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Sustainable Ultra-High-Performance Concrete: Incorporating Nano-Eggshell Waste for Improved Strength and Durability

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Abstract - This study examines the mechanical and microstructural properties of ultra-high-performance concrete (UHPC) incorporating nano-eggshell (NES) particles as a sustainable alternative to conventional nanofillers. Eggshell waste, consisting primarily of calcium carbonate, was processed through cleaning, calcination, and grinding to obtain nanosized particles. UHPC mixtures with varying NES contents (1-5%) were prepared and evaluated for compressive strength, splitting tensile strength, and sorptivity at different curing ages. The results indicate that the optimal NES dosage of 3% significantly enhanced the compressive strength of UHPC by 4.9%, 6.0%, and 4.5% at 7, 28, and 90 days, respectively, compared to the reference mixture. The splitting tensile strength at 28 days also improved by 16.9% with 3% NES. The sorptivity of UHPC was reduced by 28% at the optimal NES content, indicating its improved durability. XRD analysis revealed the presence of calcium carbonate and its interactions with the cementitious matrix. The performance improvements were attributed to the nanofiller effect, accelerated hydration, and microstructural refinement induced by NES particles. However, excessive NES addition beyond the optimal dosage led to slight reductions in the mechanical properties owing to agglomeration effects. The findings demonstrate the potential of nano-eggshell waste as a sustainable and performance-enhancing alternative in UHPC, contributing to the development of eco-friendly construction material.

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Introduction

The incorporation of nanotechnology into cement-based materials has emerged as a transformative approach in modern construction engineering, driven by the need to overcome the inherent limitations of conventional concrete materials. Despite its widespread use, traditional concrete suffers from issues such as microcracking, high porosity, weak interfacial transition zones (ITZ), and limited durability under aggressive environmental conditions [1]. Nanomaterials, typically defined as materials with at least one dimension of less than 100 nm, offer unique physicochemical properties such as extremely high specific surface area, enhanced reactivity, and superior filler capability [2]. These characteristics enable nanomaterials to interact with cement hydration processes at the molecular and nanoscale levels, leading to substantial improvements in microstructural refinement and overall performance. Numerous experimental studies have demonstrated that the inclusion of nanomaterials, such as nano-silica, nano-alumina, nano-titania, and carbon-based nanostructures, significantly enhances the compressive strength, tensile strength, and fracture toughness while reducing permeability and shrinkage [3]. The improvement mechanisms are primarily attributed to accelerated cement hydration, nucleation effects, and densification of calcium–silicate–hydrate (C–S–H) gel [4]. As a result, nano-modified concrete exhibits superior mechanical and durability properties compared to conventional mixes. These advancements have positioned nanotechnology as a key enabler of next-generation high-performance concrete, including ultra-high-performance concrete (UHPC), self-compacting concrete, and multifunctional cementitious composites. A growing body of literature confirms that nanotechnology does not merely act as an additive enhancement but fundamentally alters the hydration kinetics and microstructural evolution of cement-based systems [5].

Extensive experimental investigations have consistently reported measurable performance improvements in nanomodified concrete systems, particularly when optimal dosage and dispersion techniques are employed [6]. One of the most significant outcomes of nanomaterial incorporation is the refinement of the pore structure, characterized by a reduction in capillary porosity and a shift toward finer gel pores. Mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) analyses showed that nanomaterials effectively filled micro- and nanoscale voids, resulting in a denser cement matrix and improved load transfer mechanisms. In terms of mechanical performance, compressive strength increases of 15–40% have been widely reported, depending on the type and concentration of the nanomaterial used. Additionally, nano-modified concretes exhibit improved early age strength owing to accelerated hydration, which is particularly beneficial for fast-track construction and precast applications. Durability-related properties, including resistance to chloride ion penetration, sulfate attack, carbonation, and freeze–thaw cycles, were also significantly enhanced [7]. This is primarily due to the reduction in permeability and stabilization of hydration products. Furthermore, nanomaterials improve the interfacial transition zone between cement paste and aggregates, which is traditionally regarded as the weakest link in concrete. By reinforcing the ITZ at the nanoscale level, crack initiation and propagation are delayed, resulting in improved fatigue and impact resistance. Collectively, these outcomes demonstrate that nanotechnology provides a systematic and scalable pathway for improving concrete performance beyond the limits achievable through conventional mix design optimization alone [8].

Ultra-high-performance concrete (UHPC) is the most advanced class of cementitious materials, characterized by compressive strengths exceeding 150 MPa, extremely low permeability, and exceptional durability [9]. The role of nanotechnology in UHPC is particularly critical, as UHPC relies heavily on optimized particle packing across multiple length scales, from macro-aggregates to nano-sized fillers [10]. Nanomaterials are essential components in achieving this multiscale densification, ensuring minimal porosity and maximum matrix homogeneity. In UHPC systems, nanomaterials contribute to enhanced hydration kinetics, increased formation of C–S–H gel, and reduced calcium hydroxide content, collectively improving chemical stability and long-term durability. Research has demonstrated that nanoscale additives can significantly improve fiber–matrix bonding in fiber-reinforced UHPC, leading to superior tensile behavior and strain-hardening characteristics [11]. Additionally, nanomaterials enhance the resistance of UHPC to extreme conditions, including high temperatures, radiation exposure, and chemical attacks, making it suitable for critical infrastructure, military, and nuclear applications. However, the widespread application of UHPC is often constrained by its high material costs and environmental concerns associated with its high cement content [12]. Consequently, recent research efforts have focused on identifying alternative, cost-effective, and sustainable nanomaterials that can deliver comparable performance enhancements without increasing the environmental burden. This has opened new research avenues for bio-based and waste-derived nanomaterials [13].

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Eggshell waste has gained increasing attention as an environmentally sustainable and economically viable nanomaterial for cementitious composites. Generated in vast quantities by households, food processing industries, and commercial kitchens, eggshell waste poses significant disposal challenges owing to its organic content and slow biodegradation [14]. Eggshells consist of approximately 94–97% calcium carbonate ($CaCO_3$), along with minor amounts of magnesium carbonate, calcium phosphate, and organic matter [15]. When processed through controlled cleaning, calcination, and mechanical or chemical grinding, eggshells can be transformed into nanosized calcium carbonate particles with high purity and reactivity. The nano-eggshell powder exhibited properties comparable to commercially produced nano-$CaCO_3$, including a high surface area and excellent filler capability. From a sustainability perspective, the utilization of eggshell-derived nanoparticles aligns with circular economic principles by converting agricultural waste products into high-value construction materials. Numerous studies have confirmed that eggshell powder, particularly at the nanoscale, enhances cement hydration, reduces setting time, and improves microstructural compactness. Unlike conventional fillers, nano-eggshell particles actively participate in hydration reactions, contributing to the formation of stable carboalumination phases that improve the matrix integrity [16]. These characteristics make nano-eggshells a promising alternative nanomaterial for advanced concrete systems [17].

The incorporation of nano-eggshell particles into UHPC represents a novel and promising research direction that combines high-performance engineering with sustainable-material innovation. In UHPC matrices, the nano-eggshells function through synergistic physical and chemical mechanisms. Physically, their nanoscale dimensions enhance the particle packing density, effectively filling the nanovoids and reducing the total porosity [18]. Chemically, the high-purity calcium carbonate content promotes accelerated hydration and participates in secondary reactions that stabilize the hydration products. Experimental results reported in the recent literature indicate that the partial replacement of cement or micro-fillers with nano-eggshell powder can lead to noticeable improvements in compressive strength, flexural strength, and durability indicators, particularly at early curing ages [19]. Moreover, UHPC incorporating nano-eggshells exhibited reduced water absorption and enhanced resistance to chloride ingress, which are critical parameters for a long-term service life. Importantly, the use of eggshell-derived nanoparticles reduces the carbon footprint of UHPC by lowering cement consumption and diverting waste from landfills. This dual benefit of performance enhancement and environmental sustainability positions nano-eggshell-modified UHPC as a viable material for future infrastructure applications. As research continues to optimize processing techniques, dosage levels, and dispersion methods, nano-eggshells are expected to play a significant role in the development of next-generation sustainable UHPC [20].

The research on nano-eggshell-modified UHPC is significant due to its dual contribution to enhancing material performance and promoting environmental sustainability. By incorporating eggshell-derived nanoparticles, this approach not only improves the mechanical properties of UHPC but also reduces its carbon footprint through decreased cement consumption and waste diversion from landfills. Ongoing studies focusing on optimizing processing techniques, dosage levels, and dispersion methods are crucial for maximizing these benefits. As a result, nano-eggshells are poised to play a pivotal role in advancing next-generation sustainable UHPC, making it a viable and eco-friendly option for future infrastructure development.

Experimental program

A. Raw materials

The cement was characterized in accordance with the requirements of BS EN 197-1:2011. It exhibited a specific gravity of 3.15 and a Blaine specific surface area of 3960 cm²/g and a chemical composition shown in **Tab. 1** The initial and final setting times were 135 and 195 min, respectively. Additionally, the cement achieved compressive strength values of 24.2 MPa after 7 days and 52.5 MPa after 28 days of curing. River sand was used as sand. Comprehensive physical and chemical characterizations were conducted to evaluate the properties of the processed waste glass. Eggshells were gathered, sanitized, and finely ground using a 90 µm sieve. **Fig.1** shows XRD for nano eggshell powder

Tab. 1. Chemical composition for cement and eggshell

Chemical Component	Cement (%)	Pulverized Eggshell (%)
SiO_2	25.75	–
Al_2O_3	9.88	–
Fe_2O_3	6.2	0.12
CaO	53.2	99.18
TiO_2	0.49	–
Na_2O	0.34	–
MgO	1.15	–

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SO_3	1.59	0.08
K_2O	0.17	0.3
Others	–	0.3
Loss on ignition (L.O.I)	1.23	0.02

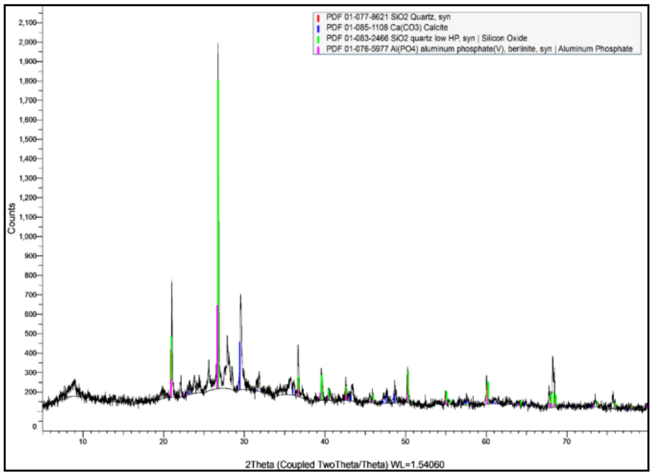

Fig.1. XRD for nano eggshell powder

B. Concrete mix design

The UHPC mixtures were designed by partially replacing cement with nano-eggshell (NES) at dosages of 0–5% by weight of cement, while maintaining constant contents of silica fume, sand, water, and superplasticizer, as summarized in **Tab. 2**. The reference mixture contained 900 kg/m³ of cement, whereas the cement content was gradually reduced with increasing NES content to ensure a constant total binder content. Silica fume was fixed at 90 kg/m³ to enhance matrix densification, and a low water-to-binder ratio was maintained to achieve the UHPC characteristics. A polycarboxylate-based superplasticizer was used at a constant dosage to ensure adequate workability for all mixtures.

Tab. 2. Mixing proportions

	Cement	NES	SF	Sand	SP	Water
Ref	900	0	90	1200	27	180
1 NES	891	9	90	1200	27	180
2 NES	882	18	90	1200	27	180
3 NES	873	27	90	1200	27	180
4 NES	864	36	90	1200	27	180
5 NES	855	45	90	1200	27	180

C. Mixing procedures

The mixing procedure was carefully controlled to ensure the homogeneous dispersion of nano-eggshell particles and prevent agglomeration. Initially, all dry constituents, including cement, silica fume, sand, and NES, were dry mixed for 2 min to achieve uniform distribution. Subsequently, approximately half of the mixing water was gradually added and mixed for 3 min to initiate hydration and improve the particle wetting.

The remaining water, which contained the dissolved superplasticizer, was then introduced, and mixing continued for an additional 5 min until a homogeneous and highly flowable UHPC mixture was obtained. Following mixing, the fresh UHPC was cast into steel molds in two layers with adequate compaction, covered to prevent moisture loss, and demolded after 24 h before curing under standard laboratory conditions until the designated testing ages [21].

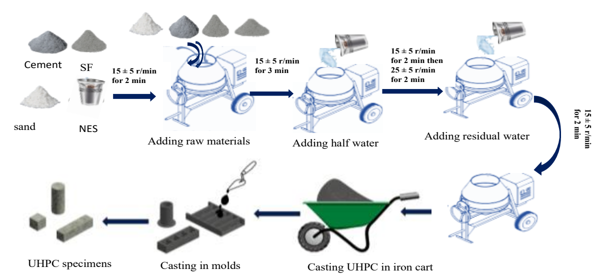

Fig. 2. Mixing procedures

D. Testing

The experimental program involved mechanical properties of compressive strength, splitting tensile strength, and sorptivity at different curing ages were tested in addition to XRD.

Results and discussion

A. Compressive strength

At the early curing age of 7 days, the reference UHPC mixture exhibited a compressive strength of 118.67 MPa. The incorporation of nano-eggshell (NES) resulted in a measurable enhancement in early age strength, with values increasing to 122.00, 123.91, and 124.54 MPa for the 1%, 2%, and 3% NES mixtures, respectively. These results correspond to strength improvements of approximately 2.8%, 4.4%, and 4.9% compared to the control mix, respectively. The

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enhancement in early-age compressive strength can be primarily attributed to the nucleation and nanofiller effects of NES particles, which accelerate cement hydration and improve the packing density within the UHPC matrix. However, further increasing the NES content to 4% and 5% led to a slight reduction in strength, indicating that excessive nano-eggshell content may hinder effective particle dispersion at early ages, as shown in **Fig. 3.**

At 28 days of curing, the reference mixture achieved a compressive strength of 137.67 MPa, whereas the UHPC mixtures containing NES demonstrated superior performance. The compressive strength increased to 141.44, 145.10, and 145.97 MPa for the 1%, 2%, and 3% NES mixtures, corresponding to improvements of approximately 2.7%, 5.4%, and 6.0%, respectively. This pronounced enhancement at the intermediate curing age suggests that NES contributes not only as a physical filler but also as a chemically active material. The calcium-rich nature of the nano eggshell particles facilitates additional hydration and promotes the formation of a denser C–S–H network, leading to reduced porosity and improved load-transfer capability [14]. Beyond the optimal dosage, the 4% and 5% NES mixtures exhibited marginally lower strength values, likely because of nanoparticle agglomeration and localized heterogeneity within the cementitious matrix [19].

At the later curing age of 90 d, the reference UHPC mixture reached a compressive strength of 149.48 MPa. The continued incorporation of NES resulted in sustained strength enhancement, with the 3% NES mixture attaining the highest value of 156.22 MPa, representing an increase of approximately 4.5% compared to the control. The strength gains observed at this stage reflect the long-term contribution of NES to microstructural refinement, including continued hydration, pore structure densification, and improved interfacial bonding within the UHPC matrix [22]. Nevertheless, UHPC mixtures containing higher NES contents (4% and 5%) showed a slight decline in compressive strength compared to the optimal mix, suggesting that excessive nano-eggshell addition may limit the long-term performance owing to agglomeration effects and reduced hydration efficiency. Overall, the results confirmed that an optimal NES dosage exists at which the UHPC exhibits enhanced compressive performance across all curing ages [23].

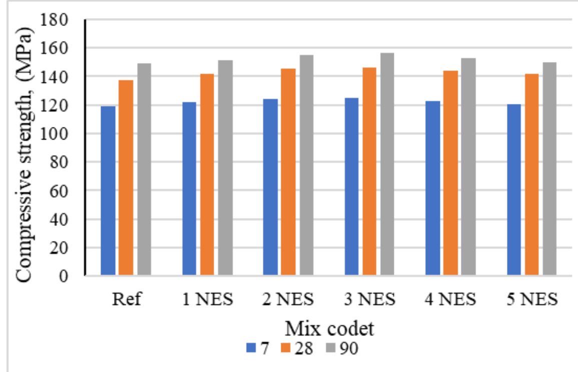

Fig. 3. Compressive strength of UHPC

*b. **Splitting tensile strength***

The splitting tensile strength results of the UHPC mixtures incorporating nano-eggshell (NES) at 28 d are presented in **Fig. 4.** The reference mixture exhibited a splitting tensile strength of 13.6 MPa. The incorporation of NES resulted in a notable improvement in tensile performance, with strength values increasing to 14.7, 15.4, and 15.9 MPa for the 1%, 2%, and 3% NES mixtures, respectively. These values correspond to enhancements of approximately 8.1%, 13.2%, and 16.9% compared with the control mix. The improvement in the splitting tensile strength can be attributed to the nanofiller and crack-bridging effects of the NES particles, which enhance matrix densification and improve stress transfer across microcracks. In addition, the calcium-rich composition of the nano-eggshell promotes improved interfacial bonding within the cementitious matrix, contributing to higher resistance to tensile cracking [24]. However, further increasing the NES content to 4% and 5% resulted in a slight reduction in splitting tensile strength to 14.7 and 15.1 MPa, respectively, although these values were higher than those of the reference mixture. This reduction is likely associated with nanoparticle agglomeration and reduced dispersion efficiency at higher dosages [25], which may introduce localized weak zones and limit the tensile performance. Overall, the results indicate that an optimal NES content of approximately 3% maximized the splitting tensile strength of UHPC at 28 days.

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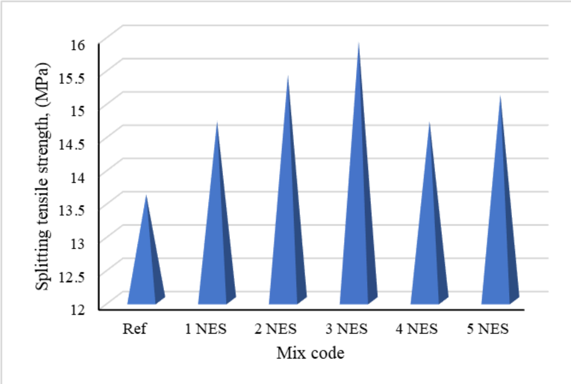

Fig. 4. Splitting tensile strength of UHPC

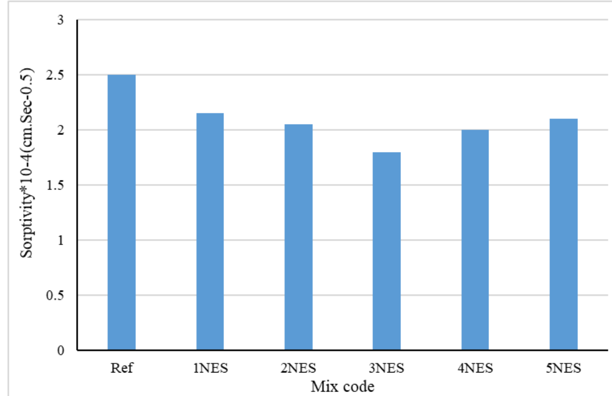

Fig. 5. Sorptivity of UHPC

C. Sorptivity

The sorptivity results of the UHPC mixtures incorporating nano-eggshell (NES) are presented in **Fig. 5**. The reference mixture exhibited a sorptivity value of 2.5×10^{-4} $cm \cdot s^{-0.5}$, indicating a relatively high rate of capillary water absorption. The incorporation of NES resulted in a clear reduction in sorptivity, reflecting an improvement in the durability-related performance of the UHPC. The sorptivity values decreased to 2.15, 2.05, and 1.80 $\times$ 10^{-4} $cm \cdot s^{-0.5}$ for the 1%, 2%, and 3% NES mixtures, corresponding to reductions of approximately 14.0%, 18.0%, and 28.0%, respectively, compared to the reference mixture. This significant reduction can be attributed to the nanofiller effect of NES, which enhances the particle packing density, refines the pore structure, and reduces the connectivity of capillary pores within the UHPC matrix. In addition, the calcium-rich composition of the nano-eggshell particles promotes the formation of additional hydration products, leading to a denser and less permeable microstructure [26]. However, further increasing the NES content beyond the optimal level resulted in a slight increase in the sorptivity values to 2.0 and 2.1 $\times$ 10^{-4} $cm \cdot s^{-0.5}$ for the 4% and 5% NES mixtures, respectively. This behavior is likely associated with nanoparticle agglomeration at higher dosages, which may introduce microstructural heterogeneity and partially offset the beneficial pore-refining effects [27]. Overall, the results demonstrate that an optimal NES dosage of approximately 3% is effective in minimizing sorptivity and enhancing the resistance of UHPC to capillary-water ingress.

D. XRD analysis

XRD analysis was performed on six samples as the control mix and five mixes in the cases of 1, 2, 3, 4, and 5 % replacement of cement with eggshells. The XRD patterns of Series I at 91 days are shown in **Fig. 6**. Ultra-High-Performance Concrete (UHPC) undergoes X-ray Diffraction (XD) exhibits unique diffraction patterns corresponding to the crystalline phases found in the composite when subjected to X-ray Diffraction (XRD) examination. When UHPC is mixed with eggshell powder, the main crystalline phases typically consist of calcium carbonate (CaCO3) from the eggshell and different phases related to cementitious materials in the concrete matrix, such as calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). X-ray diffraction patterns exhibit distinct diffraction peaks at precise angles corresponding to the atomic arrangement within the crystal lattice. The positions and intensities of these peaks provide valuable insights into the composition and crystallinity of the present phases. The presence of these peaks in the UHPC composition that includes eggshell powder signifies the existence of CaCO3 and any possible chemical interplay between the eggshell and cementitious constituents [8,28]. By evaluating the XD patterns for different dosages, such as 1%, 2%, 3%, 4%, and 5% eggshell powder, the impact of varying dosage levels on the crystalline phases and peaks can be assessed [29]. In addition, an increase in dosage can result in more prominent $CaCO_3$ diffraction peaks, indicating a greater amount of eggshell-derived material in the UHPC. However, a decrease in the highest intensity or changes in the placement of the highest levels may indicate possible interactions or phase changes within the crystalline structure of UHPC.

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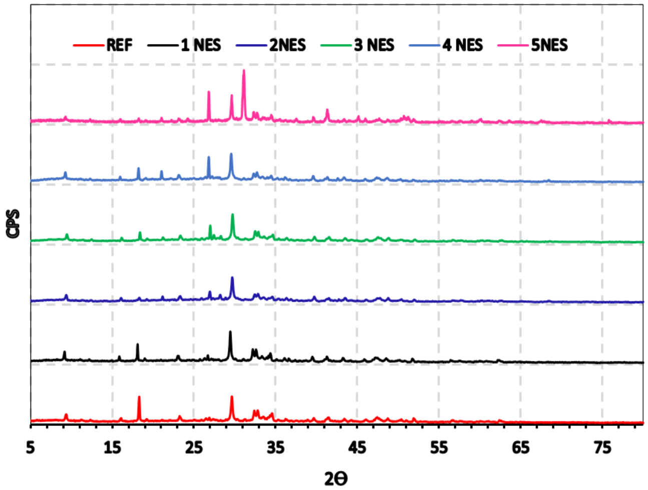

Fig. 6. XRD patterns of UHPC

Conclusions

Incorporating nano-eggshell (NES) particles into UHPC enhances its mechanical and durability performance, with an optimal dosage of approximately 3%. At 3% NES, the compressive strength improved by 4.9%, 6.0%, and 4.5% at 7, 28, and 90 days, respectively, compared to the reference mix. The splitting tensile strength at 28 days increased by 16.9% with 3% NES incorporation. Sorptivity was reduced by 28% at the optimal NES content, indicating improved resistance to capillary water absorption and enhanced durability of the bricks. XRD analysis confirmed the presence of calcium carbonate in NES and its interaction with the cementitious matrix, contributing to microstructural refinement. The performance improvements are attributed to the nanofiller effect, accelerated hydration, and improved particle packing induced by NES particles. Excessive NES content beyond 3% led to slight reductions in mechanical properties and durability, likely due to nanoparticle agglomeration and a reduced dispersion efficiency. Utilizing nano-eggshell waste in UHPC offers a sustainable and eco-friendly alternative to conventional nano-fillers, contributing to waste valorization and reduced environmental impact.

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