compelling environmental metrics: life-cycle cost of 850 $\$/m^3$, carbon emissions of 647 kg CO_2/m^3, and embodied energy of 4374 MJ/m^3, all considerably lower than those of conventional UHPC systems (life-cycle cost of 1733 $\$/m^3$, carbon emissions of 1046 kg CO_2/m^3, and embodied energy of 7432 MJ/m^3).

In addition to material substitution, UHPLC contributes to energy conservation during both construction and operation. Zaid et al. [129] highlighted that replacing traditional sand with LWAs lowers concrete density, reduces structural self-weight, and simplifies transportation and handling, thereby decreasing fossil energy consumption during casting and placement. Moreover, lighter structures require less reinforcement and foundation support, further minimizing material use and associated emissions.

The long-term durability and thermal performance of UHPLC also play a crucial role in its sustainability profile. Shang et al. [65] used LCA methods to evaluate

UHPLC from raw material collection to site placement. Although the manufacturing of hollow microspheres entails slightly higher environmental impact in the "cradle-to-gate" phase compared to UHPC—mainly due to high-temperature processing—UHPLC's superior insulation, noise attenuation, and durability extend the life span of buildings and lower energy usage during operation. Therefore, from a full "cradle-to-cradle" perspective, UHPLC is projected to outperform UHPC in terms of total environmental impact, though further data from large-scale deployment is needed to confirm this potential.

Umbach et al. [17] also examined the carbonation resistance of UHPLC made with expanded glass. Using accelerated carbonation testing, they found a carbonation coefficient as low as 0.53 mm/day$^{0.5}$, equating to a projected carbonation depth of only 5.3 mm after 100 years. This performance approaches the limits set by the Swiss SIA 262-1 standard (≤4.0 mm/day$^{0.5}$), confirming that UHPLC made with recycled glass aggregate is highly durable and contributes to long service life, which offsets early-stage environmental costs.

Nevertheless, it is important to recognize that UHPLC may involve higher initial material costs, especially when using advanced lightweight fillers or processed microspheres. However, these costs are expected to be offset by reduced operational energy demands, lower maintenance frequency, and longer durability, resulting in more favorable life-cycle economics and emissions profiles. Moreover, the development of UHPLC using industrial by-products (e.g., fly ash, slag, or calcined waste materials) further enhances its environmental value by integrating waste reuse and reducing cement clinker demand.

In summary, UHPLC presents a promising pathway toward high-performance and low-carbon construction materials. Its ability to integrate recycled aggregates, reduce structural dead loads, and enhance thermal efficiency makes it well-suited for sustainable applications. Future research should focus on standardizing life-cycle analysis frameworks for UHPLC, improving the environmental performance of lightweight filler production, and exploring regional availability of sustainable aggregates to further lower the environmental impact of UHPLC across its entire life span.

5. Engineering Applications of UHPLC

UHPC has evolved significantly since its conceptualization in the late 1970s, with the first practical applications dating back to 1997. Over the past two decades, UHPC has been implemented in a wide range of engineering domains including bridges, high-rise buildings, prefabricated construction, and marine and offshore infrastructure. However, bibliometric analysis indicates that the development and application of lightweight UHPC remains a relatively recent trend, with a marked increase in publications observed only in the past decade. As a result, most current implementations of UHPLC are limited to demonstration and pilot projects aimed at validating performance under field conditions.

5.1 Large–scale structural application: Wuhan Shuangliu Yangtze River Bridge

One of the most notable examples of UHPLC application is the Wuhan Shuangliu Yangtze River Bridge, currently the widest steel-box girder suspension bridge over the Yangtze River. Construction began in October 2022 and had reached the main cable erection phase as of March 2025. The bridge spans 1630 m in total, including a 1430 m main span formed by a simply supported steel-box girder. The approach spans utilize steel–UHPLC composite girders, representing the first large-scale implementation of UHPLC in Chinese bridge engineering.

The prefabricated deck panels in this project are cast using a proprietary UHPLC developed by Wuhan Harbour Engineering Design & Research Institute. The mix design achieves a compressive strength above 120 MPa, tensile strength exceeding 6 MPa, and an elastic modulus over 38 GPa. Its density is below 2100 kg/m^3, approximately 15% lower than that of conventional UHPC. The material utilizes porous LWAs to reduce self-weight while preserving strength. In addition to its high mechanical performance, UHPLC demonstrates superior resistance to freeze-thaw cycles, chloride ingress, and chemical attack, making it particularly well-suited for long-span bridges in harsh environmental conditions.

Fig. 9 Application of UHPLC in bridge: Wuhan Shuangliu Yangtze River Bridge, China. Image credit: https://www.wuhan.gov.cn/sy/whyw/202501/t20250113_2517072.shtml.

5.2 UHPLC in rehabilitation and retrofitting

The performance of UHPLC in structural repair has also been demonstrated in the Fuhe Bridge rehabilitation project, where UHPLC was used to strengthen deteriorated bridge piers. A 22 mm-thick jacket was cast in-situ using UHPLC with a 28-day compressive strength of 109.2 MPa and an elastic modulus of 39.5 GPa. The mix achieved a slump flow of 260 mm and had a measured density of 2095 kg/m^3, more than 20% lighter than ordinary Portland cement concrete. The application met all design and durability requirements, offering an effective lightweight alternative for structural strengthening.

Fig. 10 Application of UHPLC in rehabilitation: Fuhe Bridge, China. Image credit: https://ccpa.com.cn/site/content/17680.html.

5.3 Integration with refabrication and sustainable materials

Two additional projects—the Zhonghua Science Park Bridge and an extension of the Fuhe Bridge work—highlight the use of locally sourced LWAs and industrial by-products in UHPLC design. These projects replaced quartz sand with high-strength LWAs and quartz powder with steel slag, fly ash, and GGBFS. The modified UHPLC mix was optimized for low shrinkage and steam-free curing, offering logistical and environmental advantages for large-scale precast operations. For example, the Zhonghua Science Park Bridge employed 30-meter-long precast box girders fabricated using UHPLC. Each beam utilized 32.3 m^3 of C50-class lightweight concrete and over 6600 kg of steel reinforcement. The adoption of UHPLC significantly reduced lifting demands and construction time while maintaining structural performance.

Fig. 11 Application of UHPLC in prefabrication: Zhonghua Science Park Bridge, China. Image credit: https://ccpa.com.cn/site/content/17680.html.

Although many current UHPLC applications operate near the upper density boundary for lightweight classification (~2000–2100 kg/m^3), recent developments have shown promise for further reduction in weight while enhancing strength and functional performance. With advances in multi-scale particle packing, nano-reinforcements, and innovative lightweight fillers, UHPLC is poised to transition from experimental deployment to broader adoption in structural design. Once validated at scale, UHPLC may become a cornerstone material for next-generation bridge design, prefabricated systems, and performance-based construction.

5.4 Economic analysis

Although the material cost and curing requirements of UHPC are significantly higher than those of conventional concrete, its superior mechanical and durability performance has enabled its adoption in many structural applications. Cost data for UHPC materials and typical mixtures can be found in comprehensive review literature [13].

In the case of UHPLC, both total cost ($/m^3) and strength-normalized cost ($/m^3/MPa) have been reported in the literature. Guo et al. [63] provided a detailed breakdown of UHPLC mixture composition and cost estimation. The UHPLC mixture included cement (565.1 kg/m^3, 0.11 $/kg), slag (780.4 kg/m^3, 0.10 $/kg), glass microspheres (41.3 kg/m^3, 5.92 $/kg), river sand (780.4 kg/m^3, 0.03 $/kg), expanded glass (56.1–224.3 kg/m^3, 1.42 $/kg), high-range water reducer (≈11.5–40.5 kg/m^3, 3.6 $/kg), water (225.1–243.6 kg/m^3, 0.04 $/kg), polyethylene fiber (14.6 kg/m3, 16.2 $/kg), and steel fiber (117.0 kg/m^3, 4.76 $/kg). In the control group using 60% cement and 40% slag as the binder, the mixture was already cost-optimized due to the use of low-cost slag. The resulting cost was approximately 1110 $/m^3 (6.6 $/m^3/MPa), which is substantially lower than the UHPLC reported in the literature at 1733 $/m^3 (14.2 $/m^3/MPa). Replacing 20% of the slag with glass microspheres increased the cost slightly to 1112 $/m^3 (8.7 $/m^3/MPa) due to the high unit price of microspheres. Substituting steel fibers entirely with polyethylene fibers reduced the cost substantially to 791 $/m^3 (6.7 $/m^3/MPa). Further replacement of 25% to 100% of river sand with expanded glass slightly increased the cost, approaching the level of the microsphere-only mixture when 100% replacement was used. Overall, the cost of UHPLC remains relatively high, particularly when using large quantities of glass microspheres and steel fibers.

To improve cost-efficiency, alternative fillers such as fly ash cenospheres or ceramic microspheres can be considered, as they are significantly less expensive. Moreover, the use of low-cost SCMs, a proven approach for reducing UHPC costs, can also be effectively applied in UHPLC.

6. Conclusion and outlook

This review has comprehensively examined the development, characterization, and application of ultra-high performance lightweight concrete (UHPLC), highlighting its potential as a high-strength, durable, and sustainable alternative to traditional UHPC. Through systematic analysis of UHPLC's fresh properties, mechanical performance, shrinkage behavior, thermal conductivity, fire resistance, and environmental footprint, the review reveals both the advances and existing challenges in this emerging material system.

Despite significant progress, several critical limitations remain. The balance between strength and workability, the risk of segregation and shrinkage associated with porous lightweight aggregates (LWA), and uncertainties surrounding long-term durability in aggressive environments continue to constrain broader adoption. Moreover, while several engineering-scale applications have been demonstrated, standardization in material specification, testing methods, and performance metrics remains limited.

Future research priorities should include:

(1) Developing unified protocols for evaluating rheology, shrinkage, and durability specific to UHPLC systems;

(2) Advancing numerical models and AI-assisted mix design tools to optimize performance and reduce empirical trial-and-error;

(3) Designing multifunctional UHPLC systems with integrated thermal, acoustic, or self-healing capabilities;

(4) Performing full-scale life cycle assessments (LCA) of UHPLC with recycled lightweight fillers and aggregates;

(5) Investigating UHPLC's fire performance and post-fire residual capacity under real load-bearing scenarios.

By addressing these gaps, UHPLC has the potential to become a mainstream material for lightweight, high-performance, and low-carbon concrete construction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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