

Research Article

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Integrating micro- and nanowaste glass with waste foundry sand in ultra-high-performance concrete to enhance material performance and sustainability

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Abstract: The utilization of waste glass with micro- and nanoparticles in ultra-high-performance concrete (UHPC) has garnered significant interest due to its potential to enhance sustainability and material performance. This study focuses on the implications of integrating microwaste glass (MG) and nanowaste glass in the presence of waste foundry sand and its impact on the properties of UHPC. The particular emphasis of the current work is on compressive strength, tensile strength, sorptivity, and microstructure. It is found that MG enhances compressive strength, decreased tensile strength, reduced sorptivity, and a more compact microstructure. The results indicate that replacing cement with 20% microglass achieves the optimal compressive strength by increasing up to 11.6% at 7 days, 9.5% at 28 days, and 10.18% at 56 days. Nanowaste glass, owing to its increased reactivity and larger surface area, accelerates calcium silicate hydrate formation and improves compressive strength. At the same time, the effective utilization of nanowaste glass improves long-term resilience with an optimum compressive strength at 1.5% replacement ratios of 17.5, 18.9, and 16% at 7, 28, and 56 days, respectively. Splitting tensile strength increased by 16% at 20% MG and 21% at 1.5% nanowaste glass, respectively. Utilizing MG and nanowaste glass in UHPC with waste foundry sand is a promising method for boosting material performance and minimizing environmental impact.

Keywords: concrete, waste, glass powder, waste foundry sand, compressive strength, mechanical properties

1 Introduction

Ultra-high-performance concrete (UHPC) is an innovative cement-based material [1]. Although concrete is widely used in construction and known for its affordability, it has inherent disadvantages owing to its significant weight. For example, substantial space is required during construction to create sizable and bulky structural components with normal-strength concrete [2]. To overcome these restrictions, scientists have concentrated on enhancing conventional concrete or creating new versions with extraordinary properties such as outstanding toughness, durability, ductility, and strength, all based on the principles of packing theory [3]. The favorable characteristics of UHPC are in line with the requirements of contemporary infrastructure [4,5]. In the initial stages of UHPC development, it is necessary to have precise conditions for the manufacturing process, careful handling, and the use of superior-quality materials. This generally implies that coarse particles are not included [6]. Therefore, adopting UHPC necessitates the implementation of rigorous protocols and exceptional care in its handling [7]. UHPC formulas can be customized to fulfill various criteria and applications [8]. An example of this is the construction of the Bourg-les-Valence road bridge in France in 2005 when UHPC was employed [9]. This resulted in a 66% reduction in the weight of the structure compared with traditional concrete and a 90% decrease in the need for reinforcement. Similarly, the Mars Hill Bridge in the United States, built in 2006 with UHPC, obviated the necessity for shear reinforcement. The vast range of applications of UHPC globally is owing to its versatility, which provides unique design opportunities, ease of production, adaptation to complicated shapes, lightweight qualities, and appropriateness for harsh environmental conditions [10,11].

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UHPC has been utilized in many international projects, specifically in intricate scenarios such as architectural elements, bridges, restoration, refurbishment, and building of vertical structures [12]. These applications include hydraulic structures, windmill towers, utility towers for gas and oil sectors, offshore installations, and overlay materials [13]. UHPC is commonly used in the construction of roads and bridges; its application has been reported in various countries such as South Korea, Switzerland, the Czech Republic, France, Italy, Canada, Malaysia, New Zealand, Australia, Slovenia, Germany, China, the Netherlands, and the United States [14]. The global impetus for recycling end-of-life materials to achieve more sustainable and environmentally friendly industrial processes is growing, primarily because of the rise in the urban population [15]. Australia produces approximately 1.5 million tonnes of waste glass annually, and it is believed that up to two-thirds of this glass can be reused for other purposes, particularly in concrete manufacturing, as a replacement for cement or sand [16]. Sand is regarded as the second most vital resource globally, after water, with yearly usage of 15 billion tons in the construction industry [17]. The exhaustion of natural sand resources has resulted in notable environmental issues, necessitating the urgent need to create harmonious aggregate mixtures [18]. In addition, exploring alternate sources of sand can contribute to cost reduction, tackle ecological issues related to mining, prevent riverbank erosion, and decrease energy consumption during transportation [19]. Various reactions between waste glass and calcium hydroxide (CH) occur in concrete due to using waste glass in concrete [20]. The use of waste glass in concrete is limited because of the presence of a significant amount of amorphous silica, which can lead to alkali-silica interactions and potential contamination if improperly washed. In addition, waste glass containing lightweight materials, such as paper, flakes, and plastics, may float at the surface of concrete owing to the compaction process. This requires specific measures when adding waste glass to concrete mixtures [16,21,22]. Literature review from previous research [23,24] indicated that alkali-silica reaction (ASR) expansion occurs in case of fine and ultra-fine waste glass, which could make it difficult for the ASR expansion *via* generating non-expanding calcium silicate hydrate (CSH) *via* pozzolanic reaction in addition to the role of waste glass powder in accelerating the dissolution of aluminate phases, hence filling pores *via* increasing aluminum concentration that reduces amorphous silica dissolution.

Recent years have resulted in extensive research on recycled foundry sand (RFS), a sustainable substitute for conventional methods in the manufacturing of concrete that aims to solve environmental issues and the financial feasibility of reusing trash. According to earlier studies,

adding RFS to concrete mixtures can affect performance in both positive and negative ways [25,26]. Positively, research has demonstrated that RFS improves the durability and workability of concrete [27]. By filling in the spaces left by bigger aggregates, RFS's small particles can raise the concrete matrix's overall packing density. Additionally, foundry sand's pozzolanic qualities aid in creating new cementitious compounds, which boost strength and decrease permeability [28,29]. However, the leftover coatings and binders on the sand grains present problems since they could prevent the cement paste from properly adhering [30]. A further obstacle to obtaining consistent concrete performance is the variation in RFS quality across foundries [31]. Notwithstanding these obstacles, studies have attempted to maximize RFS's integration into concrete mixtures to maximize its benefits and minimize potential risks [32]. Use of foundry sand leftovers to create regulated low-strength materials [30].

Nanomaterials and micromaterials have a crucial effect on improving concrete performance by providing a diverse range of advantages in terms of strength, durability, and sustainability. Nanomaterials, such as nanoparticles or nanotubes, are incorporated into concrete mixtures in minuscule amounts [33]. They engage in molecular-level interactions and influence the material characteristics. For example, nanoparticles, such as nanosilica, can significantly enhance concrete's compressive and flexural strength by filling empty spaces and reinforcing the cementitious structure [34–38]. Their high surface area and reactivity also result in enhanced resistance to chemical assaults and decreased permeability, critical factors for concrete buildings' long-lasting endurance. In contrast, micromaterials denote small particles, such as sand or crushed stone, added to concrete mixtures [39–41]. These materials significantly affect concrete's workability, density, and mechanical properties [42–45]. Appropriately classified micromaterials enhance the desired compaction of concrete by minimizing the gaps between larger aggregates, thereby improving the overall durability of the structure. Moreover, they can affect concrete's strength and contraction properties, significantly influencing its overall durability and long-term behavior [46–49]. The combination of nanoparticles and micromaterials in concrete provides a flexible method for customizing the characteristics of the material to fulfill precise technical requirements. Through the strategic optimization of these materials, scientists and engineers may create concrete mix designs that exhibit exceptional performance and actively contribute to the promotion of sustainable construction methods [47,50–53].

Previous studies investigated the performance of nanomaterials or micro-size materials on UHPC, but these studies

are limited, especially in the aspect of using waste materials as sand replacement. This research objective is to compare the effect of using nanowaste glass and microwaste glass (MG) as sustainable alternatives to be replaced by cement in UHPC in the presence of waste foundry sand as an alternative source for natural sand and clarify its effect on mechanical properties involving compressive strength, splitting tensile strength in addition to durability and micro-structure of UHPC.

2 Experimental program

2.1 Raw materials

Beni-Suef factory supplied cement type I (52.5 grade) following ASTM C150 specifications for use in this investigation. In addition, silica fumes (SF) composed solely of silica with $17.8 \times 10^3 \text{ m}^2\cdot\text{kg}^{-1}$ specific surface area and 2.15 a specific gravity were utilized. The sand was obtained and used in its saturated surface dry state as a byproduct of the metal casting industry. The fineness modulus of the substance was 2.94 mm, and it did not contain any salt. High-quality dolomite extracted from Ataq Mountain, with a 10 mm maximum nominal size, was used as coarse aggregate. Sika ViscoCrete 3425, a super-plasticizer composed of a modified polycarboxylate aqueous solution, was used to enhance the workability of UHPC. Tap water was used as the mixing water. The waste glass sheets used in this study were acquired from a building site in Beni-suef as sheets of different sizes before incorporation into the concrete mixture. A thorough cleansing process was conducted to remove foreign substances and contaminants.

2.1.1 Preparation and characterization of microglass and nanoglass (NWG)

This section provides a concise overview of the steps required to prepare raw ingredients. After cleaning waste glass sheets, the cleaned samples were fragmented into smaller particles with dimensions of 10–12 mm. Afterwards, the diminished glass shards were ground using an LA grinding machine, culminating in the creation of the glass powder. The glass powder was milled for 4 h and sieved to achieve microsize till $100 \mu\text{m}$ to be used as cement replacement material. MG and nanoparticles (NWG) production involves a milling procedure to decrease their size to the nanoscale. The mechanical grading process was conducted using a “ball-milling machine”

with two horizontally rotating zirconium jars [46]. The milling process lasted for 4 h per 50 g of the material. It involved using four balls with a diameter of 20 mm rotating at a speed of 180 revolutions per minute [33,41,54]. The examination using transmission electron microscopy (TEM) showed that the particle size of NWG was approximately 40 nm, whereas that of NWC. Most of the nanoparticles had an irregular shape. The waste glass was subjected to thorough physical and chemical (XRF) evaluation to determine its composition. The analysis results showed that the waste glass contains 2.85% magnesium oxide, 72.87% silicon dioxide, 2.12% sodium oxide, 2.24% sulfur trioxide, 11.96 and 1.98% potassium oxide, 4.21% aluminum oxide, and 1.77% iron oxide that contains the sum of silica (SiO_2), calcium (CaO), and iron (Fe_2O_3) is greater than 70% which is needed for cementitious materials. According to ASTM C 618, a material can be defined as cementitious material if the sum of silica, calcium, and iron is greater than 70%. Therefore, the WGP can be used as a cementitious material according to the ASTM C 618 [55]. Furthermore, a thorough investigation was conducted to determine the physical characteristics of glass powder. The dry bulk density was measured as $1,450 \text{ kg}\cdot\text{m}^{-3}$, this examination yielded a fineness modulus of 2.18, and the porosity was calculated as 29.6%. The glass powder had a moisture content of 0.67% and a water absorption capability of 1.13%. X-ray diffraction (XRD) analysis and TEM were also performed for NG and microglass that showed an amorphous state of waste glass and micro- or nanoparticle sizes, as shown in Figures 1 and 2, respectively. The experimental setup used different amounts of glass sheet powder as a substitute for sand in the concrete mixture. The replacement ratios used were 0, 10, 20, 30, 40, and 50%.

2.2 Mix proportions

The mix proportions were determined by an iterative process including multiple experiments because there are no established standard specifications or comprehensive information standards for producing UHPC mixtures. The current study builds upon a previous inquiry [56] that explored the utilization of NG and MG as supplements. Varying amounts of these additives, ranging from 1 to 2.5% of the weight of the cement for nanowaste glass and 10–50% for MG, were used until the best results were achieved. Table 1 provides detailed information on the mixture quantities for control mix (REF), 10, 20, 30, 40, and 50 MG whereas MG refers to microglass and the number refers to replacing ratio. The second group involves 0.5, 1, 1.5, 2, and 2.5 NG while NG refers to NG and the number refers to cement replacement ratio. The studies were conducted using a fixed

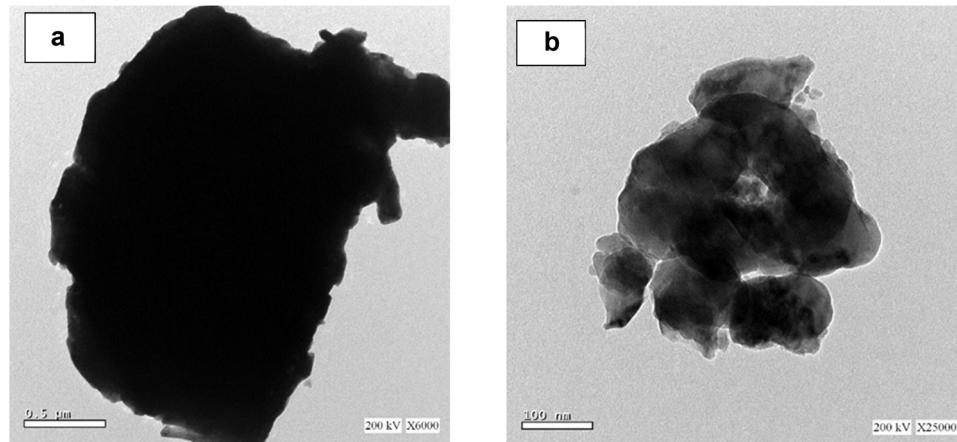


Figure 1: Images of TEM for (a) MG and (b) nanowaste glass.

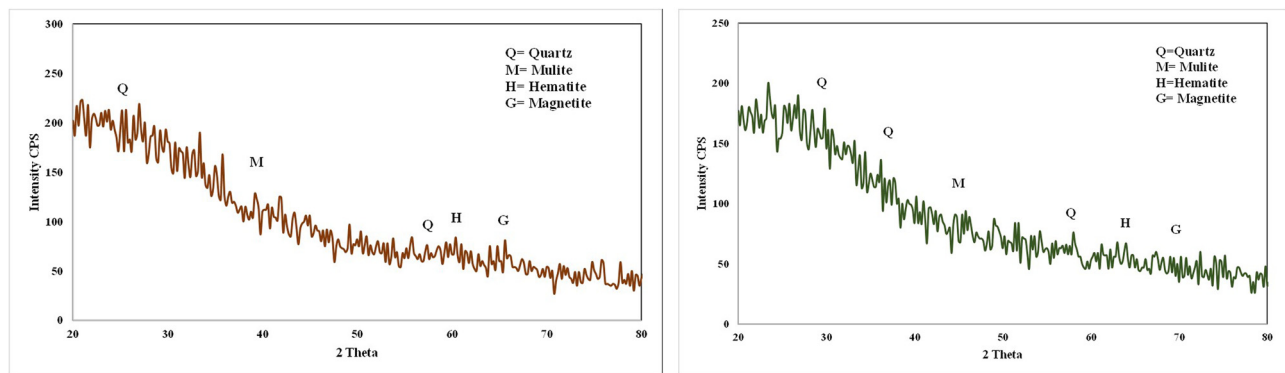


Figure 2: XRD for MG and NWG, respectively.

water/binder ratio equal to 0.173, an SF concentration of 15%, and moderate aggregate content, which remained unchanged throughout the experiments. Several experimental mixtures were created to meet the goal strength requirements for UHPC experimental mixtures.

2.3 Mixing and preparation of test specimens

This section presents a concise overview of the mixing process, as shown in Figure 3. Initially, the mixer was filled

Table 1: Mix proportions

Mixes	Cement ($\text{kg}\cdot\text{m}^{-3}$)	Foundry sand ($\text{kg}\cdot\text{m}^{-3}$)	SF ($\text{kg}\cdot\text{m}^{-3}$)	Coarse aggregate ($\text{kg}\cdot\text{m}^{-3}$)	Super-plasticizers ($\text{kg}\cdot\text{m}^{-3}$)	Water ($\text{kg}\cdot\text{m}^{-3}$)	Microwaste glass ($\text{kg}\cdot\text{m}^{-3}$)	Nanowaste glass ($\text{kg}\cdot\text{m}^{-3}$)
REF	800	433	120	800	16	160		
10 MG	720	433	120	800	16	160	80	
20 MG	640	433	120	800	16	160	160	
30 MG	560	433	120	800	16	160	240	
40 MG	480	433	120	800	16	160	320	
50 MG	400	433	120	800	16	160	400	
0.5 NG	796	433	120	800	16	160		4
1 NG	792	433	120	800	16	160		8
1.5 NG	788	433	120	800	16	160		12
2 NG	784	433	120	800	16	160		16
2.5 NG	780	433	120	800	16	160		20

with sand and dolomite. Subsequently, the components of the binder, namely, cement and SF, were introduced and thoroughly mixed for 2 min. Subsequently, half of the remaining water was added. The remaining 50% of water and superplasticizers were introduced concurrently with the aid of a magnetic stirrer. At the same time, the nanoparticles were gradually incorporated until a homogeneous and well-dispersed solution was achieved, following the procedure outlined in reference [56–58]. The remaining solution was added, and the mixture was allowed to blend for 5–10 min.

2.4 Test procedures

Compressive and splitting tensile strength tests were performed following standard specifications to study the influence of adding micro- and nanomaterials to UHPC and evaluate mechanical performance. Compressive and splitting tensile strength were assessed at several time intervals, precisely at 7, 28, and 90 days. The compressive strength tests utilized a GOTECH-7001-M5 machine with a load speed of $0.5 \text{ N} \cdot \text{mm}^{-2} \cdot \text{s}^{-1}$ and a maximum load capacity of 300 tons. The experiments were carried out following the BS12390-3 [59] standards. The tests used UHPC cube samples with dimensions of $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$.

The average outcomes of the three specimens were documented. The splitting tensile strength of the foaming concrete was assessed using cylindrical specimens measuring $100 \text{ mm} \times 200 \text{ mm}$. A GoTech GT-7001-BS300 Universal Testing Machine was used for testing, respecting the requirements of BS12390-6 [60]. The testing methodologies and tools were chosen to provide a dependable and accurate evaluation of splitting tensile strength tests. On the other hand, the durability assessment involved examining the water absorption of all the mixtures. This was achieved using cylindrical cylinders with $50 \text{ mm} \times 100 \text{ mm}$ diameter and height, respectively. The investigation followed ASTM C1403 [61]. In addition, specimens of standard dimensions were used to determine the sorptivity to assess mass transport qualities. Finally, microstructure analysis was performed. The examination utilized cubic specimens of UHPC with dimensions of $10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$. Before the research, the preparation involved the specimens being put in a vacuum chamber, and then, samples were covered with a layer of pure gold for electron flow assurance. Scanning electron microscopy (SEM) investigations were performed on the surfaces of the specimens at a specific depth of 10 mm. This methodology enabled the assessment and analysis of internal structural characteristics and the impact of including MG and NG in the UHPC matrix. SEM analysis provided crucial insights into the shape and arrangement of various constituents in UHPC samples.

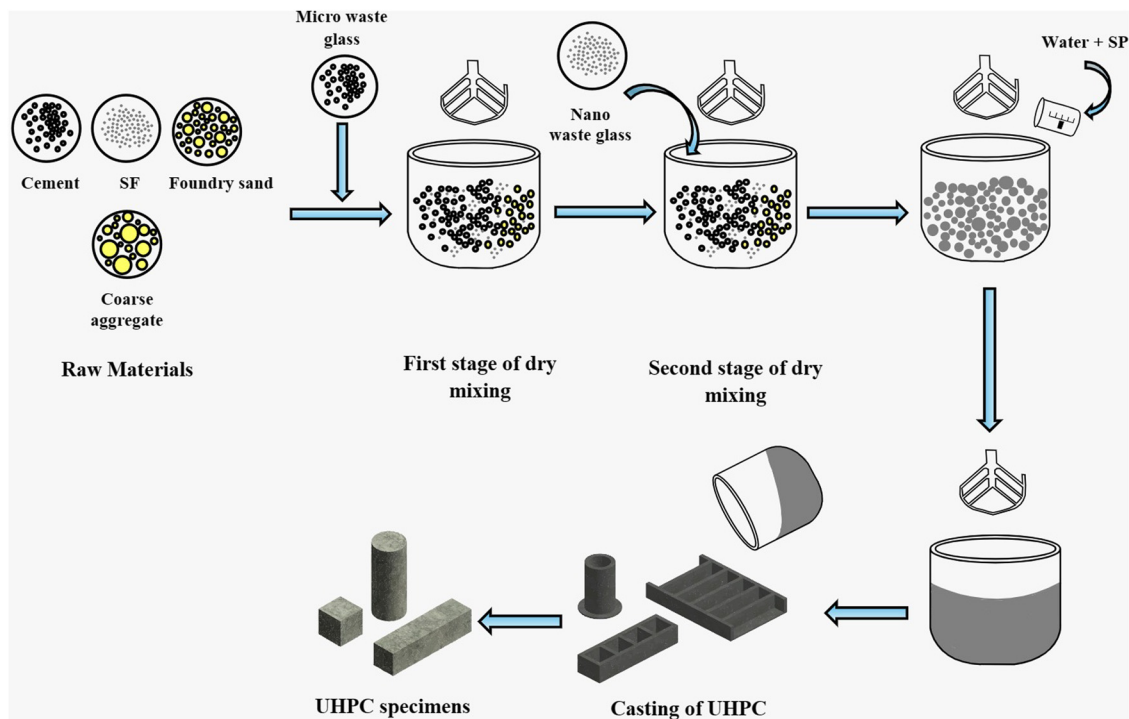


Figure 3: Mixing procedure.

3 Results and discussion

3.1 Compressive strength

MG and nanowaste glass particles are added to UHPC to study their compressive strength.

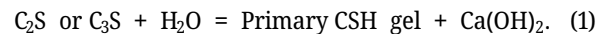
3.1.1 Compressive strength for MG

Waste glass has a significant impact on its compressive strength as the compressive strength improves at all ages. Replacing cement with 20% micro waste glass improved compressive strength by 11, 9, 10% at 7, 28 and 91 days, respectively, as optimum increasing ratio at 20% replacement dosage compared to reference mixes at the same ages as shown in Figure 4 in addition to the increasing in compressive strength exhibits improvement at all replacement ratios with recording increasing ratio of 9.7, 10.6, 9.7 and 8.7% at 7 days for 10 MG, 30 MG, 40 MG, and 50 MG at 7 days. This is primarily due to the pozzolanic effect, the creation of CSH, and the presence of CH [57]. The pozzolanic interaction between the waste glass particles and the UHPC matrix is crucial in UHPC, which includes MG [62]. MG chemical composition enhance formation of CSH gels [63,64] with more strength development at later ages with increasing compressive strength with a range between 7 and 9.5% compared to reference mix at the age of 28 days and between 8 and 10% at 90 days curing age, strength development improved up to 20% replacement level but the strength decreased again at higher dosages, this may attributed to full consuming of CH or filling effect. Consequently, the microstructure becomes more compact, improving mechanical properties such as increased

compressive strength. Furthermore, CH, a substance formed during the chemical reaction of cement, is utilized as it interacts with waste glass particles [22]. This enhances the pozzolanic effect and diminishes the vulnerability to the ASR, a prevalent issue in concrete containing glass particles [17].

3.1.2 Compressive strength for nanowaste glass

Figure 5 explains the compressive strength of UHPC mixes containing nanowaste glass and foundry sand. The results showed increasing compressive strength due to nanoparticles for all mixes and all levels of ages up to 17, 18, and 16% at 7, 28, and 90 days, respectively, at 1.5% cement replacement dosage. These results reflect that the use of nanowaste glass enhances compressive strength by leveraging the heightened reactivity and expanded surface area of these tiny particles, achieving strength improvement ranges between 11.3 and 17.5% at 7 days, 11.4–18.9% at 28 days, and the increasing ratio ranged from 11.03 to 16% at 90 days. The nanowaste glass and UHPC matrix interaction exhibited a more prominent pozzolanic response [57]. The amorphous nature of glass facilitates the swift creation of CSH gels, leading to a microstructure with a higher density [65]. In this scenario, the utilization of CH is more effective, resulting in a decrease in the overall CH content [66], as shown in Eqs. (1) and (2). This reduction can positively affect the long-term durability of the material [20,67].



Amorphous silica in waste glass powder could produce a secondary cementitious compound (CSH gel)

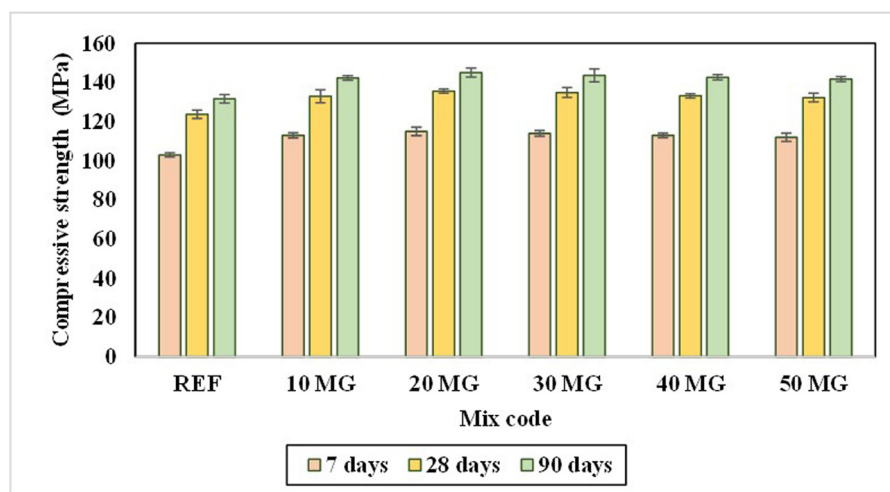


Figure 4: Compressive strength of UHPC with MG.

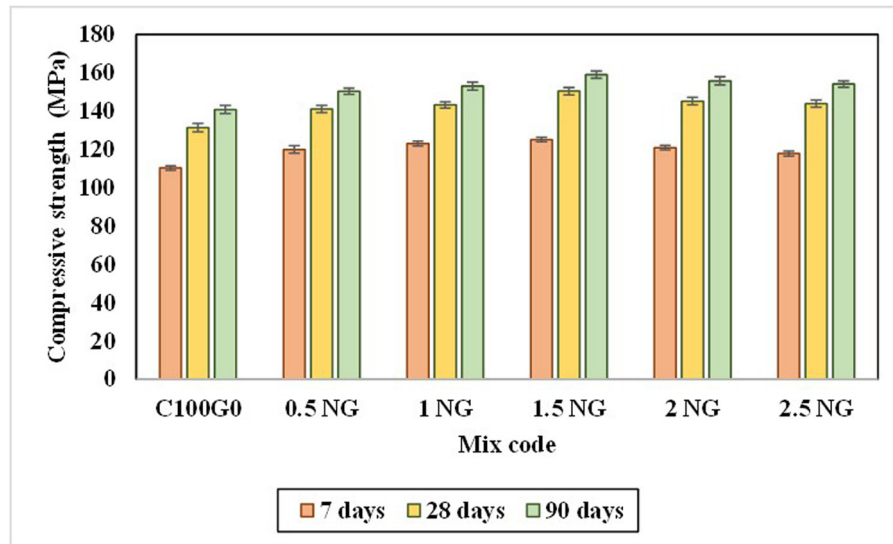


Figure 5: Compressive strength of UHPC with nanowaste glass.

3.1.3 Comparison between compressive strength of MG and nanowaste glass

Examining the compressive strength of (UHPC) that incorporates MG and nanowaste glass at the ideal concentrations of 20% MG and 1.5% nanowaste glass provides fascinating observations regarding the compressive characteristics of the material shown in Figures 6 and 7. The addition of MG particles to UHPC at a concentration of 20% has shown a significant improvement in compressive strength at all ages, with increasing compressive strength from 103 to 115 MPa at

7 days, from 123 to 135 MPa at 28 days, and from 131 to 143 MPa at 90 days with increasing ratio about 10% for all ages. The incorporation of MG as a filler in concrete serves to increase its density and reduce the occurrence of empty spaces [68,69], resulting in improved overall strength. Conversely, the inclusion of 1.5% nanowaste glass has demonstrated a precise adjustment impact on the microstructure of the concrete *via* recording the optimum strength development compared to the reference mix to obtain strength 121 MPa compared to 103 at 7 days, from 123 to 147 MPa at 28 days, and from 131 to 152 MPa with increasing ratio up to

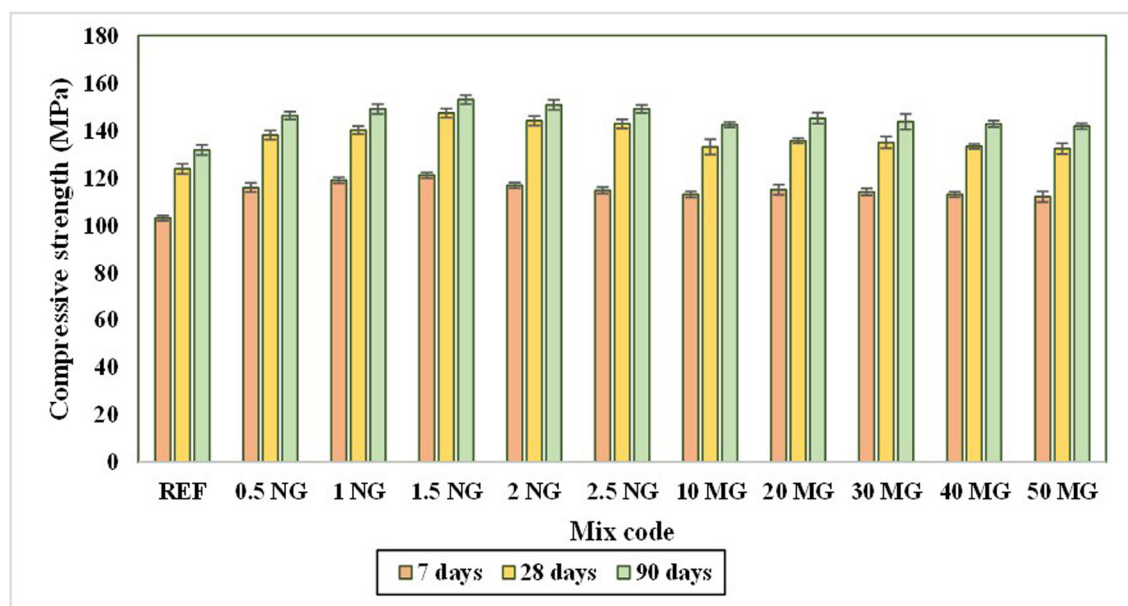


Figure 6: The compressive strength for UHPC incorporating nanowaste glass and MG.

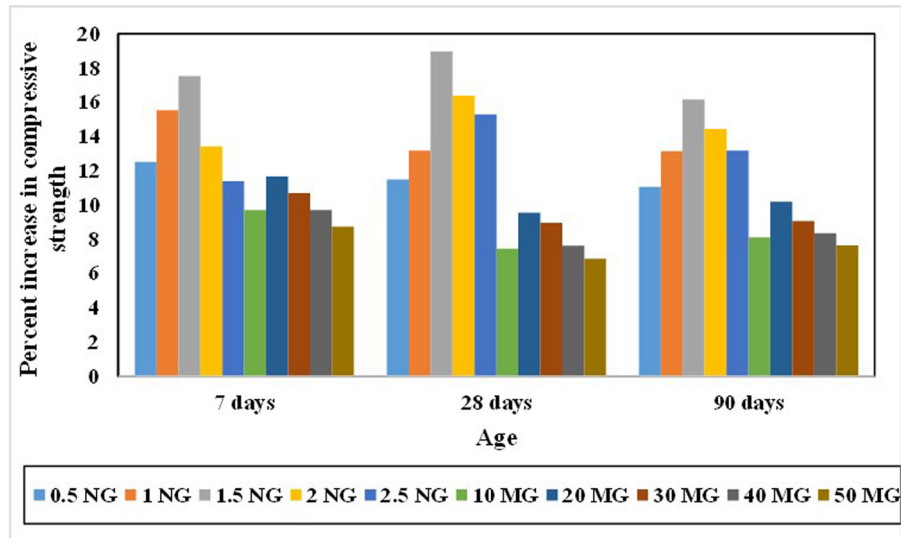


Figure 7: The percent increase for UHPC incorporating nanowaste glass and MG related to the control mix.

19%. The nanoparticles enhance the cementitious matrix, leading to better arrangement and connection [33,41,57], ultimately strengthening the compressive strength. This investigation highlights the combined effect of MG and nanowaste glass on UHPC, demonstrating a well-balanced mixture that enhances the material's mechanical performance.

3.2 Splitting tensile strength

The splitting tensile strength of UHPC, including MG and nanowaste glass particles, is strongly influenced by the pozzolanic effect, creation of CSH gel, and behavior of CH [17].

3.2.1 Splitting tensile strength for MG

The splitting tensile strength improved when microsilica were replaced with cement by 10–50% at 28 days, recording increment increasing up to 16.1% as the optimum increasing ratio at 20% replacement dosage compared to reference mixes as shown in Figure 8 in addition to the increasing in splitting strength exhibits increasing at all replacement ratios of 15.16, 15.2, 15.4, and 15.1% at 10, 30, 40, and 50% replacement ratios. The utilization of MG in UHPC has a considerable impact on the splitting tensile strength owing to the pozzolanic reaction between the glass particles and the UHPC matrix [16]. This reaction results in the formation of more CSH gel within the material, which enhances its microstructure and, consequently, improves its splitting

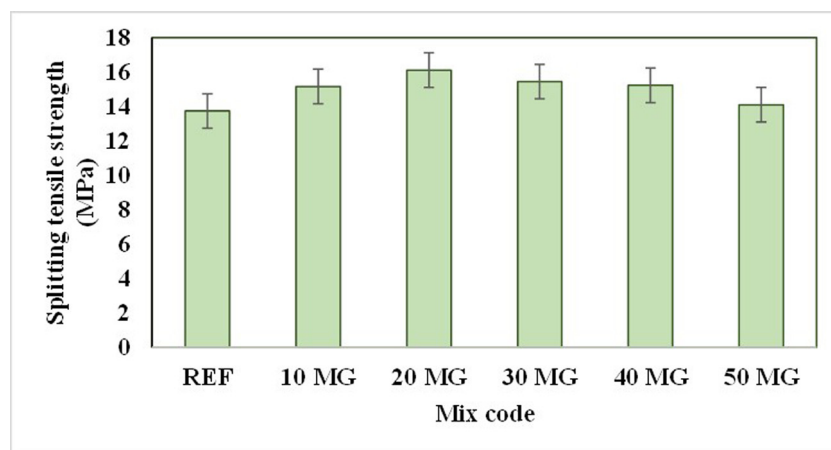


Figure 8: Splitting tensile strength of UHPC with MG.

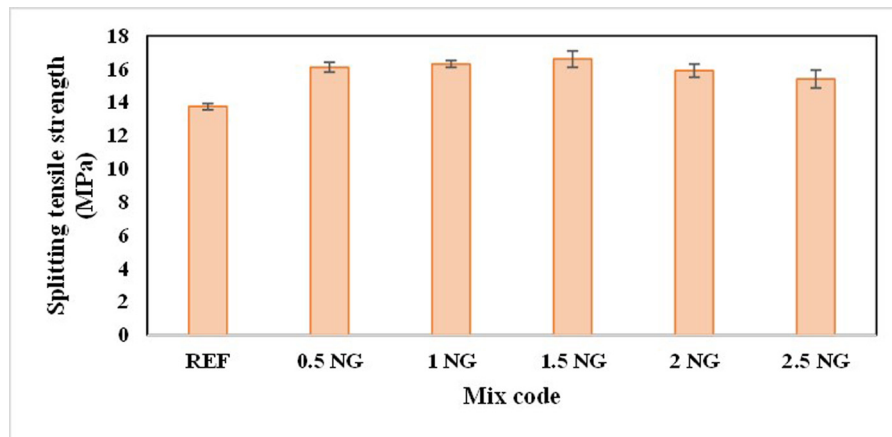


Figure 9: Splitting tensile strength of UHPC with nanowaste glass.

tensile strength. Simultaneously, the CH content produced during the cement hydration process is partially used in the pozzolanic reaction, thus enhancing the material characteristics [70].

3.2.2 Splitting tensile strength for nanowaste glass

Figure 9 shows the splitting tensile strength of UHPC mixes containing nanowaste glass and foundry sand. The results showed that increasing splitting tensile strength due to nanoparticles for all mixes and all levels of ages up to 21

at 1.5% dosage and residual mixes achieved an increasing ratio ranging between 12 and 18%; the addition of nanowaste glass significantly improved the splitting tensile strength [57]. The use of nanowaste glass particles results in increased reactivity and a larger surface area, which enhances the pozzolanic process and accelerates the formation of the CSH gel [71]. Consequently, the microstructure becomes more compact, leading to an increase in the tensile strength required to split the material [17]. The utilization of CH is more effective when nanowaste glass is employed, leading to enhanced long-term durability and performance of the material [67,71].

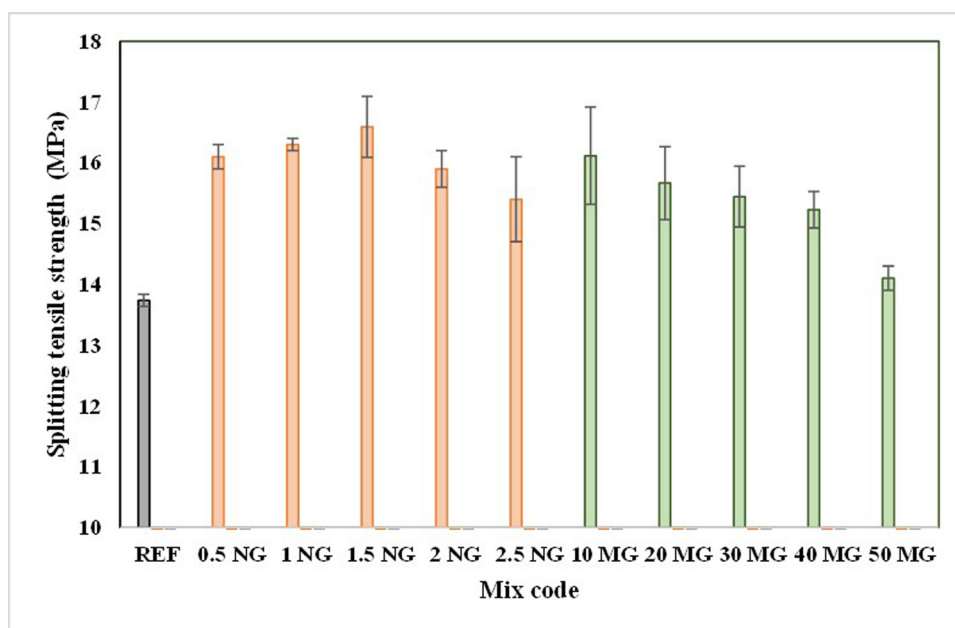


Figure 10: The compressive strength for UHPC incorporating nanowaste glass and MG.

3.2.3 Comparison between splitting tensile strength for MG and nanowaste glass

Figure 10 compares the splitting tensile strength of UHPC incorporating MG or nanowaste glass with waste foundry sand. The results declared that the replacement of 20% MG enhances the splitting tensile strength using the pozzolanic reaction, in which the silica present in the glass combines with the CH in the cement, resulting in the formation of more and more CSH gel [22]. This reaction improves the unity within the concrete structure, resulting in a higher resistance to splitting forces. Concurrently, including 1.5% nanowaste glass induces an additional improvement in the microstructure by promoting the formation of CSH gel by nucleation and precipitation. The inclusion of these nano-sized reinforcements leads to a concrete matrix that is more tightly packed and interconnected [65], resulting in increased splitting tensile strength. The combined use of MG and nanowaste glass, as demonstrated by these chemical reactions, highlights the effectiveness of the optimized combination in improving the splitting tensile strength of UHPC.

To summarize, adding MG and nanowaste glass to UHPC improves its splitting tensile strength by utilizing the pozzolanic effect, accelerating the production of CSH gel, and reducing the quantity of CH. These enhancements enhance the robustness and sustainability of UHPC, rendering it an attractive option for various construction applications.

3.3 Sorptivity

The sorptivity of UHPC, including MG and nanowaste glass particles, is an effective property that indicates the ability of the material to resist moisture penetration and, consequently, its longevity. The sorptivity of these UHPC mixes is significantly influenced by the pozzolanic effect, development of CSH gel, and dynamics of CH.

3.3.1 Sorptivity for MG

Incorporating MG in UHPC promoted the pozzolanic reaction between the glass particles and the UHPC matrix, leading to enhanced production of the CSH gel. The enhanced microstructure leads to reduced sorptivity, indicating an increased resistance to water infiltration. Moreover, when CH is partially consumed, it decreases capillary porosity, improving the composite's long-term ability to resist moisture. The least sorptivity is obtained at 20% MG, as shown in Figure 11. The addition of MG further enhanced the reduction in sorptivity. The heightened reactivity of the nanoparticles promotes a

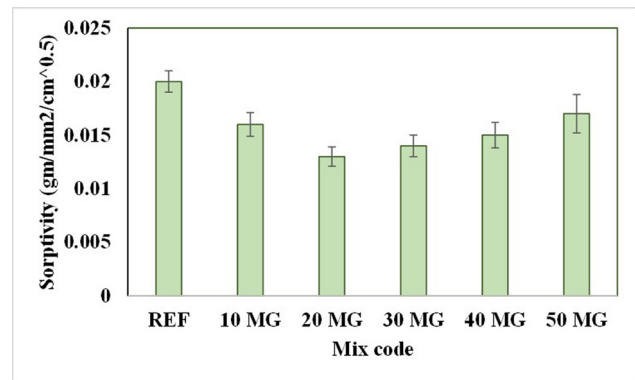


Figure 11: Sorptivity of UHPC with MG.

strong pozzolanic reaction and expedites the creation of a CSH gel, leading to a microstructure characterized by minimal capillary holes. Optimizing the CH consumption further increases the ability of the material to resist moisture penetration, resulting in better durability.

3.3.2 Sorptivity for nanowaste glass

Figure 12 illustrates the sorptivity for UHPC with nanowaste glass. The results illustrated that using nanowaste glass and foundry sand in UHPC significantly affects the material's permeability and durability by affecting its sorptivity. The incorporation of nanowaste glass into (UHPC) results in lowering sorptivity. This is because the nanowaste glass can enhance the microstructure of the concrete at the nanoscale. The presence of fine particles improves the arrangement of the cementitious matrix, resulting in a decrease in the size and connection of pores, ultimately reducing water absorption. The distinctive particle form and size distribution of foundry sand reduces sorptivity by filling voids and limiting water penetration. The synergistic effect of incorporating nanowaste glass and foundry sand into (UHPC) leads to a material that

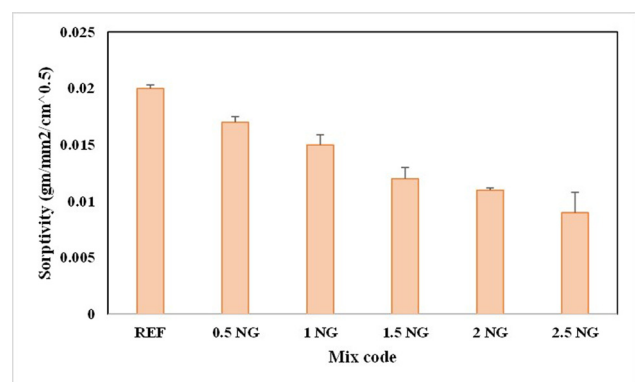


Figure 12: Sorptivity of UHPC with nanowaste glass.

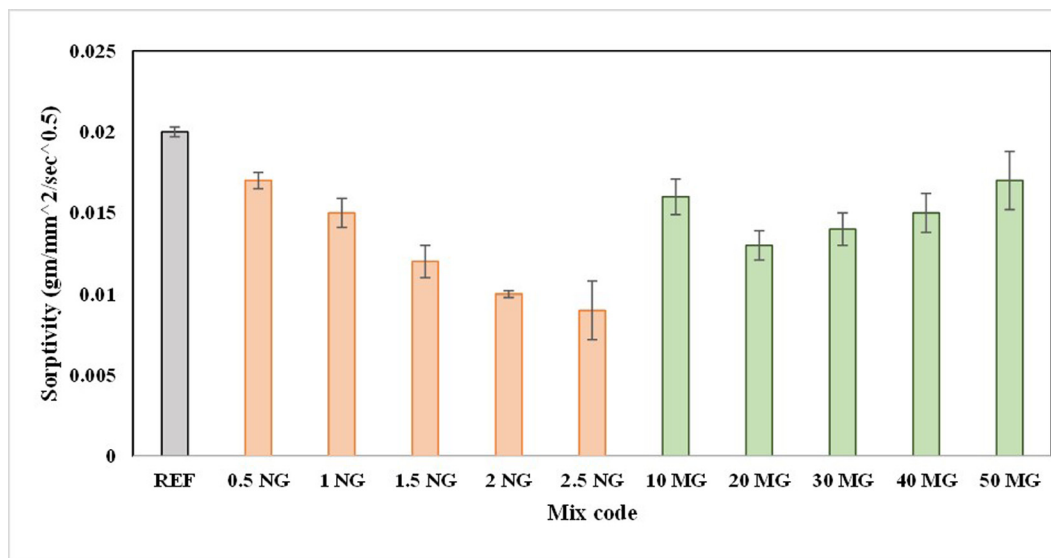


Figure 13: The sorptivity for UHPC incorporating nanowaste glass and MG.

exhibits heightened resistance to water infiltration, hence enhancing its durability and long-term performance in various environmental settings. This characteristic is especially advantageous when reducing water absorption is essential, such as in infrastructure exposed to harsh environmental conditions or maritime areas.

and nanowaste glass in UHPC results in decreased sorptivity, as shown in Figure 14, indicating enhanced moisture resistance. This improvement is accomplished by utilizing the pozzolanic effect, expediting the production of CSH gel, and decreasing the CH content. These factors ultimately enhance the resilience and long-lasting effectiveness of UHPC in diverse construction applications.

3.3.3 Comparison between sorptivity for MG and nanowaste glass

Figure 13 compares the sorptivity of UHPC incorporating MG or nanowaste glass with waste foundry sand. The results demonstrated that, in summary, using both MG

3.4 Microstructure analysis

Figure 15 shows SEM micrograph for reference mix, 20 MG, and 1.5 NG. SEM images of (UHPC) that include both MG

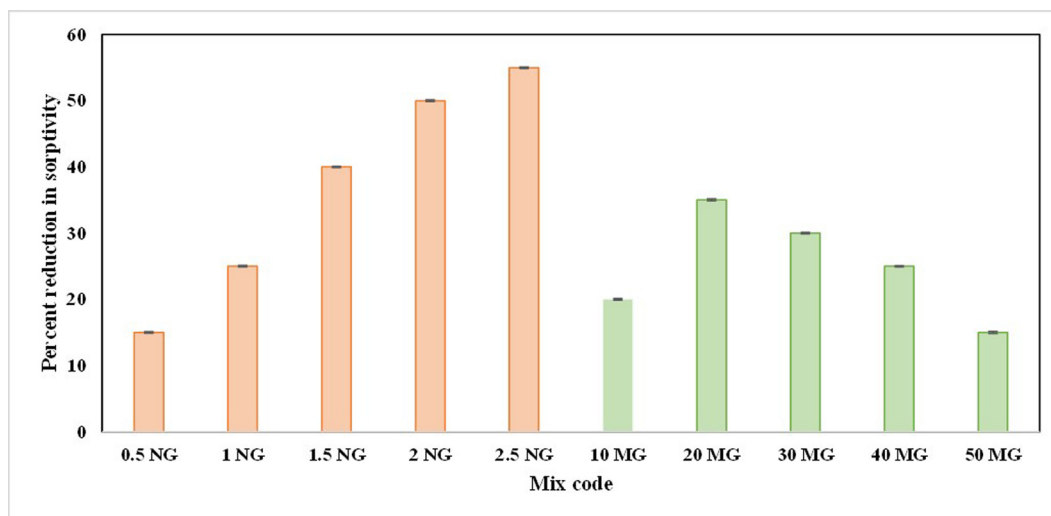


Figure 14: The reduction of sorptivity for UHPC incorporating nanowaste glass and MG.

and nanowaste glass particles provide a detailed analysis of the microstructural changes of the material and its ability to improve performance. These micrographs demonstrate high interaction between the waste glass particles and the UHPC matrix while examining the pozzolanic effect producing CSH. MG has a heightened pozzolanic response *via* consuming CH, characterized by a significant surface area conducive to chemical reactions. The micrographs illustrate the generation of pozzolanic substances that occupy the empty spaces and fractures in the matrix. This additional reaction enhances material cohesiveness and minimizes potential vulnerabilities, leading to long-lasting and strong UHPC. Regarding nanowaste glass, the micrographs reveal an alternative feature of the pozzolanic effect, wherein considerably smaller particles exhibit greater reactivity [72]. The presence of pozzolanic byproducts was observed. However, owing to their diminutive dimensions [41], these nanoparticles can infiltrate even the most minuscule gaps and microcracks, thus augmenting the material's overall density and mechanical characteristics [33]. Furthermore, when UHPC includes MG, an examination of the micrographs showed that gaps and microcracks are partially filled. This results in enhanced material strength and decreased permeability [73]. On the other hand, UHPC containing nanowaste glass demonstrates enhanced penetration into empty spaces and tiny fractures owing to the reduced particle size and increased reactivity. Consequently, the material exhibited a higher-density microstructure and reduced visible voids, resulting in remarkable resilience. In summary, the SEM micrographs in Figure 6 demonstrate that adding MG and nanowaste glass particles to UHPC improves its pozzolanic action, decreasing voids number and cracks [74].

4 Discussion

After studying the effect of different dosages of MG and nanowaste glass, the use of both MG and nanowaste glass in UHPC improves its compressive strength by leveraging the pozzolanic effect, facilitating the development of CSH gel and reducing the quantity of CH. Consequently, this results in a substance with exceptional mechanical characteristics and diminished ecological impact, rendering it a favorable option for sustainable construction [63]. The addition of nanowaste glass and MG, along with foundry sand, substantially impacts the compressive strength and splitting tensile strength of UHPC. Including tiny waste glass particles enhances the compressive strength of the concrete by serving as a filler, promoting the densification of the concrete matrix, and minimizing the presence of voids [75]. Nanowaste glass enhances the microstructure by improving the arrangement and connection of particles, hence increasing compressive strength and splitting tensile strength. By including foundry sand, which possesses distinct particle form and distribution, the strength of the concrete mix is enhanced through the optimization of packing [25,26]. Incorporating nanowaste glass and MG with foundry sand results in a UHPC that exhibits improved microstructure with low sorptivity [76]. This demonstrates the potential of these additives to enhance the mechanical properties, durability, and microstructure of the concrete in many structural uses. This composite material is highly helpful in building scenarios where remarkable strength and durability are paramount. This investigation has been carried out on the mechanical performance of UHPC with MG and nanowaste glass. Future studies can be carried out

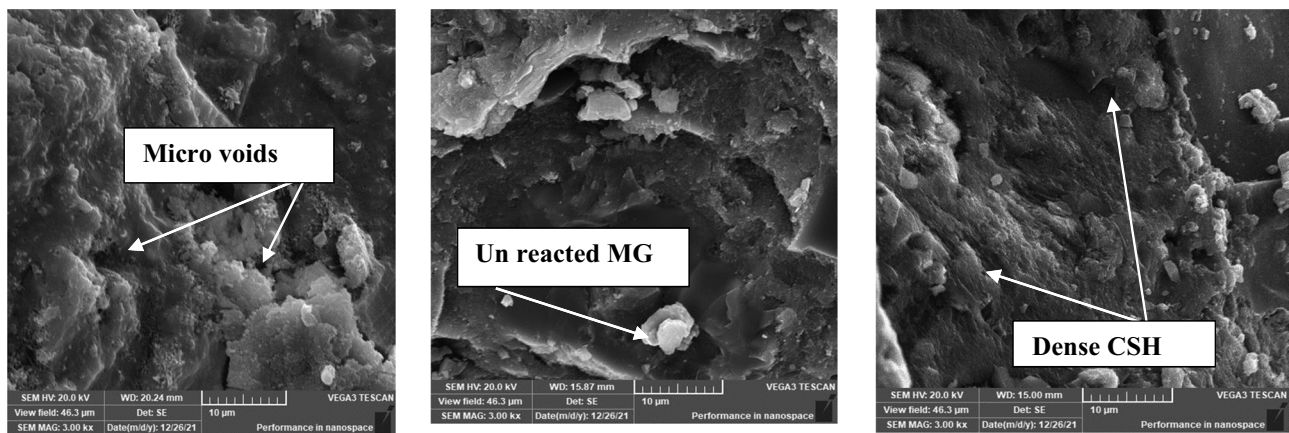


Figure 15: SEM micrographs for UHPC incorporating waste foundry sand for REF mix, 20 MG, and 1.5 NG, respectively.

using geopolymer UHPC or foaming UHPC with different cement types. Additionally, using foundry sand in UHPC subjected to aggressive environments is another area to study for achieving durable UHPC.

5 Conclusion

This study compares the effects of using nanowaste glass and MG as sustainable alternatives for cement in UHPC while incorporating waste foundry sand instead of natural river sand. The objective aims to investigate the impact of nanowaste glass and MG substitutions on various mechanical properties, including compressive strength, splitting tensile strength, durability, and matrix microstructure. Based on the experimental results and discussion, the following conclusions can be drawn:

- MG improves compressive strength by 11, 9, and 10% at 7, 28, and 90 days, respectively, when replaced with cement by up to 20%.
- Nanowaste glass has enhanced compressive strength by 17, 18, and 16% at 7, 28, and 90 days, respectively, with 1.5% replacement dosage as the optimum dosage.
- The splitting tensile strength increased by 16 at 20% content of MG and 21 at 1.5% content of nanowaste glass.
- The sorptivity decreased using MG and nanowaste glass due to the pozzolanic and filling effect.
- Utilization of nanowaste glass significantly affects UHPC with waste foundry sand compared to microparticles of waste glass.
- Both MG and nanowaste glass particles contribute to the formation of more compact microstructures, decreasing CH content and improving material performance.
- Utilizing waste glass in UHPC is a promising strategy for developing environmentally friendly construction materials that exhibit superior mechanical performance.

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