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Towards Sustainable Ultra-High-Performance Concrete: Role of Nano Rice Husk Ash and Nano Sugarcane Bagasse Ash

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Abstract - Ultra-high-performance concrete (UHPC) has gained considerable attention owing to its superior mechanical properties and durability; however, its performance can be further enhanced by incorporating nanoscale supplementary cementitious materials. This study investigates the effects of nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA) on the mechanical and durability performance of ultra-high-performance concrete (UHPC) incorporating end-hooked steel fibers. Both nanomaterials were produced through controlled calcination at 700 °C for 3 h, followed by ball milling to achieve nano-sized particles, ensuring high pozzolanic reactivity and effective dispersion. UHPC mixtures were prepared with varying nano contents, and a comprehensive experimental program was conducted to evaluate the compressive strength, splitting tensile strength, flexural strength, and sorptivity at different curing ages. The results demonstrated that the incorporation of NRHA and NSCBA significantly enhanced the mechanical performance of UHPC at both early and later ages. At 7 and 28 d, the compressive, splitting tensile, and flexural strengths showed notable improvements compared to those of the control mixture, with optimum nano contents yielding the highest strength gains. In particular, mixtures containing an intermediate dosage of NRHA exhibited the highest enhancements in tensile and flexural performance, indicating improved crack-bridging efficiency and fiber–matrix interaction. Durability assessment based on sorptivity measurements at 28 days revealed a substantial reduction in capillary water absorption for nano-modified UHPC, with NRHA-based mixtures showing the greatest improvement owing to pronounced pore refinement and matrix densification. Overall, the findings confirm that the use of agricultural waste-derived nanomaterials can effectively improve both the mechanical and durability properties of UHPC. Among the investigated mixtures, NRHA at the optimum dosage demonstrated superior overall performance, highlighting its potential as a sustainable and high efficiency nanoadditive for advanced UHPC applications.

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-Mechanical properties
-Durability;
-Sorptivity

Introduction

Ultra-high-performance concrete (UHPC) is one of the most advanced classes of cement-based materials owing to its exceptional mechanical strength, superior durability, and refined microstructure compared with conventional and high-strength concretes [1]. Typically characterized by compressive strengths exceeding 120, UHPC achieves outstanding performance through optimized particle packing, low water-to-binder ratios, high cementitious content, and the incorporation of supplementary cementitious materials and steel fibers [2]. Previous studies have demonstrated that UHPC exhibits remarkable resistance to chloride penetration, abrasion, and chemical attacks, making it suitable for demanding structural applications, such as long-span bridges, precast elements, and protective structures [3]. However, despite these advantages, UHPC production faces several challenges, including high cement consumption, increased costs, and environmental concerns related to carbon dioxide emissions associated with cement manufacturing. Consequently, recent research has focused on enhancing the performance of UHPC while simultaneously improving sustainability through the partial replacement of cement with highly reactive supplementary materials [4]. Researchers have emphasized that optimizing the UHPC composition at the micro- and nanoscale plays a critical role in achieving superior mechanical and durability properties [5]. The incorporation of fine and ultrafine materials has been shown to refine the pore structure, improve the interfacial transition zone, and enhance hydration efficiency [6]. Therefore, the development of UHPC mixtures incorporating alternative and sustainable materials has become an essential research direction in the field of concrete technology [7].

Nanotechnology has emerged as a promising approach to improve the performance of cementitious composites by modifying their behavior at the nanoscale. Nanomaterials possess extremely high specific surface areas, which significantly enhance their pozzolanic reactivity and interaction with hydration products. Previous studies have reported that nanosilica, nanoalumina, and nanoclay can accelerate cement hydration, increase calcium silicate hydrate (C–S–H) formation, and reduce porosity, leading to enhanced mechanical strength and durability [8]. In UHPC systems, the effect of nanomaterials is even more pronounced because of the dense matrix and low water content. Researchers have shown that the inclusion of nanoscale additives can improve early age strength, refine pore connectivity, and reduce permeability [9]. However, the effectiveness of nanomaterials strongly depends on their dispersion and dosage, as excessive nano content may lead to particle agglomeration and reduced performance [10]. Therefore, identifying optimum nano dosages and effective dispersion techniques is crucial. Recent experimental investigations have emphasized that nanoscale pozzolanic materials derived from industrial and agricultural waste can offer comparable or superior performance to conventional nanosilica while also contributing to sustainability and cost reduction [11].

Agricultural waste materials, such as rice husk ash (RHA) and sugarcane bagasse ash (SCBA) [12], have attracted considerable attention as sustainable supplementary cementitious materials owing to their high silica content and wide availability [13]. Numerous studies have demonstrated that properly processed RHA contains a high percentage of amorphous silica, often exceeding 85%, which contributes to its strong pozzolanic activity [14]. Similarly, SCBA reportedly contains significant amounts of reactive silica and alumina, enabling effective participation in secondary hydration reactions [15]. Previous research has shown that incorporating RHA and SCBA into conventional and high-strength concrete can improve compressive strength, reduce water absorption, and enhance resistance to chemical attacks. Recently, nanosized RHA and SCBA have been investigated, with results indicating substantial improvements in mechanical properties and durability compared to their microscale counterparts. Studies have reported strength improvements ranging from 10% to 30%, depending on the processing methods and replacement levels [16]. The transformation of agricultural waste into high-value nanomaterials aligns with global sustainability goals and

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offers a viable approach for reducing cement consumption while enhancing UHPC performance [17].

Steel fiber reinforcement is a key component of UHPC mixtures, playing a crucial role in improving the tensile strength, flexural performance, and post-cracking behavior. End-hooked steel fibers, in particular, have been shown to provide superior mechanical anchorage within the cementitious matrix, resulting in improved load transfer and ductility. Previous studies have demonstrated that the synergistic interaction between steel fibers and supplementary cementitious materials significantly influences the performance of UHPC [18]. The incorporation of nanomaterials has been reported to improve the fiber–matrix bonding by refining the interfacial transition zone and increasing the matrix compactness [19]. This enhancement leads to improved crack-bridging efficiency and higher tensile and flexural strength. Research has also shown that UHPC mixtures incorporating both fibers and nano-additives exhibit reduced crack widths and improved energy absorption capacity. However, the combined effect of agricultural waste-derived nanomaterials and end-hooked steel fibers in UHPC remains relatively underexplored, particularly with respect to durability indicators such as sorptivity and long-term water absorption behavior [20].

Durability performance is a critical consideration for UHPC applications, particularly in aggressive environments, where exposure to moisture, chlorides, and chemical agents can compromise structural integrity. Sorptivity is widely recognized as an effective indicator of concrete durability because it reflects the capillary absorption behavior and pore connectivity of the cementitious matrix [21]. Previous research has established a strong correlation between reduced sorptivity and improved resistance to chloride ingress and chemical attacks [22]. Studies have reported that the incorporation of nanomaterials significantly reduces sorptivity by refining the pore structure and blocking capillary channels through additional C–S–H formation. Nano RHA, in particular, has been shown to outperform conventional pozzolanic materials in reducing water absorption due to its high silica content and nano-scale particle size [23].Despite these findings, few studies have systematically evaluated the combined effects of nano RHA and nano SCBA on the mechanical and durability performance of UHPC reinforced with end-hooked steel fibers. This research gap highlights the need for a comprehensive experimental investigation to quantify the strength enhancement, durability improvement, and optimal nanomaterial dosage [24].

The significance of this research lies in its comprehensive evaluation of UHPC incorporating agricultural waste-derived nanomaterials and end-hooked steel fibers. Unlike previous studies that focused primarily on conventional nano-additives or single performance indicators, this study systematically investigated the compressive, splitting tensile, flexural, and sorptivity properties at different curing ages. This study provides quantitative evidence of the optimum nanomaterial dosage required to achieve maximum mechanical and durability performance while avoiding particle agglomeration. Furthermore, the utilization of nano rice husk ash and nano sugarcane bagasse ash contributes to sustainable construction practices by recycling agricultural waste and reducing cement consumption. The findings of this study offer valuable insights for the development of high-performance, durable, and environmentally friendly UHPC mixtures suitable for advanced structural applications.

Experimental program

A. Raw materials

The ultra-high-performance concrete (UHPC) mixtures investigated in this study were produced using carefully selected raw materials to achieve superior mechanical performance, enhanced durability, and optimized rheological properties of the UHPC. Ordinary Portland cement (OPC) was used as the primary binder, conforming to the ASTM C150 specifications [25]. It is characterized by a high calcium silicate content, mainly tricalcium silicate (C_3S) and dicalcium silicate (C_2S), which are responsible for the early and long-term strength development. Silica fume was incorporated as a supplementary cementitious material owing to its extremely fine particle size and high amorphous silicon dioxide (SiO_2)

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content exceeding 90%. The high pozzolanic reactivity of silica fume contributes to pore refinement, densification of the cement matrix, and improved interfacial transition zones (ITZ), which are essential characteristics of UHPC systems.

Fine sand with a controlled particle size distribution was employed as the main aggregate to ensure dense packing and minimize the internal voids [26]. In addition, waste glass powder was used as a partial fine aggregate replacement, sourced from recycled glass and ground to a fine size. Glass powder is rich in amorphous silica (SiO_2), which enhances pozzolanic activity and contributes to sustainable concrete production by recycling industrial waste materials. Potable water was used for all the mixtures to ensure consistency and avoid adverse chemical reactions [27].

End-hooked steel fibers were incorporated at a volumetric fraction of 1% to enhance the mechanical performance and crack resistance of the UHPC. These fibers provide effective crack bridging, improve post-cracking behavior, and significantly enhance the tensile and flexural strengths. The hooked ends ensure improved mechanical anchorage within the cementitious matrix, leading to better stress transfer and improved ductility [13, 28].

Nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA) were used as nano-scale pozzolanic additives in different proportions (1–3%). Rice husk ash is predominantly composed of amorphous silica (typically 85–95% SiO_2), whereas sugarcane bagasse ash contains significant amounts of SiO_2 along with minor proportions of Al_2O_3, Fe_2O_3, and CaO. After nanosizing, both ashes exhibited a high specific surface area, which accelerated hydration reactions, promoted the formation of additional calcium silicate hydrate (C–S–H) gel, and refined the pore structure, resulting in improved strength and reduced permeability [29].

A high-range water-reducing admixture based on polycarboxylate ether (PCE), commercially known as Viscocrete, was used as a superplasticizer to achieve the required flowability and self-compacting characteristics of UHPC at a low W/B ratio. The dispersing mechanism of Viscocrete relies on electrostatic repulsion and steric hindrance, ensuring uniform particle dispersion, improved workability, and the prevention of fiber agglomeration [30]. This combination of carefully selected raw materials ensures the production of UHPC with enhanced mechanical properties, durability, and sustainability of the UHPC. The mixing procedures are shown in **Tab. 1** and **Fig. 1.**

Tab. 1. Mix proportions

Item	Value
Cement (kg/m³)	800
Silica fume (kg/m³)	80
sande (kg/m³)	1200
waste glass	300
Water (L/m³)	184.8
Superplasticizer (L/m³)	6.93
steel fiber r (Vf)	1%
NRHA	1-3%
NSCBA	1-3%

Fig. 1. Mixing proportions

B. *Preparation of Nano Materials*

The preparation of nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA) was carried out through a controlled thermal and mechanical treatment process to ensure high pozzolanic activity and uniform particle dispersion. Initially, rice husks and sugarcane bagasse were collected, cleaned to remove impurities, and air-dried. The raw materials were then subjected to controlled calcination in an electric

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furnace at 700 °C for 3 h [31]. This calcination temperature was carefully selected to eliminate organic matter while preserving the amorphous structure of silica, which is essential for achieving high pozzolanic reactivity and preventing the formation of undesirable crystalline phases in the ash. After calcination, the obtained ashes were naturally cooled to room temperature and subsequently ground using a ball milling process to achieve nanosized particles. The milling parameters were optimized to obtain a particle size predominantly in the range of approximately 50–100 nm with a narrow size distribution. Careful control of the milling time and rotational speed was applied to minimize excessive heat generation and avoid particle agglomeration. The milling process was conducted under controlled conditions to ensure effective dispersion and prevent the formation of clusters or hard agglomerates. The preparation steps are summarized in **Fig. 2.**

The resulting nanosized NRHA and NSCBA exhibited a high specific surface area and enhanced pozzolanic reactivity, which significantly promoted the formation of additional C–S–H gel, refined the pore structure, and improved the mechanical and durability performance of UHPC mixtures [32].

Fig. 2. Preparation of nano ashes

C. Dispersion of Nano Materials in UHPC

To ensure the effective dispersion of nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA) and to prevent particle agglomeration, a magnetic stirrer was employed before their incorporation into the UHPC mixtures. The required amount of nanomaterial was first dispersed in a portion of the mixing water and subjected to continuous stirring using a magnetic stirrer at a controlled rotational speed for a predetermined duration [33]. This process promoted a uniform suspension of nanosized particles and enhanced their stability within the liquid medium. The application of magnetic stirring facilitates the breakdown of weak agglomerates formed owing to Van der Waals forces, thereby improving particle separation and distribution, as shown in **Fig. 3.**

The resulting nanosuspension was then gradually introduced into the concrete mixture during the water and superplasticizer addition stages. This dispersion technique significantly enhanced the homogeneity of the cementitious matrix, improved the interaction between the nanoparticles and hydration products, and promoted the formation of a denser microstructure. Consequently, the use of a magnetic stirrer contributed to improved pozzolanic reactivity, refined pore structure, and enhanced mechanical and durability properties [34].

Fig. 3. Dispersion of nano materials using a magnetic stirrer

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D. Mixing procedures

The mixing procedure of the ultra-high-performance concrete (UHPC) was carefully designed to ensure the homogeneous dispersion of all constituents, particularly the nanomaterials and steel fibers, and to achieve optimal rheological and mechanical performance. Initially, all dry materials, including cement, silica fume, fine sand, waste glass powder, and the required proportion of nano rice husk ash (NRHA) or nano sugarcane bagasse ash (NSCBA), were dry mixed for approximately 3–5 min using a high-shear laboratory mixer. This step was essential for achieving a uniform distribution and minimizing particle segregation. Subsequently, potable water was gradually added while mixing continued, followed by the incorporation of the polycarboxylate-based superplasticizer (Viscocrete), which was introduced in stages to enhance the dispersion efficiency and avoid sudden loss of workability as presented in **Fig. 4.**

After achieving a homogeneous and flowable cementitious matrix, end-hooked steel fibers were gradually introduced into the mixture while maintaining continuous mixing at low-to-moderate speeds. This controlled addition prevented fiber balling and ensured a uniform fiber distribution throughout the matrix [35]. The mixing process was continued until a consistent, self-compacting UHPC mixture with high cohesiveness and stability was achieved. The total mixing duration was carefully controlled to avoid excessive air entrainment and maintain the desired rheological properties. This optimized mixing procedure ensured the effective dispersion of nanosized materials, enhanced fiber–matrix bonding, and contributed significantly to the improved mechanical strength and durability characteristics of the UHPC mixtures.

Fig. 4. Mixing procedures

E. Testing

To evaluate the mechanical performance and durability characteristics of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA), a comprehensive experimental testing program was conducted. Compressive strength tests were performed at curing ages of 7 and 28 d to assess both early age and long-term strength development of the UHPC mixes as shown in **Fig.5.** In addition, splitting tensile strength tests were conducted at the same curing ages to evaluate the tensile performance and effectiveness of the nanomaterials and steel fiber reinforcement in enhancing crack resistance.

Furthermore, flexural strength tests were conducted at 7 and 28 days to investigate the bending behavior and post-cracking performance of the UHPC mixtures, particularly reflecting the contribution of end-hooked steel fibers and nano-additives to load transfer and ductility. To assess the durability-related properties, sorptivity tests were performed at 28 days to evaluate the water absorption characteristics and pore structure refinement of the UHPC matrix. Sorptivity measurements provide valuable insights into the influence of nanomaterials on capillary suction and permeability reduction.

All test results were systematically recorded and analyzed to quantify the percentage improvement of each UHPC mixture relative to the control. The combined assessment of the compressive, tensile, flexural, and sorptivity results enabled a comprehensive evaluation of the mechanical efficiency and durability enhancement achieved through the incorporation of NRHA and NSCBA.

Fig. 5. Mixing and testing procedures

Results and discussion

A. Compressive strength at 7 days

The 7-day compressive strength results clearly demonstrated the significant influence of nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA) on the early age mechanical performance of UHPC mixtures. As illustrated in **Fig.6**, the control mixture achieved a compressive strength of approximately 98.68 MPa, which was used as the reference baseline. All modified mixtures exhibited higher compressive strength values, confirming the effectiveness of nanomaterial incorporation in enhancing early hydration reactions and matrix densification.

For the NSCBA-based mixtures, a gradual improvement in compressive strength was observed with increasing nano content up to an optimum level. NSCBA1 and NSCBA3 achieved compressive strengths of approximately 101.03 MPa and 107.25 MPa, corresponding to improvement ratios of about +2.38% and +8.69%, respectively. The maximum enhancement was recorded for NSCBA2, which reached approximately 118.83 MPa, representing an improvement of approximately 20.42% compared to the control mixture. This optimum performance indicates that the intermediate NSCBA dosage provided the most effective balance between pozzolanic reactivity and particle dispersion [15, 36].

Similarly, UHPC mixtures incorporating NRHA exhibited a marked increase in early-age compressive strength. NRHA1, NRHA2, and NRHA3 demonstrated strength improvements of approximately +11.81%, +20.42%, and +15.10%, respectively, compared to the Among these mixtures, NRHA2 exhibited the highest compressive strength, confirming the presence of an optimal nano content beyond which marginal strength reduction may occur owing to the particle agglomeration effects [37].

The relatively low standard deviation values observed for all UHPC mixtures indicated good repeatability and consistency of the experimental results. The limited scatter in the compressive strength measurements reflects the effectiveness of the adopted mixing and dispersion procedures, particularly the use of magnetic stirring and controlled fiber addition. Moreover, the slightly lower standard deviation recorded for the optimum mixtures (NSCBA2 and NRHA2) suggests improved homogeneity and a more uniform microstructure than the control and higher-dosage mixes.

Overall, the results confirm that both nano materials significantly enhance the early-age compressive strength of UHPC; however, NSCBA2 can be identified as the optimum mixture at 7 days, combining the highest strength gain with stable performance and minimal variability

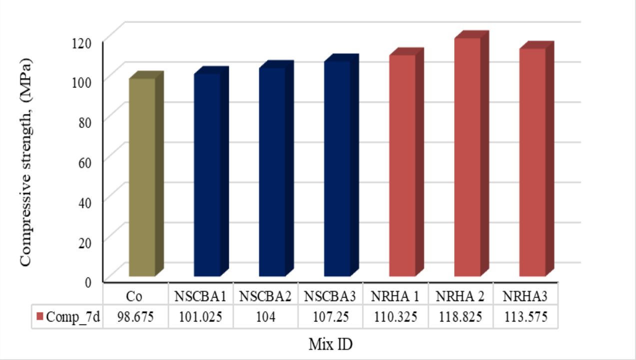

Fig. 6. Compressive strength for UHPC with different types of nanoparticles

B. Compressive strength at 28 days

The 28-day compressive strength results provide a clear assessment of the long-term mechanical performance of UHPC mixtures incorporating nano rice husk ash (N-RHA) and nano sugarcane bagasse ash (N-SCBA). As shown in **Fig. 7**, the control mixture achieved a compressive strength of approximately 130.03 MPa, which was considered the reference value for evaluating the strength enhancement at later curing ages. Compared to the 7-day results, all mixtures exhibited a noticeable increase in compressive strength at 28 d, reflecting the continued hydration and pozzolanic reactions promoted by the nanomaterials.

For the NSCBA-modified mixtures, a consistent increase in compressive strength was observed with increasing nano content. NSCBA1 and NSCBA3 achieved compressive strengths of approximately 134.70 MPa and 143.00 MPa, corresponding to improvement ratios of about +3.60% and +9.98%, respectively, relative to the control mix. The highest strength within this group was recorded for NSCBA2, which reached approximately 163.75 MPa, representing a substantial improvement of approximately 25.94%. This result confirms that the optimum NSCBA dosage significantly enhances the long-term strength by contributing to sustained pozzolanic activity, increased C–S–H gel formation, and improved microstructural compactness [38].

Similarly, the UHPC mixtures incorporating NRHA exhibited a pronounced long-term strength enhancement. NRHA1, NRHA2, and NRHA3 recorded compressive strengths of approximately 146.93 MPa, 163.75 MPa, and 158.03 MPa, corresponding to improvement ratios of +13.00%, +25.94%, and +21.53%, respectively. Among these, NRHA2 exhibited the highest 28-day compressive strength, indicating that the intermediate NRHA dosage provided the most efficient balance between silica availability and particle dispersion, whereas higher contents led to slightly reduced gains owing to possible agglomeration effects [39].

The low standard deviation values observed at 28 d indicate the high repeatability and reliability of the test results. The reduced scatter in compressive strength, particularly for the optimum mixtures (NSCBA2 and NRHA2), suggests a more homogeneous microstructure and improved uniformity in nanoparticle dispersion and fiber–matrix interaction. This behavior highlights the effectiveness of the adopted dispersion and mixing procedures in achieving a stable long-term performance.

Overall, the 28-day results confirmed that both nanomaterials significantly enhanced the long-term compressive strength of UHPC. However, NRHA2 and NSCBA2 were identified as the optimum mixtures, providing the highest strength improvement combined with consistent performance and minimal variability.

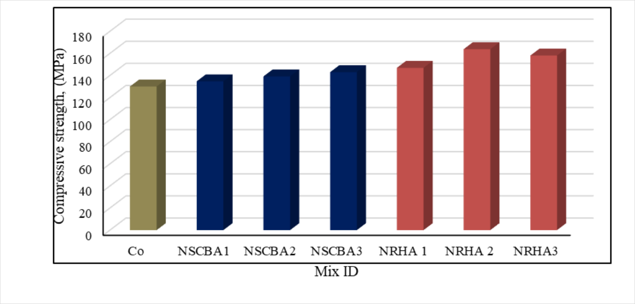

Fig. 7. compressive strength for UHPC with different types of nanoparticles

C. Early tensile strength

The splitting tensile strength results at 7 days provide valuable insights into the early age cracking resistance and tensile performance of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA). As illustrated in **Fig. 8**, the control mixture exhibited a splitting tensile strength of approximately 14.54 MPa, which was used as a reference value to assess the effectiveness of the

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incorporation of nanomaterials. Compared with the control mix, all modified UHPC mixtures demonstrated improved tensile strength, confirming the beneficial role of nano additives and steel fiber reinforcement in enhancing early age tensile behavior [40].

For the NSCBA-modified mixtures, a gradual increase in splitting tensile strength was observed with an increase in the nano content. NSCBA1 achieved a tensile strength of approximately 14.93 MPa, corresponding to an improvement ratio of about +2.69% relative to the control mix. A more pronounced enhancement was recorded for NSCBA2, which reached approximately 15.32 MPa, representing an improvement of approximately +5.38%. The highest tensile strength within this group was observed for NSCBA3, with a value of approximately 15.78 MPa, corresponding to an improvement ratio of approximately +8.54%. This progressive enhancement indicates that the nano-SRBA effectively contributes to matrix densification and improves stress transfer at the fiber–matrix interface during early age loading [41].

Similarly, UHPC mixtures incorporating NRHA exhibited a superior splitting tensile strength at 7 d. NRHA1, NRHA2, and NRHA3 recorded tensile strength values of approximately 16.56 MPa, 17.48 MPa, and 16.79 MPa, corresponding to improvement ratios of approximately +13.92%, +20.25%, and +15.51%, respectively. Among these mixtures, NRHA2 exhibited the highest splitting tensile strength, indicating that the intermediate NRHA dosage provided the most effective balance between nanoscale reactivity and particle dispersion. The slight reduction observed for NRHA3 suggests the onset of nanoparticle agglomeration at higher contents, which may reduce the stress distribution efficiency.

The relatively low standard deviation values recorded for all the mixtures reflect the good repeatability and consistency of the tensile test results. The reduced scatter observed for the optimum mixtures, particularly NRHA2, indicates the enhanced homogeneity and uniform dispersion of the nanoparticles and steel fibers within the UHPC matrix. Overall, the results confirm that both NRHA and NSCBA significantly enhanced early age splitting tensile strength; however, NRHA2 can be identified as the optimum mixture at 7 d, achieving the highest tensile improvement combined with stable and reliable performance [42].

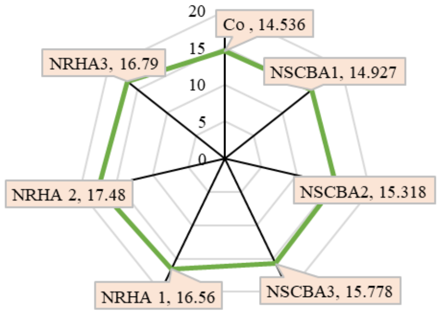

Fig. 8. Early tensile strength for UHPC with different types of nanoparticles

D. 28 days tensile strength

The 28-day splitting tensile strength results provide a comprehensive evaluation of the long-term tensile behavior and crack resistance of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA). As illustrated in Fig. 9, the control mixture exhibited a splitting tensile strength of approximately 19.44 MPa, which was considered the reference value for assessing tensile enhancement at later curing ages. Compared with the control mix, all UHPC mixtures containing nanomaterials demonstrated noticeable improvements, highlighting the sustained contribution of nanoscale pozzolanic reactions and improved fiber–matrix interactions over time.

For the NSCBA-modified mixtures, moderate but consistent enhancements in the splitting tensile strength were observed. NSCBA1 recorded a tensile strength of approximately 19.94 MPa, corresponding to an improvement ratio of about +2.60%. A higher enhancement was achieved by NSCBA2, which reached approximately 20.47 MPa, representing an improvement of approximately +5.33%. The highest tensile strength within this group was observed for NSCBA3, with a value of approximately 21.44 MPa, corresponding to an improvement ratio of approximately +10.30%. This trend suggests that increasing the NSCBA content promotes further matrix densification and enhances the stress transfer mechanisms at the fiber–matrix interface, particularly at later ages [43].

In contrast, the UHPC mixtures incorporating NRHA exhibited more pronounced tensile strength gains at 28 days. NRHA1, NRHA2, and NRHA3 achieved splitting tensile strength values of approximately 22.31 MPa, 23.76 MPa, and 23.12 MPa, corresponding to improvement ratios of approximately +14.79%, +22.25%, and +18.93%, respectively. Among these mixtures, NRHA2 exhibited the highest splitting tensile strength, confirming the presence of an optimal NRHA dosage that maximized pozzolanic efficiency and microstructural refinement. The slight reduction in strength observed for NRHA3 may be attributed to partial nanoparticle agglomeration at higher contents, which can reduce the effective stress distribution.

The relatively low standard deviation values recorded at 28 days indicate high test repeatability and reliable tensile performance. The reduced scatter associated with the optimum mixtures, particularly NRHA2, reflects improved homogeneity, effective nanoparticle dispersion, and stronger fiber–matrix bonding. Overall, the results demonstrate that both NRHA and NSCBA significantly enhance the long-term splitting tensile strength; however, NRHA2 can be identified as the optimum mixture at 28 d, combining the highest tensile improvement with stable and consistent performance [44].

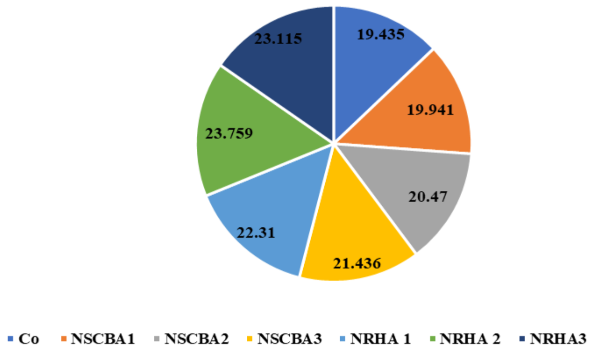

Fig. 9. 28 days tensile strength for UHPC with different types of nanoparticles

E. Early flexural strength

The flexural strength results at 7 days provide important insights into the early age bending performance and crack-bridging efficiency of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA). As illustrated in **Fig. 10**, the control mixture exhibited a flexural strength of approximately 20.05 MPa, which was adopted as the reference value for evaluating the influence of nanomaterial incorporation. All modified mixtures demonstrated enhanced flexural performance compared to the control mix, highlighting the combined contribution of nanomaterials and end-hooked steel fibers in improving the early age load-carrying capacity under bending.

For the NSCBA-modified mixtures, a gradual increase in the flexural strength was observed with increasing nano content. NSCBA1 achieved a flexural strength of approximately 20.37 MPa, corresponding to an improvement ratio of about +1.64%. A more noticeable enhancement was recorded for NSCBA2, which reached approximately 21.15 MPa, representing an improvement of approximately +5.51% relative to the control mix. The highest flexural strength within this group was observed for NSCBA3, with a value of approximately 22.02 MPa, corresponding to an improvement ratio of approximately +9.85%. This progressive improvement indicates that increasing the NSCBA content effectively enhances matrix densification and improves the fiber–matrix interfacial bond, which plays a critical role in the flexural behavior at early ages.

In contrast, UHPC mixtures incorporating NRHA exhibited more pronounced improvements in flexural strength at 7 d. NRHA1, NRHA2, and NRHA3 recorded flexural strength values of approximately 22.04 MPa, 22.89 MPa, and 22.63 MPa, corresponding to improvement ratios of approximately +9.96%, +14.19%, and +12.90%, respectively. Among these mixtures, NRHA2 exhibited the highest flexural strength, indicating that the intermediate NRHA dosage provided the most effective enhancement of the early age bending resistance. The slight reduction observed for NRHA3 suggests the onset of nanoparticle agglomeration at higher contents, which may reduce the stress transfer efficiency despite increased silica availability [45].

The relatively low standard deviation values observed for all mixtures reflect good test repeatability and consistency. The reduced scatter associated with the optimum mixtures, particularly NRHA2, indicates improved homogeneity, uniform nanoparticle dispersion, and effective fiber distribution within the UHPC matrix. Overall, the results confirmed that both NRHA and NSCBA significantly enhanced the early age flexural strength; however, NRHA2 was identified as the optimum mixture at 7 d, providing the highest flexural strength improvement combined with stable and reliable performance.

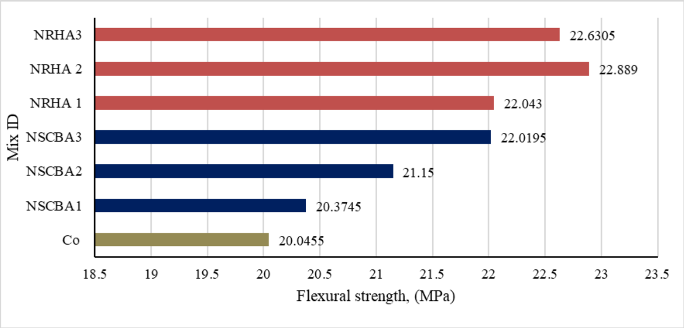

Fig. 10. Flexural strength for UHPC with different types of nanoparticles

F. *flexural strength at 28 days*

The flexural strength results at 28 days provide a clear indication of the long-term bending performance and post-cracking behavior of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA). As shown in **Fig. 11**, the control mixture exhibited a flexural strength of approximately 26.78 MPa, which was adopted as the reference value for evaluating the effectiveness of the nanomaterial incorporation at later curing ages. Compared to the control mix, all UHPC mixtures containing nanomaterials demonstrated substantial improvements, reflecting the sustained contribution of pozzolanic reactions and enhanced fiber–matrix interaction over time.

For the NSCBA-based mixtures, a pronounced increase in flexural strength was observed with increasing nano content. NSCBA1 and NSCBA2 achieved flexural strength values of approximately 30.70 MPa and 32.38 MPa, corresponding to improvement ratios of about +14.67% and +20.94%, respectively. The highest flexural strength within this group was recorded for NSCBA3, which reached approximately 34.38 MPa, representing a significant improvement of approximately +28.39% compared to the control mixture. This trend highlights the effectiveness of NSCBA in enhancing the long-term flexural performance by promoting matrix densification, refining the interfacial transition zone, and improving stress transfer across microcracks bridged by steel fibers.

In contrast, the UHPC mixtures incorporating NRHA exhibited even greater enhancements in flexural strength at 28 d. NRHA1, NRHA2, and NRHA3 recorded flexural strength values of approximately 37.00 MPa, 37.80 MPa, and 35.57 MPa, corresponding to improvement ratios of approximately +38.20%, +41.18%, and +32.86%, respectively. Among these mixtures, NRHA2 exhibited the highest flexural strength, indicating that the intermediate NRHA dosage provided the most effective enhancement of the bending resistance. The slight reduction observed for NRHA3 suggests that excessive nano content may lead to partial agglomeration, which can reduce the stress redistribution efficiency despite the increased availability of reactive silica [46].

The relatively low standard deviation values recorded for the flexural strength results indicate the good repeatability and consistency of the experimental program. The reduced scatter associated with the optimum mixtures, particularly NRHA2 and NSCBA3, reflects improved homogeneity, effective nanoparticle dispersion, and strong fiber–matrix bonding within the UHPC matrix. Overall, the results confirmed that both nanomaterials significantly enhanced the long-term flexural performance of UHPC; however, NRHA2 was identified as the optimum mixture at 28 d, providing the highest flexural strength improvement combined with stable and reliable performance.

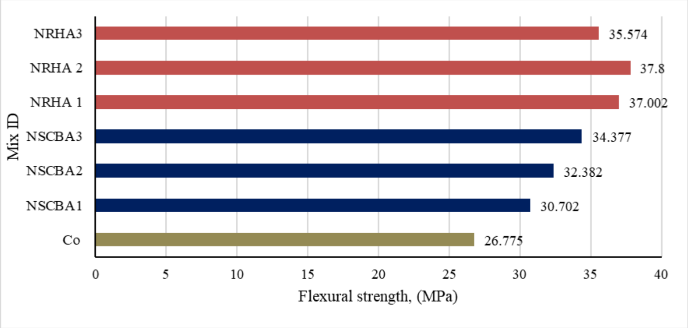

Fig. 11. Flexural strength for UHPC with different types of nanoparticles

G. Sorptivity

The sorptivity results at 28 days provide a clear assessment of the durability performance and capillary water absorption behavior of UHPC mixtures incorporating nano rice husk ash (NRHA) and nano sugarcane bagasse ash (NSCBA). As shown in **Fig. 12**, the control mixture exhibited a sorptivity value of approximately 2.26%, which was considered the reference for evaluating the effectiveness of nanomaterial incorporation in reducing water absorption and refining the pore structure. Lower sorptivity values indicate improved resistance to capillary suction and enhanced durability of the concrete.

For the NSCBA-modified mixtures, a noticeable reduction in sorptivity was observed with an increase in the nano content. NSCBA1 and NSCBA3 recorded sorptivity values of approximately 2.69% and 2.45%, respectively. Compared to the control mixture, NSCBA3 achieved a reduction of approximately 8.07%, whereas NSCBA2, with a value of approximately 2.48%, showed a reduction of approximately 9.58%. These results indicate that NSCBA contributes to partial pore refinement and matrix densification; however, its effectiveness in reducing capillary absorption is relatively moderate compared to that of NRHA [8, 47].

In contrast, the UHPC mixtures incorporating NRHA exhibited a more pronounced reduction in sorptivity at 28 d. NRHA1, NRHA2, and NRHA3 achieved sorptivity values of approximately 1.89%, 1.78%, and 1.82%, corresponding to reductions of approximately 16.63%, 21.39%, and 19.49%, respectively, relative to the control mix. Among these mixtures, NRHA2 exhibited the lowest sorptivity, indicating the highest resistance to capillary water absorption. This superior performance can be attributed to the high amorphous silica content and nanoscale particle size of NRHA, which promote extensive pozzolanic reactions and result in the formation of additional C–S–H gel that effectively blocks capillary pores [48].

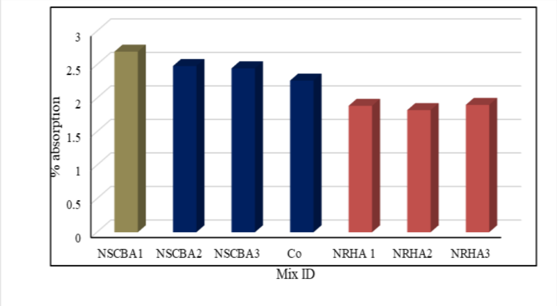

Fig. 12. Sorptivity for UHPC with different types of nanoparticles

Conclusion

The experimental investigation conducted in this study clearly demonstrated the effectiveness of incorporating nano rice husk ash (N-RHA) and nano sugarcane bagasse ash (N-SCBA) in enhancing the mechanical and durability performance of UHPC. The compressive strength of UHPC was significantly enhanced by incorporating nanomaterials. At 7 days, strength improvements reached up to ≈20.4%, while at 28 days, the maximum improvement increased to approximately ≈25.9%, confirming the sustained contribution of nanoscale pozzolanic reactions over time. The splitting tensile strength showed notable enhancement with nanomaterial incorporation. At 7 days, the tensile strength increased by up to ≈20.3%, whereas at 28 days, the improvement reached approximately ≈22.3%, indicating improved crack resistance and fiber–matrix interaction. The flexural strength exhibited the most pronounced enhancement among all the mechanical properties. At 7 days, the flexural strength increased by up to ≈14.2%, whereas at 28 days, the improvement reached approximately ≈41.2%, highlighting the strong synergistic effect between nanomaterials and end-hooked steel fibers under bending loads.

Durability assessment based on sorptivity measurements at 28 days revealed a significant reduction in the water absorption. UHPC mixtures incorporating NRHA achieved a maximum sorptivity reduction of approximately 21.4%, whereas NSCBA-based mixtures showed a moderate reduction of up to 9.6%, demonstrating enhanced pore refinement and matrix densification. Among all investigated mixtures, the UHPC containing an intermediate dosage of NRHA consistently achieved the highest overall performance, combining maximum improvements in compressive, tensile, and flexural strengths with the greatest reduction in sorptivity. The relatively low standard deviation values observed across all test results confirmed good repeatability, uniform dispersion of nanomaterials, and consistent behavior of the UHPC mixtures. The use of agricultural waste-derived nanomaterials, particularly NRHA, offers a sustainable and efficient approach for producing high-performance UHPC with superior mechanical properties and enhanced durability.

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