

Effect of Al₂O₃ Nanoparticles on the Workability, Strength, and Durability Properties of High-Strength Concrete

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Abstract — Concrete's mechanical qualities and endurance might be greatly enhanced by recent developments in the technology, especially via the investigation of nanoparticles. The purpose of this research is to evaluate the effects of adding Nano Al₂O₃ particles to M60 grade concrete mixes on mechanical qualities, durability traits, and compressive strength. Nano Al₂O₃ has an average diameter of 15 nm and is tested at various weight percentages of 0.5%, 1.0%, 1.5%, and 2.0% in accordance with IS 456-2000 standards. The experimental effort focused on compressive strength and durability evaluations by conducting systematic comparisons between ordinary cement concrete and NanoAl₂O₃ blended concrete. The research provides a comprehensive evaluation of the contributions of fly ash, silica fume, and metakaolin to concrete performance by examining their synergistic effects. The findings show that adding NanoAl₂O₃ significantly increases the concrete's compressive strength and durability, which enhances the mechanical qualities of high-strength concrete. Important conclusions on the efficacy of NanoAl₂O₃ as an additive are presented in this work, promoting robust and sustainable infrastructure solutions. The expected benefits to society include long-lasting buildings, lower maintenance costs, and safer construction practices, which will enable the development of complex and sustainable built environments. This research shows how nanotechnology may be included into concrete formulation to support sustainable building methods that strengthen resilient infrastructure and encourage long-lasting built environments.

Keywords: High-Performance, Nanoparticles, Workability, Nanoparticle, Microstructure

I. INTRODUCTION

Second only to water in terms of global usage, concrete is the most commonly used building material worldwide. In high-rise structures, long-span bridges, and specific infrastructure projects where greater load-bearing capacity, enhanced durability, and smaller cross-sectional dimensions are necessary, High Strength Concrete (HSC) has become more and more popular over the last several decades.

Conventional concrete satisfies basic building requirements, but it is inappropriate for several contemporary engineering applications due to its shortcomings in terms of strength-to-weight ratio, permeability, and long-term durability. HSC uses quality-controlled raw ingredients, optimum mix design, and, more recently, nanotechnology integration to overcome these issues.

One innovative method for improving the performance of concrete is the use of nanoparticles to cementitious systems. Because of their large surface area, exceptional hardness, and chemical stability—all of which affect the cement paste's hydration process and microstructural densification—Aluminum Oxide (Al₂O₃)

nanoparticles are becoming more and more popular. Through microstructure modification, Al₂O₃ nanoparticles may enhance HSC's workability, mechanical strength, and durability, providing answers to persistent problems in concrete technology.

In the realm of materials science, innovative technology often excels. In recent years, nanotechnology has attracted a lot of attention as a cutting-edge technology. It entails dealing with very sophisticated nanoparticles and nanoscale materials, which have a wide range of uses. Because of their increased surface area, nanoparticles, which usually vary in size from 1 to 100 nanometers, help to improve the characteristics of materials. Concrete, the most frequently used non-metallic building material in contemporary industry, is made possible by Portland cement, which is utilized extensively in construction. Cement contains a variety of oxides, including C₃S, C₃A, C₂S, C₄AF, MgO, and trace quantities of CaO, that are essential for the strength of concrete. By adding certain additives, concrete's compressive strength may be considerably increased by improving the composition of cement oxides.

A. High strength concrete:

High Strength Concrete (HSC) is defined as concrete having a compressive strength greater than 60 MPa as per most international standards (ASTM C39, ACI 363R), though some codes set the threshold at 55 MPa. The primary characteristics of HSC include low water-cement ratio, high binder content, and the use of supplementary cementitious materials like silica fume or fly ash to achieve superior performance.

Applications of HSC include:

- High-rise buildings – Reduces column size, increasing usable floor space.
- Long-span bridges – Provides higher load capacity with reduced structural weight.
- Offshore structures – Offers improved resistance to chloride and sulphate attack.
- Nuclear power plants – Ensures low permeability and enhanced radiation shielding.
- Precast elements – Enables higher strength in thinner sections, improving efficiency.

High Strength Concrete (HSC) is a type of concrete that has a compressive strength greater than 40 MPa (megapascals) or 6000 psi after 28 days of curing. In modern construction, HSC typically refers to concrete with strengths of 60 MPa to 100 MPa or more.

It is designed using a lower water-cement ratio, high-quality aggregates, and sometimes mineral admixtures like silica fume, fly ash, or chemical admixtures such as superplasticizers to improve workability.

According to its compressive strength, concrete may be divided into two categories for use in construction: regular

concrete and high-strength concrete. High-strength concrete has a compressive strength more than 50 MPa, while ordinary concrete typically has a strength of less than 50 MPa. Compressive strengths of 60 to 100 MPa are indicative of high-strength concrete. Nonetheless, in a few of nations, such as the US, France, and Norway, strengths exceeding 100 MPa have been achieved and used. This material is especially well-suited for use in structural elements and precast concrete in the building sector. Road infrastructure, large skyscrapers, long-span bridges, and offshore projects all often use high-strength concrete.

The skills and knowledge needed to produce high-strength concrete are essentially the same as those needed to produce ordinary-strength concrete. To guarantee optimum performance, it is essential to maintain a low water-to-cement ratio, usually between 0.30 and 0.35, or even lower. Portland cement and mixed cements are two types of cement that may be used to create high-strength concrete. To improve the benefits of water reduction, it is advised to use well-graded aggregates, particularly crushed aggregates of an appropriate size. Super plasticizers, also referred to as water reducers, are essential additives used to provide the necessary workability without sacrificing strength.

II. LITERATURE REVIEW

Li, Langan, and Ward (1996), The study focused on the compressive strength and microstructure of high strength paste, specifically examining the inclusion of silica fume and its effects. The selected water-cement ratios were 0.24, 0.27, 0.30, and 0.33. Testing was conducted at 14, 28, and 90 days of age. Silica fume was applied at 5% and 10% of the total cementitious content by weight. The authors achieved the optimal strength at a water-to-cement ratio of 0.24, and the x-ray diffraction analysis indicated that the inclusion of 10% silica fume effectively eliminated the calcium hydroxide component.

Rafat Siddique and Navneet Chahal (2024) The review encompassed a comprehensive analysis of the physical and chemical characteristics of cement paste and

mortars. This included an exploration of their reaction mechanisms, hydration parameters, consistency, setting times, workability, and compressive strength. The authors indicate that the extreme fineness and high concentration of amorphous silicon dioxide in silica fume demonstrate its characteristics as a reactive pozzolanic material. In each phase of hydration, the incorporation of silica fume enhances the hydration process of standard Portland cement. The consistency of the cement increased with the addition of silica fume to the mixture. The incorporation of micro silica leads to a decrease in workability. The use of silica fume as a partial replacement for cement resulted in an increase in compressive strength.

III. OBJECTIVE

- 1) To investigate the effect of varying percentages of Al₂O₃ nanoparticles on the workability of high strength concrete.
- 2) To identify the optimum percentage of Al₂O₃ nanoparticles that achieves the best balance between workability, strength, and durability.

IV. RESULTS AND DISCUSSIONS

A. Workability

Workability is the property of fresh concrete that determines the ease and homogeneity with which it can be mixed, transported, placed, compacted, and finished.

SN	% of NanoAlumina (NA)	Slump (mm)
1	0	51
2	0.25	50
3	0.5	48
4	0.75	47
5	1	46
6	1.25	43
7	1.5	40

Table 1: Workability for different mixes with slump cone test(mm)

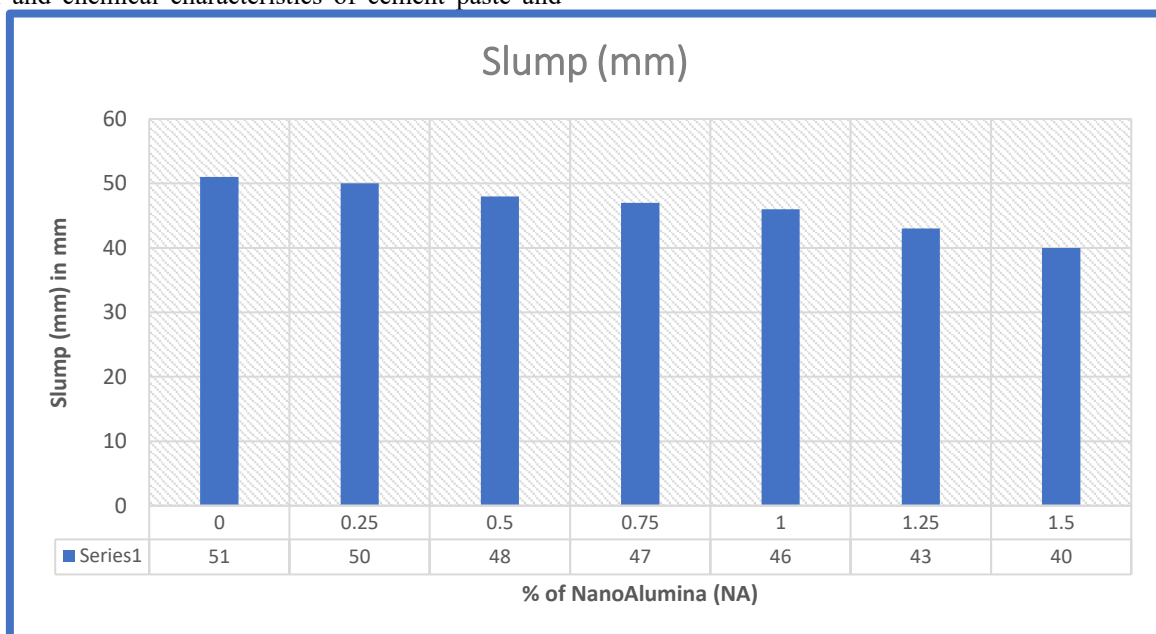


Fig. 1: Slump Value in mm at different % of NanoAlumina

- 1) The control mix (0% NA) showed the highest slump value of 51 mm, indicating maximum workability.
- 2) With the gradual increase in Nano-Alumina (NA) content, the slump values consistently decreased.
- 3) At 1.5% NA, the slump dropped to 40 mm, showing a significant reduction in workability compared to the control mix.
- 4) This reduction in slump is due to the high surface area and fine particle size of Nano-Alumina, which increases water demand and reduces fluidity.
- 5) Hence, the incorporation of Nano-Alumina leads to a loss in workability, and additional measures such as using superplasticizers may be required for practical applications when higher percentages of NA are used.

B. cube compressive strength (MPa) at Various % of Nano Alumina

MIX ID	% of Nano-Alumina (NA)	Compressive strength (MPa)			
		3day	7 Days	21Days	28Days
NC	0	23.17	43.69	54.4	67.27
NA - 0.25	0.25	33.8	48.32	56.3	71.12
NA -0.5	0.5	39	51.54	57.34	73.74
NA - 0.75	0.75	44.12	53.18	58	74.48
NA -1	1	48.12	55.99	59	77.47
NA - 1.25	1.25	49.34	58.24	62.3	76.28
NA -1.5	1.5	44	56.42	56	74.93

Table 2: Compressive strength (MPa)

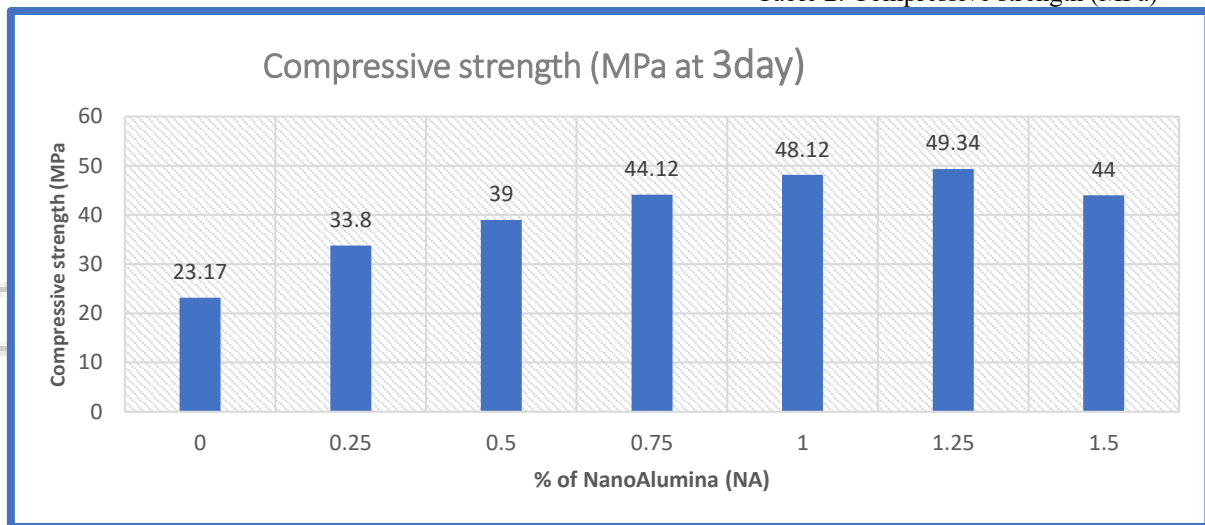


Figure 2: Compressive strength (MPa at 3 day) at various % of NA

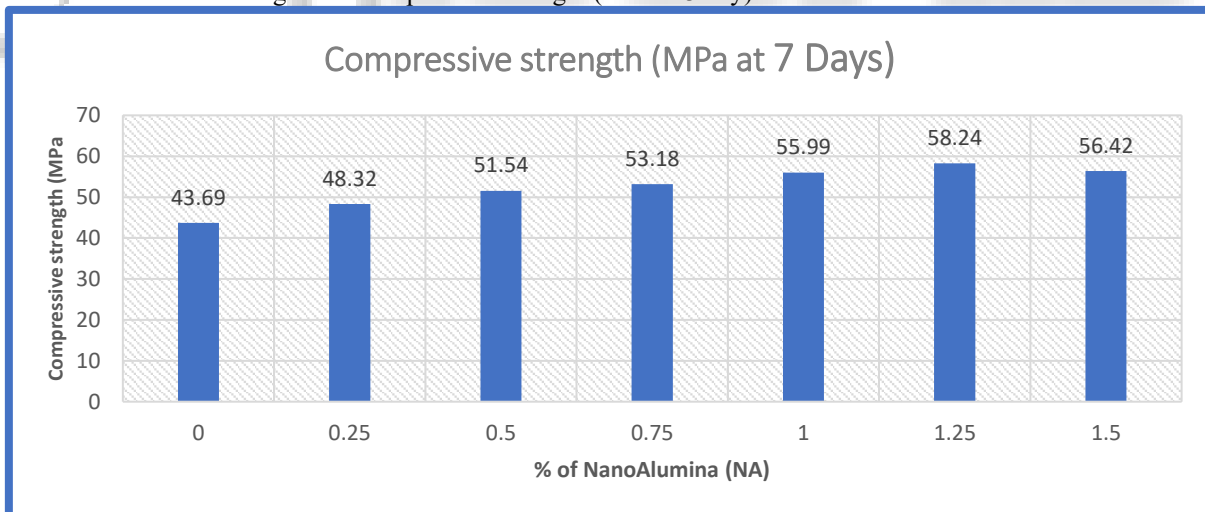


Figure 3 Compressive strength (MPa at 7 Days) at various % of NA

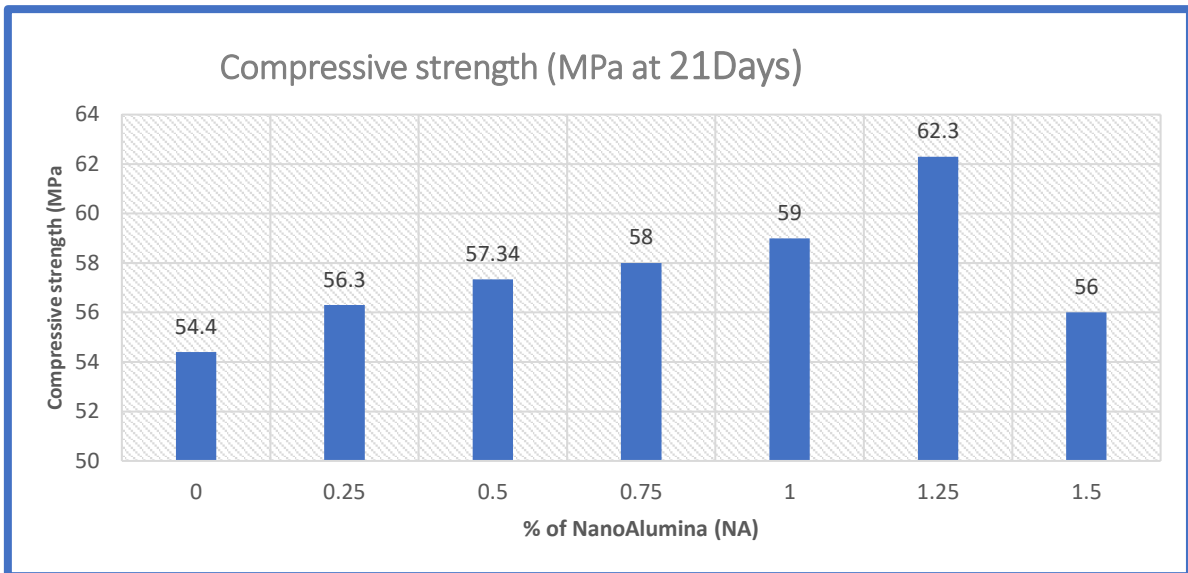


Fig. 4: Compressive strength (MPa at 21 Days) at various % of NA

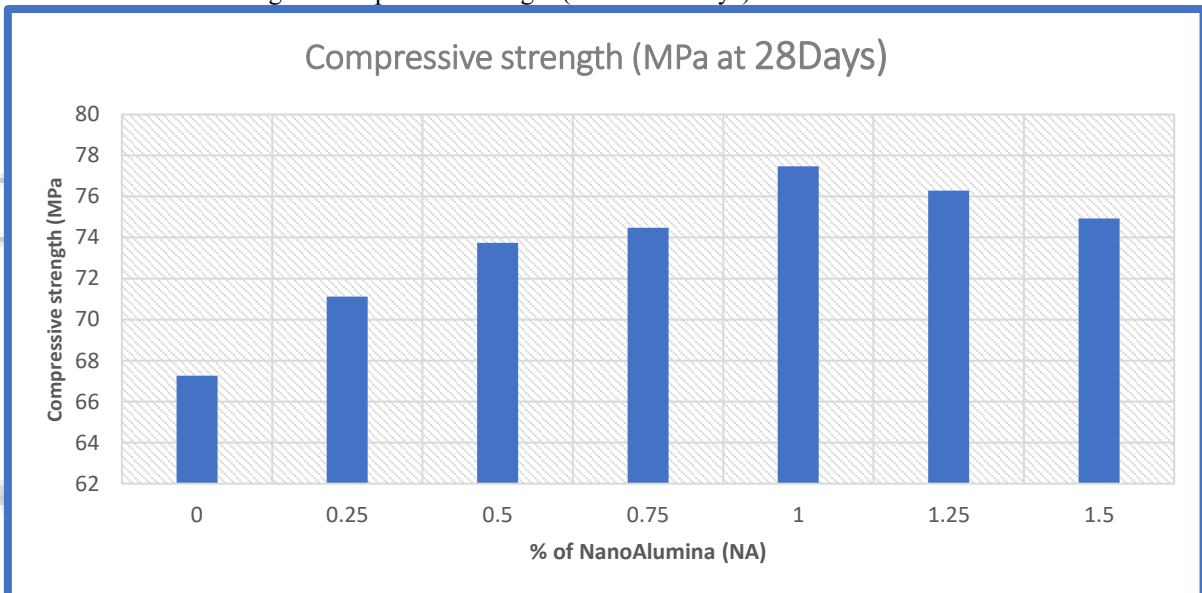


Fig. 5: Compressive strength (MPa at 28 Days) at various % of NA

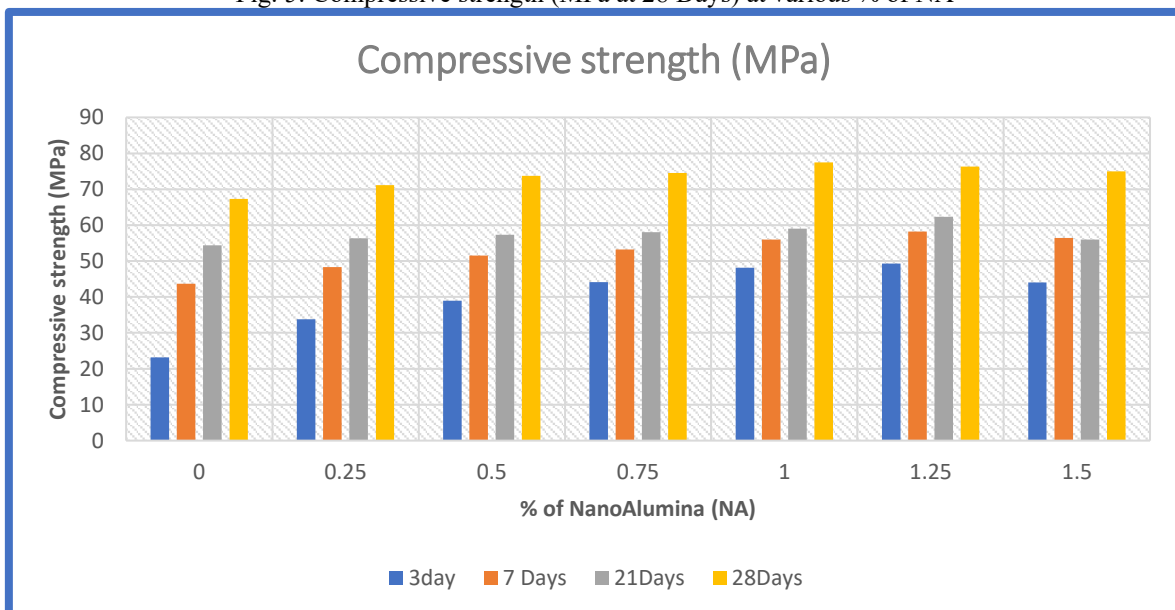


Fig. 6: Compressive strength (MPa at 7, 21, 28 Days)

- The control mix (NC) achieved compressive strengths of 23.17 MPa (3 days), 43.69 MPa (7 days), 54.4 MPa (21 days), and 67.27 MPa (28 days).
- The incorporation of Nano-Alumina (NA) significantly improved early-age as well as long-term strength. At 3 days, the strength increased from 23.17 MPa (NC) to a maximum of 49.34 MPa at 1.25% NA, showing rapid strength gain due to the nucleation and pozzolanic activity of NA.
- At 7 days, strength increased consistently up to 58.24 MPa (1.25% NA), which is about 33% higher than the control mix.
- At 21 days, the highest strength (62.3 MPa) was again recorded at 1.25% NA, whereas further increase to 1.5% NA led to a drop (56 MPa), indicating overdosing effect.
- At 28 days, the control mix reached 67.27 MPa, while the maximum strength of 77.47 MPa was achieved at 1% NA, followed closely by 76.28 MPa at 1.25% NA. Beyond this, the strength decreased slightly (74.93 MPa at 1.5%).
- Overall, the optimum dosage of Nano-Alumina lies between 1% and 1.25%, where the maximum compressive strength improvement is observed.
- Beyond this range, excess NA particles may lead to agglomeration, increased water demand, and micro-cracks, slightly reducing strength.

C. Cube Compressive Strength (MPa) at Various % of NanoAlumina & silica fume

MIX ID	% Replacement of Cement with Silica Fume	% of Nano Alumina (NA)	Compressive strength (MPa)
			28 day
NC	0	1.25	76.28
SF -5& NA-1.25	5		81.29
SF -10& NA-1.25	10		82.71
SF -15& NA-1.25	15		84.3
SF -20& NA-1.25	20		86.25
SF -25& NA-1.25	25		82.96

Table 3: cube compressive strength (MPa) at Various % of NanoAlumina & silica fume

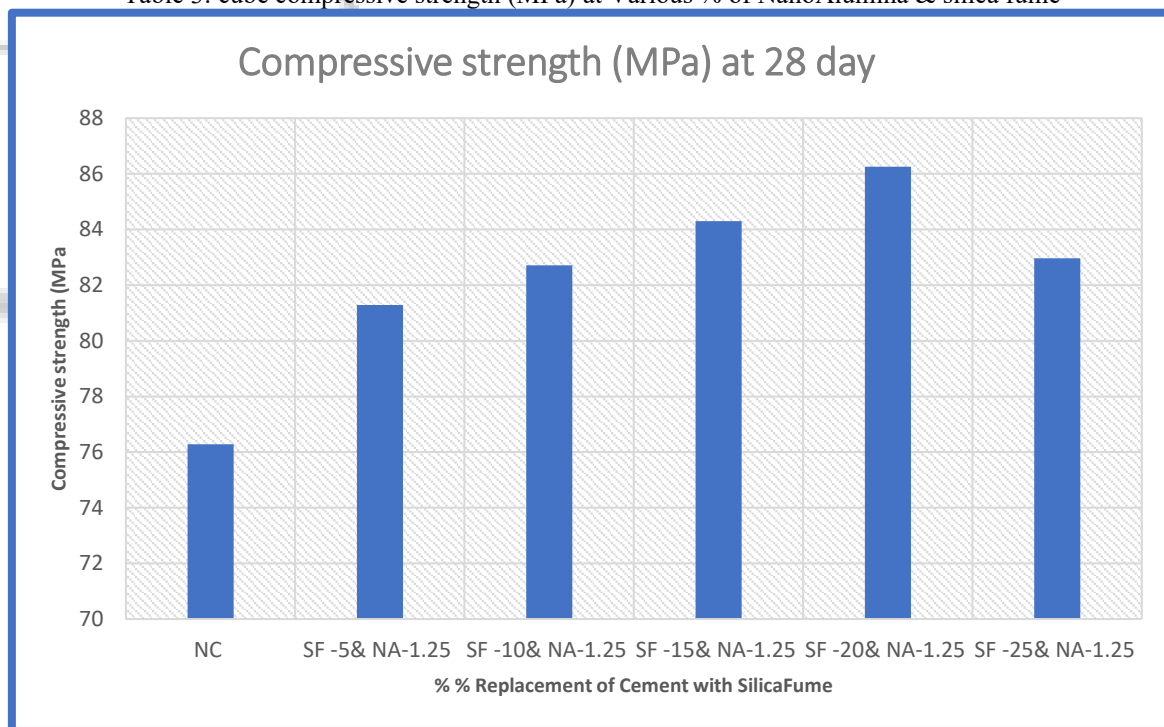


Fig. 7: cube compressive strength (MPa) at Various % of NanoAlumina & silica fume

- The reference mix with 1.25% Nano-Alumina alone (NC) achieved a 28-day compressive strength of 76.28 MPa.
- Partial replacement of cement with Silica Fume (SF) further enhanced the compressive strength significantly due to its high pozzolanic reactivity and filler effect.
- At 5% SF, the strength increased to 81.29 MPa, while further increase to 10% SF yielded 82.71 MPa.
- The maximum strength of 86.25 MPa was obtained at 20% SF with 1.25% NA, showing about a 13% improvement over the reference mix.
- Beyond this optimum level, at 25% SF, the strength dropped to 82.96 MPa, indicating that excessive replacement may lead to reduced cementitious content and poor workability, thus lowering strength.
- Overall, the results confirm that the synergistic effect of 1.25% Nano-Alumina and 20% Silica Fume provide the optimum compressive strength in the studied mixes.

V. CONCLUSION

- The slump values decreased with the increase in Nano-Alumina content, reducing from 51 mm (control) to 40 mm at 1.5% NA, indicating a loss in workability due to the high surface area of NA.
- The control mix achieved 67.27 MPa (28 days), while the addition of NA significantly enhanced strength.
- Maximum compressive strength was observed at 1% NA (77.47 MPa) and 1.25% NA (76.28 MPa), indicating an optimum range of 1–1.25% NA. Beyond this, strength decreased due to agglomeration and reduced workability.
- With Silica Fume and 1.25% NA, compressive strength further improved, peaking at 86.25 MPa with 20% SF, showing about a 28% increase compared to the control mix.

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