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Comparative Analysis of Nano Zinc Oxide, Nano Silica Fume, and Nano Marble Powder as Cement Replacements in Self-Compacting Concrete

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Abstract - Self-compacting concrete (SCC) is an advanced class of concrete that offers significant advantages in terms of constructability and quality. However, achieving an optimal balance between mechanical performance and durability remains challenging. This study investigated the effects of incorporating nano zinc oxide, nano silica fume, and nano marble powder as partial replacements of cement on the fresh, mechanical, and durability properties of SCC. Ten SCC mixtures were prepared, including a control mix and nine nano-modified mixes with varying replacement levels. Nano zinc oxide was used at replacement ratios of 0.5%, 1.0%, and 1.5%, whereas nano silica fume and nano marble powder were incorporated at 1%, 2%, and 3% replacement levels. The fresh properties of SCC were evaluated to ensure compliance with self-compacting requirements, whereas the hardened performance was assessed through compressive strength (CS), splitting tensile strength (TS), and flexural strength (FS) tests at 7 and 28 days. In addition, sorptivity was measured at 28 days to evaluate the durability-related performance. The results demonstrated that the incorporation of nanomaterials significantly influenced the performance of SCC depending on the type and dosage of the nanomaterial. Nano silica fume exhibited the most pronounced improvement in both mechanical strength and durability, with an optimum replacement level of 2%, achieving notable enhancements in compressive, tensile, and FSs, and the lowest sorptivity values. Nano zinc oxide provided moderate but consistent improvements in mechanical properties; however, it increased sorptivity at higher dosages. In contrast, the nano marble powder primarily acted as an inert filler, resulting in moderate strength enhancement and improved durability at low replacement levels, whereas excessive replacement led to marginal performance gains. Overall, the findings highlight the critical role of nanomaterial selection and dosage optimization in enhancing SCC performance.

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Introduction

Self-compacting concrete (SCC) has gained significant attention in recent decades as an advanced class of concrete, characterized by its ability to flow under its own weight, fill formwork, and pass through congested reinforcement without the need for mechanical vibration [1]. This unique behavior results in improved construction efficiency, enhanced surface finish, reduced labor requirements, and minimized noise pollution at construction sites. However, achieving an optimal balance between flowability, segregation resistance, and mechanical performance remains a major challenge in SCC mix design. These challenges have driven extensive research on modifying the binder system and incorporating advanced materials to improve the fresh and hardened properties of SCC [2].

In parallel with the development of SCC, nanotechnology has emerged as a promising approach for enhancing cementitious material performance. Nanosized particles possess extremely high specific surface areas and unique physicochemical characteristics, which enable them to significantly influence cement hydration, microstructural development, and pore structure refinement [3]. When incorporated into concrete, nanomaterials can act as nucleation sites for hydration products, fill nanoscale voids, and enhance the interfacial transition zone (ITZ) between cement paste and aggregates. Consequently, improvements in mechanical strength, durability, and transport properties have been widely reported [4]. Consequently, the application of nanotechnology in SCC has attracted increasing research interest because of the sensitivity of SCC properties to microstructural modifications.

Nano silica fume is one of the most extensively studied nanomaterials in cement-based composites owing to its high pozzolanic reactivity and ultra-fine particle size. Previous studies have demonstrated that nanosilica fume can significantly enhance compressive, tensile, and FSs by promoting the formation of additional C–S–H gel and refining the pore structure [5]. In SCC mixtures, nano silica fume has been shown to improve both mechanical performance and durability-related properties, such as water absorption and permeability, particularly when used at optimized replacement levels. However, excessive incorporation may lead to particle agglomeration and increased water demand, highlighting the importance of optimizing the dosage [6].

Nano-ZnO has also been investigated as a functional nanomaterial in cementitious systems [7]. Research has indicated that nano-Zn particles can influence hydration kinetics, improve early age strength development, and enhance microstructural densification [8]. In SCC, nano-ZnO has been reported to improve the mechanical performance through filler effects and hydration acceleration, particularly at low replacement levels. Nevertheless, some studies have noted that improper dispersion or higher dosages may adversely affect durability-related properties owing to changes in pore connectivity, emphasizing the need for careful evaluation of its performance when used as a partial cement replacement [9].

In contrast, nano marble powder has received comparatively less attention despite its potential as a sustainable and cost-effective nanofiller [10]. Derived from marble waste, nano marble powder primarily acts as an inert material that enhances particle packing and matrix densification in cementitious materials [11]. Previous studies have reported moderate improvements in the mechanical properties and durability of concrete when nano marble powder is used at low replacement levels. In SCC applications, its fine particle size may contribute to improved flowability and reduced porosity; however, excessive replacement of cement can lead to binder dilution and reduced hydration product. Therefore, understanding the combined effects of the nano marble powder on the fresh, mechanical, and durability properties of SCC remains an important research gap [12].

Based on the above considerations, the present study aims to investigate the influence of nano-ZnO, nano-silica fume, and nano marble powder as partial replacements of cement on the fresh, mechanical, and durability properties of SCC. Different

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replacement levels were adopted to identify the optimum dosage of each nanomaterial. The performance of the nanomodified SCC mixtures was evaluated in terms of CS, TS, FS, and sorptivity at different curing ages. This comprehensive experimental approach provides valuable insights into the effectiveness of various nanomaterials in enhancing SCC performance and contributes to the development of optimized, high-performance, and durable SCC mixtures [13].

The significance of this research lies in its comprehensive evaluation of the combined mechanical and durability performance of SCC incorporating different nano materials as partial replacements of cement. While previous studies have extensively examined individual nanomaterials in conventional concrete, limited research has systematically compared the effects of nano-ZnO, nano silica fume, and nano marble powder within the same SCC framework and under identical testing conditions. This study addresses this gap by providing a direct comparison of the influence of nanomaterial type and dosage on compressive, tensile, and FSs, as well as sorptivity as a key durability indicator. Moreover, the use of nano marble powder derived from waste materials introduces an environmentally beneficial perspective by promoting sustainable construction practices through waste valorization and cement reduction. The findings of this study contribute to a deeper understanding of the role of nanoscale modifications in SCC, identify optimal replacement levels for each nanomaterial, and offer practical guidance for designing high-performance and durable SCC mixtures. Consequently, this study provides valuable insights for researchers and practitioners seeking to enhance SCC performance using advanced and sustainable nanobased approaches.

Experimental program

A. Raw materials

Ordinary Portland cement (OPC) was used as the primary binder in this study, with a cement content of 550 kg/m³ to provide sufficient paste volume and ensure the flowability and stability required for the SCC. The cement was obtained from a local cement manufacturer and complied with ASTM C150/C150M requirements. Silica fume was incorporated as a supplementary cementitious material at a dosage of 27.5 kg/m³ to enhance particle packing, reduce pore connectivity, and improve the fresh and hardened properties of the concrete. The silica fume consisted mainly of amorphous silicon dioxide, met the specifications of ASTM C1240, and was supplied by a certified commercial source.

Natural aggregates were used in both the coarse and fine fractions. Coarse aggregates with a maximum nominal size suitable for SCC mixtures were used at a content of 762 kg/m³ to achieve adequate flow without blocking or segregation. Fine aggregates were incorporated at the same dosage (762 kg/m³) and had a well-graded particle size distribution to enhance homogeneity and passing ability. Both coarse and fine aggregates were sourced from local quarries and satisfied the grading, cleanliness, and physical property requirements specified in ASTM C33/C33M standard.

Potable water conforming to ASTM C1602/C1602M [14] was used for mixing at a content of 184.8 L/m³, ensuring compatibility with cement hydration and durability. A high-range water-reducing admixture (HRWRA) was added at a dosage of 6.93 L/m³ to achieve self-compacting characteristics without increasing the water-to-binder ratio. The superplasticizer was a polycarboxylate-ether-based admixture supplied by a commercial manufacturer and complied with ASTM C494/C494M Type F **[15]**. The optimized combination of cementitious materials, aggregate grading, and chemical admixture resulted in an SCC mixture exhibiting a slump flow diameter exceeding 65 cm in accordance with ASTM C1611/C1611M **[16]**, adequate passing ability, and a characteristic cube CS of 73.6 MPa. **Tab. 1** summarizes the mix proportions

Tab. 1. Mix proportions

Item	Value
Cement (kg/m³)	550
Silica fume (kg/m³)	27.5
Coarse aggregate (kg/m³)	762
Fine aggregate (kg/m³)	762
Water (L/m³)	184.8

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Superplasticizer (L/m³)	6.93
Slump flow diameter (cm)	≥ 65
Time to reach 50 cm slump, T_{50} (s)	4.2
J-ring height difference (cm)	0.4
Characteristic cube strength (MPa)	73.6

A. Preparation of Nano Materials

Nano-sized zinc oxide, nano silica fume, and nano marble powder were prepared using a mechanical grinding technique to achieve particle sizes in the nanometer range that are suitable for SCC applications. The raw materials were initially dried to remove any residual moisture and then subjected to high-energy mechanical milling using a laboratory ball mill. The grinding process was performed for a controlled duration to ensure sufficient particle size reduction while avoiding excessive agglomeration [17]. The milling parameters, including the rotation speed and grinding time, were carefully selected to obtain uniformly fine particles with a high specific surface area. The produced nanomaterials were subsequently sieved and stored in airtight containers to prevent moisture absorption and particle agglomeration before use. Mechanical grinding was selected because of its simplicity, scalability, and effectiveness in producing nanoscale powders for cementitious systems [18].

B. Dispersion of Nano Materials in SCC

The dispersion of n-ZnO, n-SF, and n-MP within the SCC matrix was performed to ensure a homogeneous distribution and prevent particle agglomeration, which could negatively affect the fresh and hardened properties of the concrete. The nanomaterials were first dispersed in a portion of the mixing water using mechanical stirring to promote particle separation and uniform suspension using a magnetic stirrer shown in **Fig. 1** The dispersed suspension was then introduced into the concrete mixture during mixing, followed by the addition of a polycarboxylate-ether-based superplasticizer to further enhance dispersion through electrostatic repulsion and steric hindrance mechanisms. This dispersion approach improved the stability of fresh SCC, enhanced particle packing, and facilitated better interaction between the nanoparticles and cement hydration products. Consequently, flowability, reduced segregation, and enhanced mechanical performance of the hardened SCC were achieved [19].

Fig. 1. Raw materials

C. Mixing procedures

The mixing procedures for the SCC mixtures were carefully designed to ensure uniformity, proper dispersion of nanomaterials, and consistent fresh properties. Initially, all dry constituents, including cement, aggregates, and the designated amount of nanomaterial (nano zinc oxide, nano silica fume, or nano marble powder) used as a partial replacement of cement, were dry-mixed in a pan mixer for approximately 2–3 min to achieve a homogeneous blend. This step was essential to prevent the localized concentration of nanoparticles and ensure an even distribution within the binder matrix. Subsequently, approximately two-thirds of the mixing water was gradually added, while mixing continued to initiate cement hydration and improve workability. The remaining mixing water, pre-mixed with the required dosage of polycarboxylate-ether-based superplasticizer, was then introduced slowly to enhance flowability and promote further dispersion of nanoparticles through electrostatic repulsion and steric hindrance mechanisms. Mixing was continued for an additional 3–5 min until a uniform, highly flowable, and stable SCC mixture was obtained. Special attention was given to the mixing time and sequence to minimize nanoparticle agglomeration and segregation, ensuring that all SCC mixtures exhibited consistent fresh properties before casting. Immediately after

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mixing, the fresh concrete was subjected to SCC workability tests before casting it into molds for subsequent curing and testing

D. Testing

An experimental testing program was conducted to assess the performance of the formulated SCC combination. Ten concrete mixtures were formulated, comprising one control mixture devoid of nanomaterials and nine modified mixtures integrating three distinct dosage levels of each nanomaterial (nano-ZnO, nano-SF, and nano-MP). The fresh and hardened characteristics of all mixtures were evaluated under uniform curing and testing settings to ensure the uniformity and reliability of the outcomes. CS tests were conducted on the cube specimens at curing ages of 7 and 28 days in accordance with ASTM C39/C39M. The TS was assessed at identical ages in accordance with ASTM C496/C496M, whereas FS tests were performed on prism specimens according to ASTM C78/C78M. To assess the durability characteristics of the SCC mixtures, water sorptivity was quantified at 28 days of curing in line with ASTM C1585 [20]. All specimens were immersed in water under regulated laboratory conditions until they attained the specified testing age as shown in **Fig.2**. The test findings were used to evaluate the impact of nanomaterial type and dosage on the mechanical and transport properties of SCC[21].

Fig.2: Mixing and testing procedures

Results and discussion

A. Compressive strength at 7 days

Fig. 3 illustrates the CS results of the SCC mixtures incorporating different nanomaterials as partial replacements for cement, compared with the control mix. The control mix (CT00), which contained no nanomaterials, achieved a CS of approximately 39.47 MPa. The incorporation of nano zinc oxide at replacement levels of 0.5%, 1.0%, and 1.5% resulted in a gradual improvement in CS, reaching approximately 40.41, 41.60, and 42.90 MPa, respectively. This corresponds to an enhancement of approximately 2.4%, 5.4%, and 8.7% relative to the control mix, respectively. The observed improvement can be attributed to the filler effect of the nano-Zn particles and their ability to accelerate cement hydration by providing additional nucleation sites for the hydration products [7].

A more pronounced enhancement was observed for mixes incorporating nano silica fume at replacement levels of 1%, 2%, and 3%. The CS increased significantly to approximately 44.13, 47.53, and 45.43 MPa. The mix containing 2% nano silica fume exhibited the highest CS among all the tested mixes, with an improvement of nearly 20.4% compared with the control mix. This superior performance is mainly attributed to the high pozzolanic reactivity of the nano silica fume, which enhances the formation of secondary C–S–H gel and significantly refines the pore structure. However, a slight reduction in strength was observed at 3% replacement, likely due to particle agglomeration and an increase in water demand, which may have negatively affected dispersion efficiency and matrix homogeneity [22]

In contrast, the incorporation of nano marble powder at replacement levels of 1%, 2%, and 3% showed a marginal improvement at lower dosages, followed by a reduction in CS at higher percentages of replacement. The CS values were approximately 39.57, 40.05, and 38.04 MPa for NM10, NM20, and NM30, respectively. While the nanomarbles primarily act as an inert filler that enhances particle packing and matrix densification at low replacement levels, excessive replacement of cement reduces the available binder content and limits the formation of hydration products, resulting in lower strength development [12, 23].

Overall, the results demonstrate that replacing cement with nanomaterials significantly influences the CS of SCC, depending on both the type and dosage of the nanomaterial. Nano silica fume was the most effective additive, particularly at an optimum replacement level of 2%, whereas nano zinc oxide provided moderate but consistent strength enhancement.

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Conversely, the nano marble powder exhibited limited effectiveness and should be used at low replacement levels to avoid adverse effects on mechanical performance. These findings highlight the importance of optimizing the nanomaterial dosage to balance the benefits of the nanomaterial-scale effects with the overall binder chemistry and rheology of SCC.

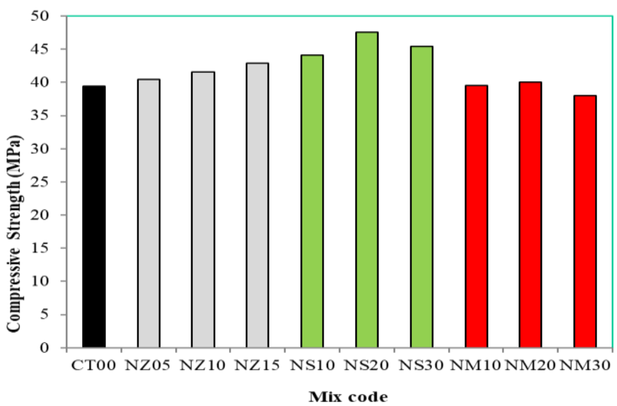

Fig. 3. Compressive strength for SCC with different types of nanoparticles

B. Compressive strength at 28 days

Fig. 4 presents the CS results of the SCC mixtures at 28 days of curing for the control mix and mixes incorporating different nanomaterials as partial replacements for cement. As expected, all mixtures exhibited a noticeable increase in CS compared to their corresponding 7-day results, reflecting the continued hydration process and progressive densification of the cementitious matrix. The control mix (CT00) achieved a CS of approximately 52.01 MPa at 28 days, which served as the reference for evaluating the effectiveness of incorporating the nanomaterial.

The inclusion of nano-ZnO at replacement levels of 0.5%, 1.0%, and 1.5% led to a consistent enhancement in CS, with values of approximately 53.88 MPa, 55.65 MPa, and 57.20 MPa, respectively. These results correspond to strength improvements of approximately 3.6%, 7.0%, and 10.0% compared to the control mix. The continued strength gain at 28 d suggests that nano-ZnO not only accelerates early hydration but also contributes to long-term strength development by improving microstructural refinement and enhancing the interfacial transition zone (ITZ) between the cement paste and aggregates.

A more pronounced improvement was observed in the mixes incorporating nanosilica fume. Replacement levels of 1%, 2%, and 3% resulted in CSs of approximately 58.77, 65.50, and 63.21 MPa, respectively. The mixture containing 2% nano silica fume (NS20) exhibited the highest CS among all tested mixes, with an enhancement of nearly 26% relative to the control mix. This superior performance is primarily attributed to the high pozzolanic reactivity and extremely fine particle size of the nano silica fume, which promotes the formation of additional C–S–H gel, significantly reduces porosity, and refines the pore structure. The slight reduction in strength observed at the 3% replacement level may be attributed to particle agglomeration and increased water demand, which can negatively affect the dispersion efficiency and limit further strength development.

In contrast, the incorporation of nano-marble powder showed moderate improvements at 28 d. The CSs of NM10, NM20, and NM30 were approximately 57.00, 59.36, and 59.14 MPa, respectively. While the nano marble powder primarily acts as an inert filler, its fine particle size enhances the packing density and contributes to matrix densification at moderate replacement levels. However, increasing the replacement ratio beyond the optimum level reduces the effective cement content, which limits hydration product formation and restricts further strength enhancement.

Overall, the 28-day results confirmed that the effectiveness of nanomaterials in SCC is strongly dependent on both the material type and dosage. Nano silica fume demonstrated the most significant contribution to long-term CS, particularly at an optimum replacement level of 2%, followed by nano zinc oxide, which provided a steady and sustained improvement. The nano marble powder exhibited limited effectiveness and should be carefully optimized to balance the filler benefits against the cement dilution effects. These findings highlight the importance of dosage optimization when incorporating

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nanomaterials as cement replacements in high-performance SCC mixtures.

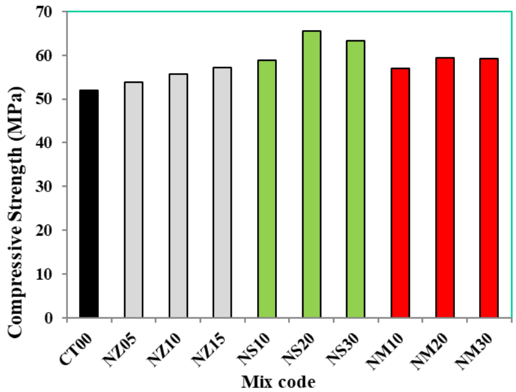

Fig. 4. Compressive strength for SCC with different types of nanoparticles

C. Early tensile strength

Fig. 5 illustrates the TS results of the SCC mixtures at 7 days of curing for the control mix and mixes incorporating different nanomaterials as partial replacements of cement. The control mix (CT00) recorded TS of approximately 6.32 MPa, which was used as a benchmark to assess the influence of nanomaterial incorporation at early ages. In general, all modified mixes exhibited comparable or improved tensile strength values relative to the control mix, indicating the positive role of nanomaterials in enhancing early-age tensile performance.

For mixes incorporating nano-ZnO at replacement levels of 0.5%, 1.0%, and 1.5%, the TS increased gradually to approximately 6.49, 6.66, and 6.86 MPa, respectively. These values represent improvements of approximately 2.7%, 5.4%, and 8.5% compared to the control mix. The enhancement in tensile strength can be attributed to the nano zinc particles acting as micro-fillers that improve particle packing and reduce microcrack initiation, in addition to their contribution to accelerating cement hydration at early ages, which improves the matrix cohesion.

A more significant improvement was observed in the mixes containing nanosilica fume. Replacement levels of 1%, 2%, and 3% resulted in TS values of approximately 7.20, 7.60, and 7.30 MPa, respectively. The mix with 2% nano silica fume (NS20) exhibited the highest tensile strength among all tested mixes, achieving an enhancement of nearly 20% relative to the control mix. This pronounced improvement is mainly attributed to the high pozzolanic activity and extremely fine particle size of the nano silica fume, which promotes the formation of additional C–S–H

gel and significantly strengthens the interfacial transition zone (ITZ). The slight reduction observed at the 3% replacement level may be related to particle agglomeration and reduced dispersion efficiency at higher nanofiller contents.

In contrast, the mixes incorporating nano-marble powder showed limited improvement in TS. The values of NM10, NM20, and NM30 were approximately 6.23, 6.45, and 6.12 MPa, respectively. While the nano marble powder contributes to matrix densification through a filler effect at lower dosages, its largely inert nature and the dilution of cement content limit its effectiveness in enhancing tensile resistance, particularly at higher replacement levels.

Overall, the 7-day tensile strength results demonstrate that nanosilica fume is the most effective nanomaterial in improving the early age tensile performance of SCC, followed by nanozinc oxide, which provides moderate but consistent enhancement. The nano marble powder exhibited minimal influence and should be used cautiously to avoid compromising the tensile behavior. These results highlight the sensitivity of tensile strength to nanomaterial type, dosage, and dispersion efficiency at early curing ages.

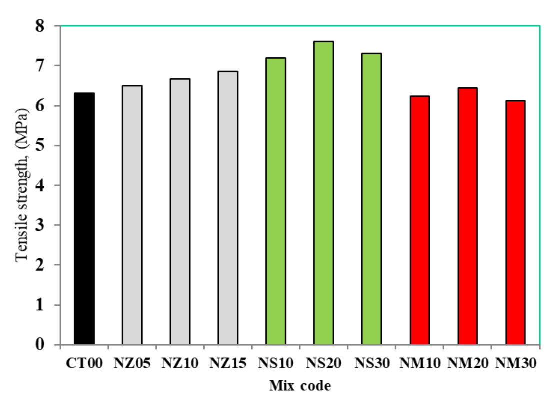

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Fig. 5. Early tensile strength for SCC with different types of nanoparticles

D. 28 days tensile strength

Fig. 6 shows the TS results of the SCC mixtures at 28 days of curing for the control and nanomodified mixes. A general increase in tensile strength was observed for all mixtures compared to the corresponding 7-day results, reflecting the continuous hydration process and the progressive development of a denser and more cohesive cementitious matrix. The control mix (CT00) exhibited aTS of approximately 8.45 MPa at 28 d, which served as the reference value for assessing the effectiveness of the incorporation of the nanomaterial.

The incorporation of nano-ZnO as a partial replacement of cement resulted in a steady enhancement in tensile strength with increasing dosage. The mixes NZ05, NZ10, and NZ15 achieved tensile strength values of approximately 8.67 MPa, 8.90 MPa, and 9.32 MPa, respectively, corresponding to improvements of approximately 2.6%, 5.3%, and 10.3% relative to the control mix. This behavior indicates that nano-ZnO contributes not only to early age strength enhancement but also to sustained tensile performance at later ages, mainly through improved particle packing, reduced microcrack propagation, and refinement of the interfacial transition zone (ITZ).

A more pronounced improvement was observed in the mixes incorporating nano silica fume. At replacement levels of 1%, 2%, and 3%, the tensile strength increased significantly to approximately 9.70 MPa, 10.33 MPa, and 10.05 MPa, respectively. The mix containing 2% nano silica fume (NS20) demonstrated the highest tensile strength among all tested mixtures, with an enhancement of nearly 22% compared with the control mix. This superior performance can be attributed to the high pozzolanic reactivity and ultrafine particle size of the nano silica fume, which promotes the formation of additional C–S–H gel, strengthens the paste–aggregate bond, and significantly improves the resistance to tensile cracking. The slight reduction observed at the 3% replacement level suggests that excessive nano silica fume may lead to particle agglomeration and increased water demand, which can adversely affect the dispersion efficiency.

In contrast, the mixes incorporating nano marble powder showed moderate improvements in the tensile strength at 28 days. The tensile strengths of NM10, NM20, and NM30 were approximately 9.12, 9.56, and 9.46 MPa, respectively. Although the nano marble powder mainly acts as an inert filler, its fine particle size enhances matrix densification and contributes to improved tensile behavior at moderate replacement levels. However, increasing the replacement ratio beyond the optimum level limits cement hydration owing to binder dilution, resulting in marginal gains or slight reductions in tensile strength.

Overall, the 28-day tensile strength results confirmed that the nano silica fume is the most effective nano material for enhancing the tensile performance of SCC, particularly at an optimum replacement level of 2%, followed by nano zinc oxide, which provides consistent and gradual improvement. The nano marble powder exhibited limited effectiveness and should be carefully optimized to avoid compromising the tensile resistance. These findings emphasize the strong dependence of the tensile behavior on the nanomaterial type, dosage, and dispersion efficiency in SCC mixtures.

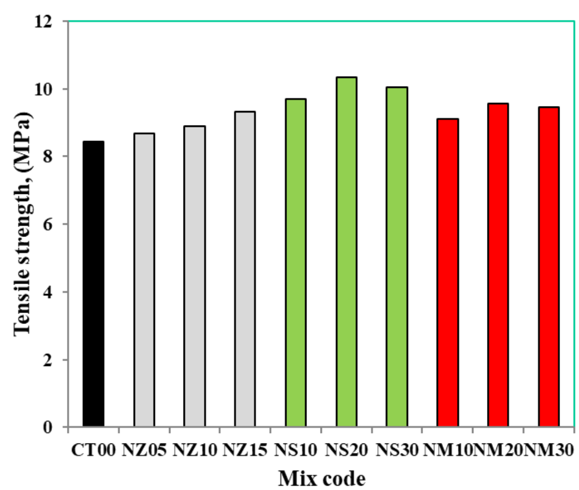

Fig. 6. 28-days tensile strength for SCC with different types of nanoparticles

E. Early flexural strength

Fig.7 presents the FS results of the SCC mixtures at 7 days of curing for the control and nanomodified mixes. The control mix

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(CT00) exhibited an FS of approximately 8.53 MPa, which was adopted as the reference value to evaluate the influence of nanomaterial incorporation on the early age flexural performance. In general, all nanomodified mixtures demonstrated equal or improved FS compared to the control mix, indicating the beneficial role of nanomaterials in enhancing crack resistance and load-carrying capacity at early ages.

For mixes incorporating nano ZnO at replacement levels of 0.5%, 1.0%, and 1.5%, the FS increased gradually to approximately 8.67 MPa, 9.00 MPa, and 9.37 MPa, respectively. These values corresponded to improvements of approximately 1.6%, 5.5%, and 9.8% relative to the control mix. The enhancement in FS can be attributed to the ability of the nano-Zn particles to improve matrix homogeneity and reduce microcrack initiation, particularly under bending stresses, where tensile cracking governs the failure behavior.

A more pronounced improvement was observed in the mixes incorporating nanosilica fume. Replacement levels of 1%, 2%, and 3% resulted in FS values of approximately 9.38, 9.74, and 9.63 MPa, respectively. The mix containing 2% nano silica fume (NS20) achieved the highest FS among all tested mixes, with an enhancement of nearly 14% compared with the control mix. This improvement is mainly attributed to the high pozzolanic reactivity and ultra-fine particle size of the nano silica fume, which enhances the formation of secondary C–S–H gel and significantly strengthens the interfacial transition zone (ITZ), thereby improving the resistance to flexural cracking. The slight reduction observed at the 3% replacement level suggests that excessive nano silica fume may result in particle agglomeration, reducing its effectiveness at early ages [24, 25].

In contrast, the incorporation of nano marble powder showed limited improvement in FS at 7 d. The FSs of NM10, NM20, and NM30 were approximately 8.83, 9.16, and 8.72 MPa, respectively. While nanomarbles mainly act as inert fillers that improve particle packing and matrix densification at low dosages, higher replacement levels reduce the effective cement content, limiting early age strength development.

Overall, the 7-day FS results demonstrate that nanosilica fume is the most effective nanomaterial for enhancing the early age flexural performance of SCC, followed by nano-ZnO, which provides gradual and consistent improvement. The nano marble powder exhibited modest effectiveness and should be optimized carefully to avoid compromising the early age flexural resistance. These findings highlight the sensitivity of FS to nanomaterial type, dosage, and dispersion efficiency during the early curing stages.

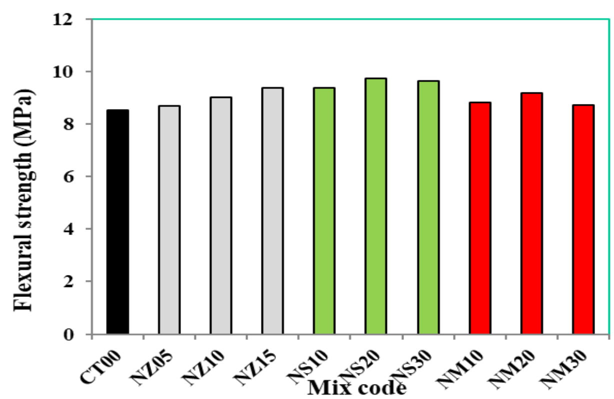

Fig. 7. Flexural strength for SCC with different types of nanoparticles

F. flexural strength at 28 days

Fig. 8 shows the FS results of the SCC mixtures at 28 days of curing for the control mix and mixes incorporating different nanomaterials as partial replacements of cement. As expected, all mixtures exhibited a significant increase in FS compared to the corresponding 7-day results, indicating a continuous hydration process and progressive improvement in the microstructure of the cementitious matrix. The control mix (CT00) achieved an FS of approximately 12.75 MPa at 28 d, which was considered the reference value for evaluating the influence of nanomaterial incorporation.

The addition of nano zinc oxide at replacement levels of 0.5%, 1.0%, and 1.5% resulted in noticeable enhancements in FS, reaching approximately 14.62, 15.42, and 16.37 MPa,

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respectively. These values correspond to improvements of approximately 14.7%, 21.0%, and 28.3% compared to the control mix. The observed enhancement can be attributed to the ability of the nano Zn particles to refine the pore structure, improve matrix continuity, and enhance crack-bridging capacity under bending stresses, particularly at later curing ages [26].

A more pronounced improvement was observed in mixtures incorporating nanosilica fume. Replacement levels of 1%, 2%, and 3% resulted in FS values of approximately 17.62, 18.00, and 16.94 MPa, respectively. The mixture containing 2% nano silica fume (NS20) achieved the highest FS among all the tested mixtures, with an improvement of nearly 41% relative to the control mix. This superior performance is mainly attributed to the high pozzolanic activity and ultrafine particle size of the nano silica fume, which promotes the formation of C–S–H gel, significantly densifies the matrix, and strengthens the interfacial transition zone (ITZ). The slight reduction in FS at 3% replacement may be related to particle agglomeration and increased water demand, which negatively affect dispersion efficiency and crack resistance.

In contrast, the incorporation of the nano marble powder led to moderate improvements in the FS at 28 d. The FSs of NM10, NM20, and NM30 were approximately 13.50, 13.87, and 12.95 MPa, respectively. While the nano marble powder primarily acts as an inert filler that enhances particle packing and matrix densification at low to moderate replacement levels, excessive replacement of cement reduces the amount of hydration products, thereby limiting further enhancement in flexural performance [27, 28].

Overall, the 28-day FS results confirm that nanosilica fume is the most effective nanomaterial for improving the flexural behavior of SCC, particularly at an optimum replacement level of 2%, followed by nano ZnO, which provides consistent and substantial strength gains with increasing dosage. The nano marble powder exhibited limited effectiveness and should be carefully optimized to avoid adverse effects on flexural performance. These findings emphasize the strong dependence of FS on nanomaterial type, dosage, and curing age in SCC mixtures [21].

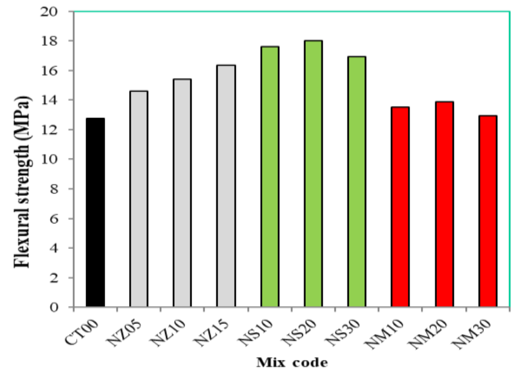

Fig. 8. Flexural strength for SCC with different types of nanoparticles

G. *Sorptivity*

Fig. 9 presents the sorptivity results of the SCC mixtures at 28 days of curing for the control mix and mixes incorporating different nanomaterials as partial replacements of cement. Sorptivity is a key durability indicator that reflects the capillary water absorption behavior and pore connectivity within the concrete matrix. The control mix (CT00) exhibited a sorptivity value of approximately 2.057 × 10^{-6} $m/s^{1/2}$, which served as a reference for evaluating the influence of nanomaterial incorporation on the transport properties of SCC.

The incorporation of nano zinc oxide led to an increase in the sorptivity values compared to the control mix. At replacement levels of 0.5%, 1.0%, and 1.5%, the sorptivity values increased to approximately 2.449 × 10^{-6}, 2.254 × 10^{-6}, and 2.223 × 10^{-6} m/s, respectively. This increase suggests that nano-ZnO, despite its positive effect on mechanical properties, may alter pore continuity or introduce microstructural heterogeneity at higher dosages, potentially due to incomplete dispersion or localized agglomeration, which can increase capillary suction pathways [29].

In contrast, mixes incorporating nano silica fume exhibited a significant reduction in sorptivity values compared to the control mix. Replacement levels of 1%, 2%, and 3% resulted in sorptivity values of approximately 1.715 × 10^{-6}, 1.617 × 10^{-6}, and 1.656 × 10^{-6} $m/s^{1/2}$, respectively. The mix containing 2%

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nano silica fume (NS20) achieved the lowest sorptivity value among all tested mixes, representing a reduction of approximately 21% compared with the control mix. This pronounced improvement is attributed to the high pozzolanic reactivity and ultra-fine particle size of the nano silica fume, which promotes the formation of additional C–S–H gel, significantly refines the pore structure, and reduces capillary pore connectivity. The slight increase observed at 3% replacement may be associated with particle agglomeration and reduced dispersion efficiency.

The incorporation of nano marble powder resulted in moderate reductions in sorptivity compared with the control mix. The sorptivity values for NM10, NM20, and NM30 were approximately 1.911×10^{-6}, 1.890×10^{-6}, and 1.763×10^{-6} m/s^2, respectively. Although the nano marble powder is largely inert, its fine particle size contributes to pore filling and matrix densification, thereby reducing water absorption at moderate replacement levels. However, its effectiveness remains lower than that of nanosilica fume because of the absence of significant pozzolanic activity.

Overall, the 28-day sorptivity results clearly demonstrated that the nano silica fume is the most effective nano material for enhancing the durability performance of SCC by reducing capillary water absorption. Nano marble powder provides moderate improvement through a filler effect, whereas nano zinc oxide may negatively influence sorptivity when used as a cement replacement. These findings highlight the importance of optimizing the nanomaterial type and dosage to achieve a balanced improvement in both the mechanical and durability properties of SCC.

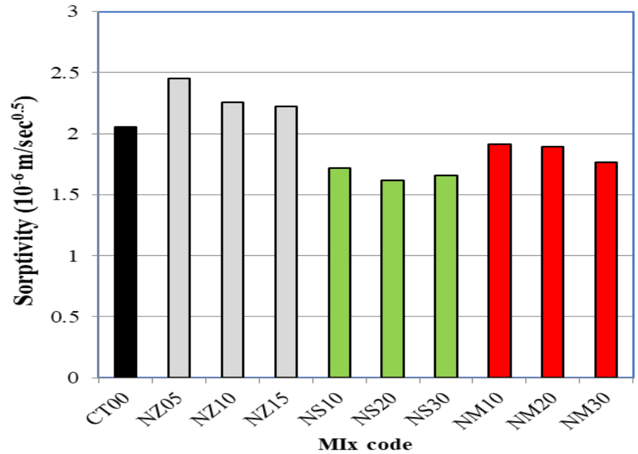

Fig. 9. Sorptivity for SCC with different types of nanoparticles

Conclusion

This study evaluated the influence of different nanomaterials as partial replacements of cement on the fresh, mechanical, and durability properties of SCC. Based on the experimental results and comparative analysis, the incorporation of nanomaterials significantly affects the performance of SCC, with the observed behavior strongly dependent on the type and replacement level of the nanomaterial. Among the investigated nanomaterials, nano silica fume proved to be the most effective, particularly at an optimum replacement level of 2%, resulting in the greatest improvements in compressive, splitting tensile, and FSs at both 7 and 28 days. The use of nanosilica fume also led to a substantial reduction in sorptivity at 28 d, indicating a denser microstructure and improved durability performance owing to enhanced pozzolanic activity and pore refinement. Nano zinc oxide provided moderate and consistent improvements in the mechanical properties, particularly at higher replacement levels. However, it exhibited increased sorptivity, suggesting a potential negative impact on durability when used as a cement replacement. The nano marble powder primarily acted as an inert filler, contributing to improved particle packing and matrix densification at low to moderate replacement levels, whereas excessive replacement resulted in limited mechanical enhancement owing to cement dilution effects. The results highlight that improper dosage or excessive incorporation of nanomaterials may lead to particle agglomeration, reduced dispersion efficiency, and diminished performance benefits.

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The combined evaluation of mechanical and durability properties emphasizes the importance of optimizing the nanomaterial type and dosage to achieve balanced and high-performance SCC mixtures. The findings of this study support the potential application of nano-based cement replacements in SCC for developing high-performance and more sustainable concrete, while also promoting the utilization of industrial waste materials such as marble powder.

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