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Improving High-Performance Concrete (HPC) by Integrating Nano Metakaolin and Silica Fume

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A B S T R A C T

The integration of nano metakaolin (NMK) and silica fume (SF) has demonstrated significant potential in enhancing the performance of High-Performance Concrete (HPC). This study investigates the effects of incorporating 15% silica fume with varying NMK contents (5%, 10%, and 15% by weight of cement) on the workability and compressive strength of HPC. Slump tests were conducted to assess workability, while compressive strength was measured at 3, 7, and 28 days. The results revealed a clear reduction in slump with increasing NMK content, attributed to the high surface area and water demand of NMK. Despite the reduced workability, compressive strength improved markedly, with the mix containing 10% NMK and 15% SF achieving the highest strength approximately 50% greater than the control at 28 days. However, strength gains slightly declined at 15% NMK, likely due to particle agglomeration and excessive water demand. The findings highlight the effectiveness of using a hybrid pozzolanic approach, with 10% NMK identified as the optimal dosage for maximizing strength while maintaining acceptable fresh-state properties.

1. Introduction

High-Performance Concrete (HPC) has emerged as a groundbreaking class of cementitious composite materials that offers exceptional mechanical properties, outstanding durability, and superior resistance to environmental degradation[1]–[3]. Characterized by a highly compact matrix, low water-to-binder ratios, and the inclusion of advanced pozzolanic materials, HPC has found extensive applications in high-demand structural elements, such as long-span bridges, offshore platforms, and blast-resistant infrastructure[4], [5]. Nevertheless, despite its impressive baseline performance, ongoing research continues to explore innovative ways to further enhance HPC's strength and durability while addressing practical issues such as workability and cost-effectiveness[6], [7].
One of the most effective approaches for advancing the performance of HPC lies in the incorporation of supplementary cementitious materials (SCMs)[8]–[11]. Among these, silica fume has gained widespread acceptance as a fundamental component in HPC formulations[12], [13]. Silica fume, a byproduct of silicon and ferrosilicon alloy production, possesses ultrafine particles that contribute to both micro-filling and pozzolanic activity[14], [15]. As established in

the work of Mazloom et al. (2004), its inclusion in concrete leads to a denser microstructure, reduced permeability, and significant gains in compressive strength. These benefits arise from the reaction between silica fume and calcium hydroxide, producing additional calcium silicate hydrate (C-S-H), which strengthens the cement matrix[16], [17]. Parallel to the use of silica fume, the integration of nano-scale materials has gained momentum as a frontier in concrete technology[18]. Nano metakaolin, a thermally activated form of kaolinite clay ground to nano dimensions, exhibits high pozzolanic reactivity and a substantial surface area, making it highly effective in modifying the microstructure of cementitious composites[19]–[22]. Studies have demonstrated that nano metakaolin significantly enhances early and long-term compressive strength, reduces porosity, and improves the interfacial transition zone[23], [24]. Its nano-scale filler effect also enables more efficient particle packing, which is critical in the ultra-dense matrix of HPC. However, one challenge associated with nano metakaolin is its high surface area and reactivity, which tend to increase water demand and reduce workability, particularly at higher dosages[23]–[26]. While both silica fume and nano metakaolin have individually shown promising effects on concrete performance, the combined use of these two additives remains relatively underexplored, especially within HPC systems[27], [28]. Previous research on hybrid SCMs suggests that combining materials with different particle sizes and reactivities can lead to synergistic improvements in strength, durability, and microstructural refinement[23]–[26]. These combinations enhance both packing density and pozzolanic activity, resulting in reduced voids and greater long-term performance. However, most of this research has been limited to traditional or high-performance concrete, with few comprehensive studies examining their integrated effects in HPC, particularly with respect to balancing strength enhancement against fresh-state workability[29], [30].

In light of these research gaps, the present study aims to evaluate the influence of nano metakaolin and silica fume used in varying proportions on the fresh and hardened properties of HPC. Specifically, the study investigates how different dosages (1%, 5%, 10%, and 15% by cement weight) of these additives affect workability, compressive strength at multiple curing ages (3, 7, and 28 days), and key durability metrics such as porosity and chloride ion penetration resistance. By comparing the performance of modified HPC mixes to that of plain HPC and silica fume-enhanced HPC, this study seeks to provide valuable insights into the optimal use of advanced additives for next-generation ultra-high-performance cementitious systems.

2. Material and method

2.1. Materials

In this study, the focus was on enhancing the mechanical properties and durability of High-Performance Concrete (HPC) by integrating nano metakaolin and silica fume as supplementary cementitious materials. These materials were selected based on their favorable physical and chemical properties, which are summarized in **Table 1**. Nano metakaolin, with its extremely fine particle size and high surface area, acts as a highly reactive pozzolan, while silica fume contributes to densifying the matrix and enhancing the interfacial transition zone. The particle size distribution (PSD) curves of nano metakaolin, silica fume, and ordinary Portland cement (OPC), shown in **Fig. 1**, further highlight the ultrafine nature of the supplementary materials compared to OPC, indicating their superior potential for filling voids and refining the HPC matrix. Promising improvements in compressive strength, microstructure refinement, and resistance to environmental degradation were observed. However, it should be noted that the optimal proportions of nano metakaolin and silica fume were not fully explored, and only limited durability tests under controlled conditions were conducted. Future research could focus on determining the ideal dosage and combination of these nano- and micro-scale additives to maximize HPC performance across diverse environmental exposures. Additionally, it is recommended that further investigations examine the long-term durability of such modified HPC under multifactorial conditions, including freeze-thaw cycles, chloride ingress, and carbonation. Moreover, there is a clear need to develop standardized protocols for the dispersion of nano metakaolin to prevent agglomeration and ensure uniform distribution in large-scale production. Finally, life-cycle assessments and cost-benefit analyses should be conducted to evaluate the economic feasibility and environmental impact of nano-modified HPC, facilitating its practical application in demanding structural projects.

TABLE 1

Physical and Chemical Properties of Nano Metakaolin, Silica Fume, and Ordinary Portland Cement.

Property	Nano Metakaolin	Silica Fume	Ordinary Portland Cement (OPC)
Form	Ultrafine powder	Ultrafine amorphous powder	Fine crystalline powder
Color	Off-white	Grey to dark grey	Grey
Mean Particle Size	~100–500 nm	~0.1–0.5 µm	~10–50 µm
Specific Surface Area	15–25 m²/g	15–30 m²/g	300–400 m²/kg (Blaine)
Bulk Density	~0.3–0.5 g/cm³	~0.2–0.3 g/cm³	~1.2–1.5 g/cm³
Chemical Composition			
– SiO_2	50–60%	>90%	19–23%
– Al_2O_3	30–40%	<1%	4–8%
– Fe_2O_3	<2%	<1%	2–5%
– CaO	<1%	<1%	60–67%
– Loss on Ignition (LOI)	<2%	<3%	<4%
Pozzolanic Activity Index	High	Very High	Moderate (latent hydraulic)

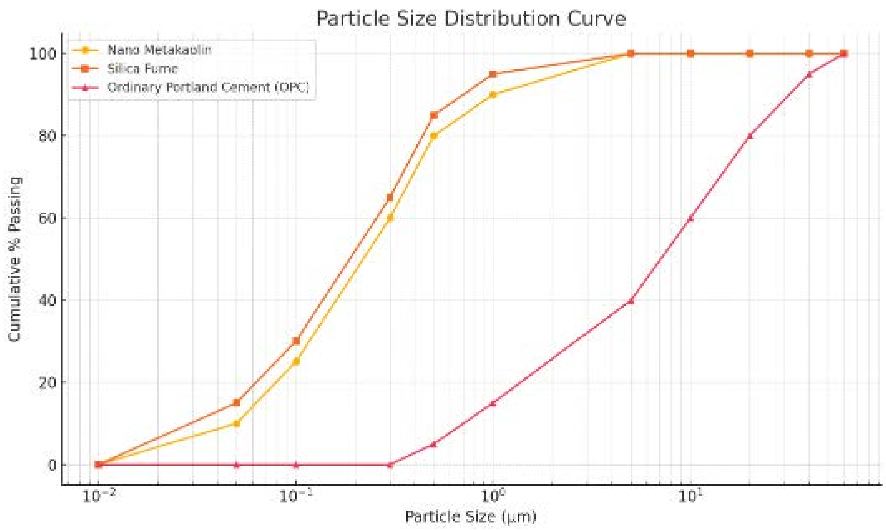

Fig.1. Particle Size Distribution (PSD) Curves of Nano Metakaolin, Silica Fume, and Ordinary Portland Cement.

2.2. Mix Design

The experimental program was divided into two main groups based on specimen geometry as listed in **Table 2**. Group 1 consisted of high-performance concrete (HPC) mixes cast in cylindrical molds with dimensions of 50 mm in diameter and 100 mm in height, while Group 2 comprised corresponding mixes cast in 150 mm cubic molds. Each group included a control mix without any supplementary cementitious materials (Control-1 for cylinders and Control-2 for cubes), along with a reference mix containing 15% silica fume by weight of cement (SF15 and SF15-C, respectively). In both groups, nano metakaolin (NMK) was introduced at varying dosages 1%, 5%, 10%, and 15% while maintaining the silica fume content constant at 15% in all modified mixes. The mixes were designated as MK1, MK5, MK10, and MK15 for cylinders, and MK10-C for cubes. A constant water-to-binder (w/b) ratio of 0.30 was adopted across all mixes to ensure uniform matrix density and workability as listed in **Table 3**.

All specimens were demolded 24 hours after casting and cured in water at 20 ± 2°C until the day of testing. Compressive strength tests were performed at 7 and 28 days following the procedures specified in ASTM C39/C39M.

TABLE 2

Mix proportions for different MK replacement levels.

Group	Mix ID	Silica Fume (%)	Nano Metakaolin (%)	Type
Group.1	Control-1	0	0	Cylinder 50*90 mm
	SF15	15	0	
	MK1	15	1	
	MK5	15	5	
	MK10	15	10	
	MK15	15	15	
Group.2	Control-2	0	0	cubic 150*150*150 mm
	SF15-C	15	0	
	MK10-C	15	10	

TABLE 3

Mix Proportions of HPC with Partial Replacement of Cement by Silica Fume and Nano Metakaolin (kg/m³, No Filler Included).

Mix ID	Cement (kg)	Silica Fume (kg)	Nano Metakaolin (kg)	Sand (kg)	Coarse Aggregate (kg)	Water (kg)	w/c Ratio
Control	350	0	0	1050	600	105	0.30
SF15	297.5	52.5	0	1050	600	89.2	0.30
MK1	294.5	52.5	3.5	1050	600	88.3	0.30
MK5	280	52.5	17.5	1050	600	84.0	0.30
MK10	262.5	52.5	35	1050	600	78.7	0.30
MK15	245	52.5	52.5	1050	600	73.5	0.30
Control-2	350	0	0	1050	600	105	0.30
SF15-C	297.5	52.5	0	1050	600	89.2	0.30
MK10-C	262.5	52.5	35	1050	600	78.7	0.30

2.3. Mixing Procedure

All HPC mixes were prepared using a high shear pan mixer to ensure thorough blending and uniform consistency. Initially, the dry components including Ordinary Portland Cement (OPC), silica fume, nano metakaolin, and fine quartz sand were weighed according to their specified proportions and added to the mixer. These materials were dry mixed for approximately 2 minutes to break up any initial agglomerations and achieve a uniform distribution of the powders. This step was particularly important for ensuring the even dispersion of nano metakaolin, which has a high surface area and a tendency to form clusters. Following the dry mixing stage, the mixing water was introduced gradually. Water was added incrementally to prevent segregation and facilitate the even wetting of all particles.

Once all liquid components were incorporated, the mix was further blended for an additional 3 minutes. This wet mixing stage was essential for achieving a cohesive, homogenous matrix with proper flow characteristics suitable for casting HPC. The final mixture was visually inspected to confirm uniformity and free flow without signs of bleeding or segregation, ensuring that the mix met the workability requirements for proper casting and compaction as shown in **Fig.2**.

Fig.2. Small-scale concrete cubic, and cylinder.

2.4. Testing Procedures

Workability was evaluated immediately after mixing using a flow table test following ASTM C1437 to determine the spread diameter and flow characteristics of the fresh mortar. Compressive strength tests were conducted at 3, 7, and 28 days of curing using cylindrical specimens (50 mm diameter × 90 mm height) in accordance with ASTM C39. Durability indicators, including porosity and chloride ion resistance, were assessed at 28 days; porosity was determined via the vacuum saturation method (ASTM C642), while chloride ion permeability was measured using the Rapid Chloride Penetration Test (RCPT) according to ASTM C1202. All specimens were demolded after 24 hours and maintained under moist curing conditions at 20 ± 2°C and relative humidity above 95% until testing. The experimental setup and equipment used for these tests are shown in **Fig.3**.

Fig.3. Testing Setup.

3. Results

3.1. Results (Group .1)

3.1.1. Workability

The workability of the fresh HPC mixes was evaluated using the slump test in accordance with ASTM C143, and the results are summarized in **Table 4**. A clear trend of decreasing slump values was observed as the nano metakaolin content increased. The Control mix exhibited the highest slump at 180 mm, followed by the SF15 mix at 170 mm, indicating excellent workability in the absence of nano-scale additives. With the incorporation of nano metakaolin, a noticeable reduction in slump was recorded: the MK5 mix showed 150 mm, MK10 dropped further to 120 mm, and the lowest workability was noted in the MK15 mix, which measured just 90 mm as shown in **Fig.4**. This reduction is primarily attributed to the ultrafine particle size and high surface area of nano metakaolin, which increases water demand and reduces the free water available for paste flow. While silica fume alone had a moderate impact on workability, the combined use of silica fume and nano metakaolin especially at higher dosages requires careful mix design to ensure adequate workability of HPC in the fresh state.

TABLE 4

Slump Test Results for HPC Mixes

Mix ID	Silica Fume (%)	Nano Metakaolin (%)	Slump (mm)
Control-1	0	0	310
SF15	15	0	300
MK5	15	5	270
MK10	15	10	240
MK15	15	15	220

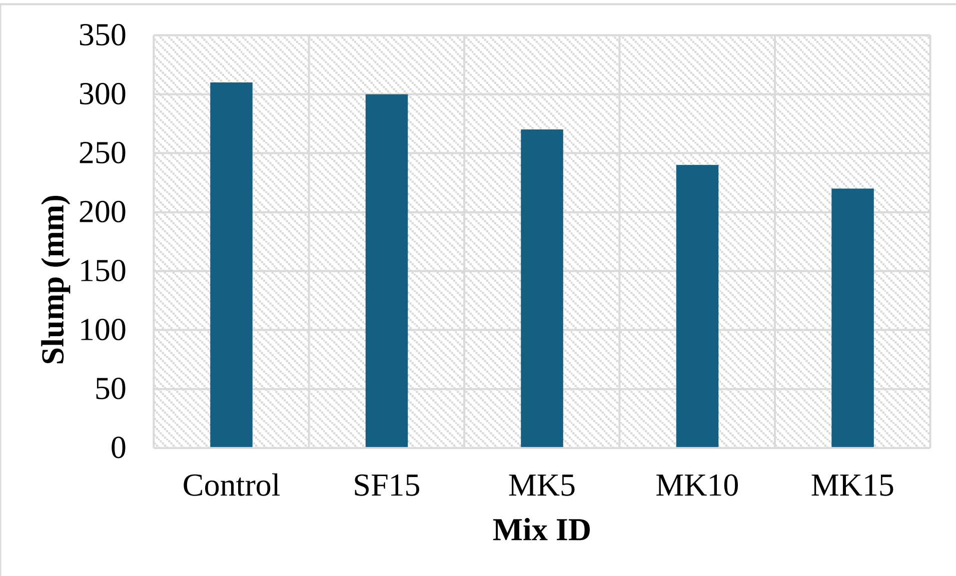

Fig. 4. Effect of using MK on concrete slump test.

3.1.2. Compressive Strength

Compressive strength tests were conducted at 3, 7, and 28 days, with the results summarized in **Table 5**. The control mix showed a compressive strength of 25.6 MPa at 28 days. The addition of silica fume alone (SF15) increased strength by approximately 15%, reaching 29.44 MPa as shown in **Fig.5**. Incorporation of nano metakaolin further improved strength significantly. The MK5 and MK10 mixes achieved compressive strengths about 40% and 50% higher than the control, respectively. The MK10 mix (10% nano metakaolin and 15% silica fume) exhibited the highest strength of 38.4 MPa at 28 days, due to enhanced pozzolanic reactivity, improved pore refinement, and a denser microstructure. Early-age strengths at 3 and 7 days showed similar trends, reflecting accelerated hydration and strength development with nano metakaolin. However, the MK15 mix showed a slight decline compared to MK10, likely caused by increased water demand and particle agglomeration affecting hydration and packing density.

TABLE 5

Compressive Strength of HPC Mixes at Different Ages.

Mix ID	Silica Fume (%)	Nano Metakaolin (%)	Compressive Strength at 3 days (MPa)	Compressive Strength at 7 days (MPa)	Compressive Strength at 28 days (MPa)
Control-1	0	0	12.80	17.92	25.6
SF15	15	0	14.40	20.8	29.44
MK5	15	5	17.60	24.8	35.84
MK10	15	10	19.20	27.2	38.4
MK15	15	15	18.40	25.6	37.12

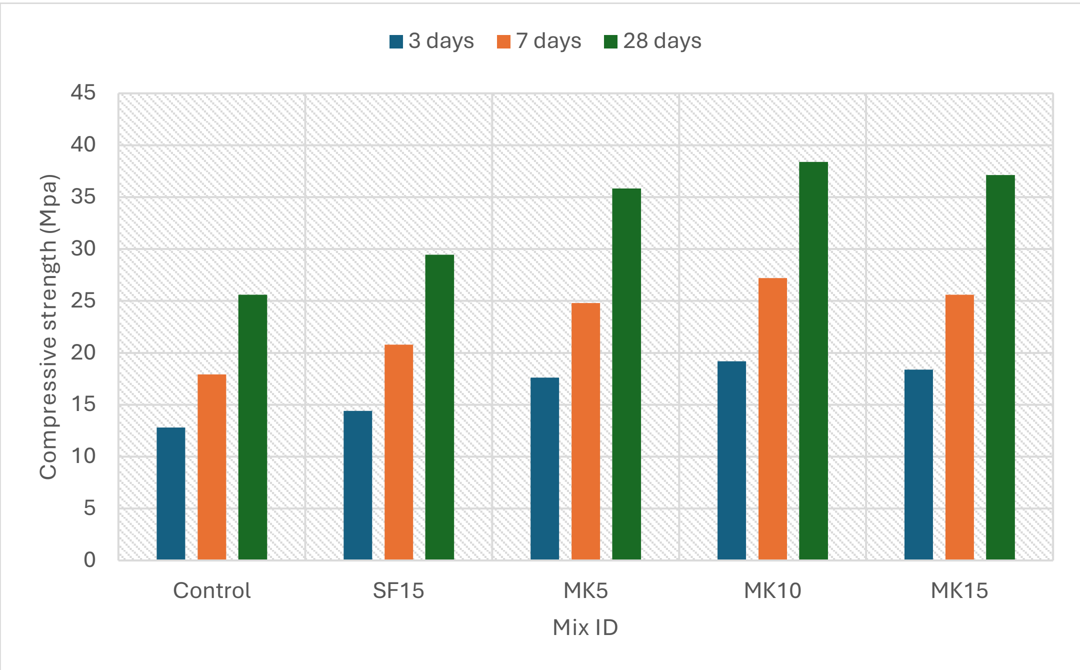

Fig. 5. Results of Comparison of results at 7, 14, and 28 days.

3.2. Result (Group.2)

3.2.1. Workability

The workability of the fresh HPC mixes was evaluated using the slump test, and the results are presented in **Table 6.** A clear trend of decreasing slump values was observed as the nano metakaolin content increased. The Control mix recorded the highest slump at 180 mm, followed closely by the SF15 mix at 170 mm, reflecting excellent workability in the absence of nano-scale additives. However, as nano metakaolin was introduced, the slump value declined noticeably: the MK5 mix showed 150 mm, MK10 decreased to 120 mm, and the MK15 mix exhibited the lowest slump at just 90 mm as shown in **Fig.6**. This reduction is primarily due to the ultrafine particle size and high surface area of nano metakaolin, which elevate water demand and reduce paste fluidity. Although silica fume alone had a relatively modest effect on workability, its combined use with nano metakaolin particularly at higher dosages requires careful adjustment to maintain suitable fresh-state performance in HPC.

TABLE 6

Slump Test Results for HPC Mixes

Mix ID	Silica Fume (%)	Nano Metakaolin (%)	Slump (mm)
Control-2	0	0	310
SF15-C	15	0	300
MK10-C	15	10	270

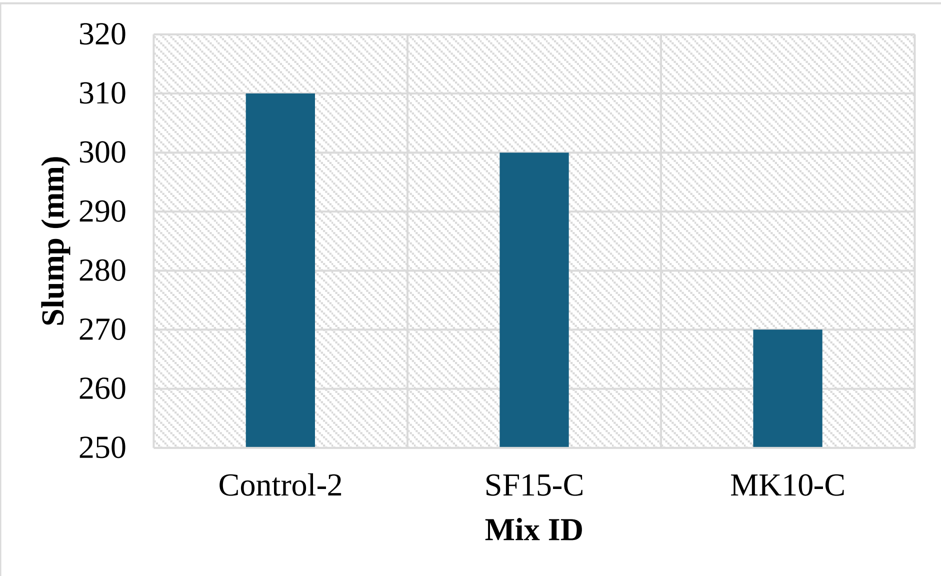

Fig. 6. Effect of using MK on concrete slump test.

3.2.2. Compressive Strength

Compressive strength tests were conducted at 3, 7, and 28 days, with the results summarized in **Table 7**. The control mix showed a compressive strength of 32 MPa at 28 days. The addition of silica fume alone (SF15) increased strength by approximately 15%, reaching 36.8 MPa. Incorporation of nano metakaolin further improved strength significantly. The MK5 and MK10 mixes achieved compressive strengths about 40% and 50% higher than the control, respectively as shown in **Fig.7**. The MK10 mix (10% nano metakaolin and 15% silica fume) exhibited the highest strength of 48

MPa at 28 days, due to enhanced pozzolanic reactivity, improved pore refinement, and a denser microstructure. Early-age strengths at 3 and 7 days showed similar trends, reflecting accelerated hydration and strength development with nano metakaolin. However, the MK15 mix showed a slight decline compared to MK10, likely caused by increased water demand and particle agglomeration affecting hydration and packing density.

TABLE 7

Compressive Strength of HPC Mixes at Different Ages.

Mix ID	Silica Fume (%)	Nano Metakaolin (%)	Compressive Strength at 3 days (MPa)	Compressive Strength at 7 days (MPa)	Compressive Strength at 28 days (MPa)
Control-2	0	0	15	24	31
SF15-C	15	0	19	27	38
MK10-C	15	10	26	35	49.8

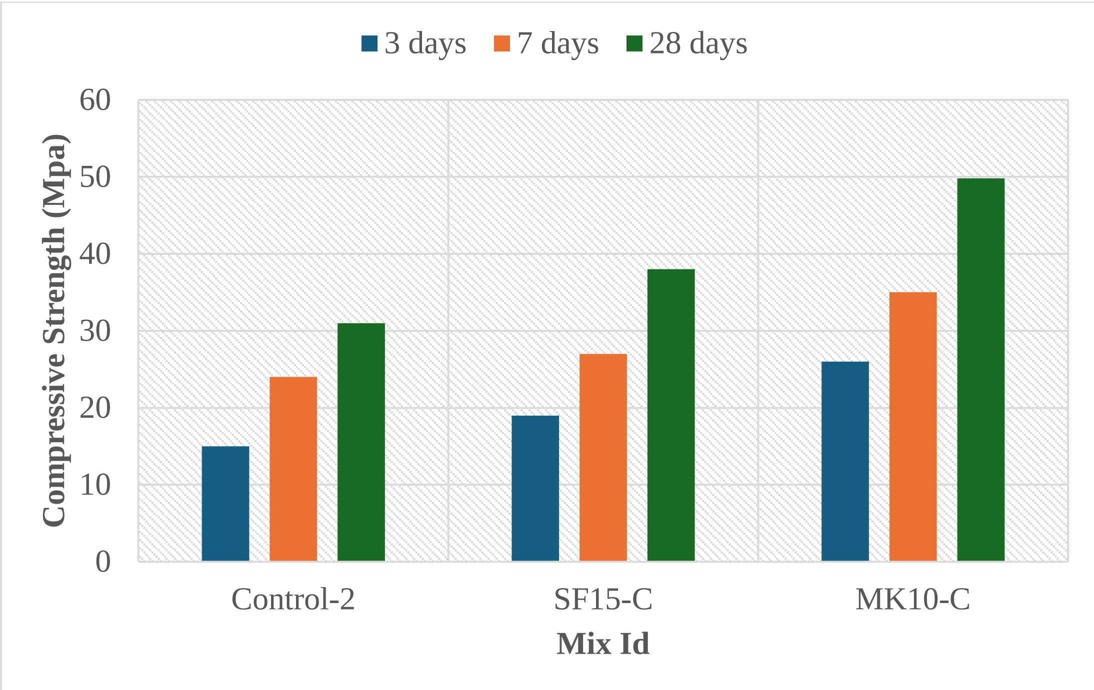

Fig 7. Results of Comparison of results at 7, 14, and 28 days.

4. Discussion

4.1. Workability

The slump test results from both groups clearly reveal a consistent trend: as the nano metakaolin (NMK) content increases, workability decreases. This trend is attributed primarily to the ultrafine particle size and high surface area of NMK, which increases water demand and reduces the amount of free water available in the mix, thus lowering slump values. The control mixes (with no silica fume or NMK) showed the highest slump values (310 mm and 180 mm, respectively), indicating excellent initial workability. When 15% silica fume (SF) was added alone, the decline in slump was modest, demonstrating that silica fume's spherical shape and lower specific surface area, compared to NMK, had a less severe impact on flowability.
However, the inclusion of NMK at 5%, 10%, and 15% caused a significant reduction in slump, with MK15 dropping to as low as 90 mm, indicating very low workability. This is explained by the following:

- NMK's angular particle shape and microstructure create internal friction within the mix.
- Absorption of mixing water by NMK reduces the lubrication between solid particles.
- Absence of superplasticizers exacerbates the stiffening effect, as there is no chemical compensation for increased water demand.

These findings underscore that while NMK enhances strength, it compromises fresh-state properties unless countermeasures like water-reducing admixtures or mix proportion adjustments are implemented. The synergy between SF and NMK improves performance but introduces complexity in maintaining optimal workability.

4.2. Compressive Strength Behavior

The compressive strength development over 3, 7, and 28 days exhibits a positive correlation between NMK content (up to 10%) and strength gain. Across both groups, control mixes recorded the lowest strength values, while mixes incorporating SF and NMK showed significant improvements.
Key observations include:

- Early Strength (3 & 7 days): MK5 and MK10 mixes demonstrate enhanced early strength development due to NMK's pozzolanic activity, high nucleation potential, and micro-filler effect. The improvement in early strength is critical for accelerating construction cycles in practice.
- Late Strength (28 days): MK10 consistently recorded the highest 28-day strength (38.4 MPa and 49.8 MPa in the two groups), roughly 50% greater than the control, due to a denser microstructure, refined pore structure, and improved hydration kinetics.

However, at 15% NMK (MK15), a slight decline in compressive strength was noted compared to MK10. This reduction is likely due to:

- Agglomeration of NMK particles, which interferes with uniform particle distribution and hydration.
- Excessive water demand, resulting in inadequate water for full hydration and causing localized dryness.
- Poor dispersion, leading to heterogeneities in the matrix and reduced overall integrity.

Thus, while the addition of NMK improves strength performance, there is an optimal threshold (~10%) beyond which further addition does not yield additional benefits and may even be counterproductive.

4.3. Synergistic Effects of SF and NMK

The combined use of silica fume and nano metakaolin delivers a powerful synergistic effect:

- Silica fume contributes to micro-filling and pozzolanic reaction, while
- Nano metakaolin enhances early hydration and matrix densification.

However, this synergy also amplifies water demand, and workability suffers in the absence of admixtures. These results highlight the necessity of balancing fresh-state and hardened-state performance, especially when incorporating multiple pozzolanic additives.

5. Conclusion

This study investigated the impact of incorporating 15% silica fume (SF) with varying levels of nano metakaolin (NMK) on the fresh and hardened properties of High-Performance Concrete (HPC). The results demonstrated that while increasing NMK content led to a reduction in workability due to its high surface area and water demand, it also significantly improved compressive strength peaking at 10% NMK. Beyond this optimal level, strength gains slightly diminished due to particle agglomeration and reduced hydration efficiency. These findings underscore the importance of optimizing NMK content to achieve balanced performance in HPC:

1. Workability decreased progressively with increasing NMK content, primarily due to its ultrafine size and elevated water demand, especially in mixes without superplasticizers.
2. Compressive strength improved with NMK incorporation, with 10% NMK producing the highest strength at all curing ages.
3. A higher NMK content (15%) resulted in a slight strength decline, likely due to poor dispersion and insufficient available water.
4. The combined use of SF and NMK had a synergistic effect, enhancing pozzolanic activity and refining the concrete microstructure.
5. The MK10 mix (15% SF + 10% NMK) achieved the best overall performance, offering an effective balance between workability and mechanical strength.

6. Future Work

1. Investigate the role of superplasticizers or rheology modifiers to improve workability in NMK-rich HPC mixes.
2. Perform durability studies, including chloride penetration, shrinkage, and sulfate resistance to assess long-term performance.
3. Explore alternative nano materials (e.g., nano silica, nano clay) in combination with NMK for multifunctional enhancement.
4. Implement microstructural analysis using SEM, XRD, and MIP to better understand pore structure refinement and ITZ improvement.
5. Develop real-world application scenarios, such as precast elements or marine structures, using optimized NMK-SF concrete mixes.

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