Flexural Behavior of Nano Silica incorporated in concrete with and Partial Replacement of Fly Ash with ANN Analysis

Dr. Ashwini.B[1], Dhanalakshmi.J[2], Eshayini.P[3], Gayathri.J[4]

[1]*Associate Professor, Dept. of Civil Engineering, E.G.S Pillay Engineering College (Autonomous), Nagapattinam, Tamilnadu, India.*

[2,3,4] *Under Graduate Student, Dept. of Civil Engineering, E.G.S. Pillay Engineering College (Autonomous), Nagapattinam, Tamilnadu, India.*

***Abstract*—This study aims to evaluate the flexural behavior of concrete through the combined application of nanosilica and partial replacement of fly ash in cementitious materials, with experimental results compared against Artificial Neural Network (ANN) analysis. By incorporating nanosilica as a supplementary cementitious material and partially substituting conventional fly ash, the research seeks to achieve significant improvements in concrete performance. A comprehensive investigation is conducted to assess the effects of nanosilica addition and fly ash replacement on the mechanical properties of concrete. The study also aims to determine the optimal replacement level for fly ash and the appropriate dosage of nanosilica, alongside identifying the most effective dispersion solution and method to ensure uniform distribution of nanosilica within the concrete matrix. Through this work, valuable insights are offered toward enhancing the mechanical performance of concrete using innovative materials and advanced techniques.Keywords: Concrete, Nanosilica, Flyash replacement, Flexural Strength, ANN**

1. INTRODUCTION

The construction industry continuously seeks innovative approaches to enhance the mechanical properties of concrete, a critical material for a wide range of infrastructure projects. This study investigates the combined effects of nano silica incorporation and partial fly ash replacement on concrete, examining their potential synergistic impact on strength and durability. The selection of OPC 53 grade cement, Class F fly ash, and Manufactured Sand (M-Sand) aligns with current construction practices that prioritize sustainability and high performance.

1.1 Concrete Properties and Composition

Concrete is a composite material composed of cement, aggregates, water, and various additives. A thorough understanding of concrete's fundamental properties and composition is crucial for evaluating the influence of nano silica and fly ash on its mechanical behavior. Ordinary Portland Cement (OPC) 53 grade, known for its high early strength and durability, is widely utilized in modern construction projects.

1.2 Cement

Cement serves as a binding agent in construction, setting and hardening to unite different materials into a cohesive structure.

Fig. 1 Cement

1.2.1 Composition of Cement

The chemical composition of cement primarily consists of key compounds formed during the clinker production process. These include calcium silicates (C_3S and C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The formation of these compounds during cement manufacturing can be represented by the following chemical reactions:

1.2.2 Types of Cement

- Ordinary Portland cement (OPC): Commonly

used in general construction.
- Portland Pozzolana Cement (PPC): Contains pozzolonic materials like flyash.
- Rapid Hardening Cement: Sets quickly and gains strength early.
- Portland Slag Cement(PSC): Includes granulated blast furnace slag.
- White Cement: Produced from raw materials low in iron and manganese.

1.3 Aggregate

Aggregates are granular materials, such as sand, gravel, or crushed stone, used in concrete mixtures.

1.3.1 Types of aggregate
- Fine Aggregates (Sand): Particles smaller than 4.75 mm.
- Coarse Aggregates (Gravel, Crushed Stone): Particles larger than 4.75mm

Fig. 2 Types of Aggregate

1.4 Admixtures

Admixtures are chemicals added to concrete to modify its properties.

Fig.3 Admixtures

1.4.1 Types of admixtures
- Water Reducers: Improve workability without increasing water content.
- Retarders: Delay setting time.
- Accelerators: Speed up setting time.
- Air-Entraining Agents: Introduce air bubbles to improve freeze-thaw resistance.
- Super plasticizers: Significant water reduction with improved workability.

1.4.2 Functions of admixture
- Workability Enhancement: Improves the ease of handling and placing concrete.
- Setting Time Control: Alters the time it takes for the concrete to set.
- Strength Enhancement: Can increase early or final strength.

1.5 Fly Ash

Fly ash is a byproduct of coal combustion in power plants, and when mixed with cement, it enhances concrete properties.

Fig. 4 Flyash

1.5.1 Properties of flyash
- Pozzolonic: Reacts with lime to form compounds contributing to strength.
- Fineness: Similar to cement, affects surface area.
- Chemical Composition: Influences reactivity and strength development.
- Spherical Particle Shape: Enhances workability.

1.5.2 Benefits of flyash
- Improved Workability: Reduces water demand.
- Increased Durability: Enhances resistance to sulphate attack and alkali-aggregate reaction.

1.6 Nano Particles

Nano particles in concrete are very small particles, often less than 100 nanometers in size, used to modify concrete properties.

1.6.1 Major types of nano particle
- Nano Silica (Nano-SiO2): Enhances strength and durability.
- Nano Titanium Dioxide (Nano-TiO2): Provides self-cleaning properties.

Fig.5 Nano SIlica

1.6.2 Properties of nano particle

- High Surface Area: Allows for better interaction with cement particles.
- Reactivity: Improves pozzolonic activity.
- Uniform Dispersion: Enhances the overall performance.

1.6.3 Applications of nanoparticles

- Strength Enhancement: Improves mechanical properties.
- Durability Improvement: Increases resistance to chemical and environmental factors.
- Self-Healing Properties: Repairs micro cracks at a nanoscale level.

1.6.4 Significance of Flyash in Concrete

Class F Fly Ash

Class F fly ash, a by-product of coal combustion, has emerged as a prominent supplementary cementitious material in concrete production. Its pozzolanic properties enhance workability, reduce the heat of hydration, and improve long-term strength development. In this study, 35% of the cement content is replaced with fly ash, aligning with sustainable construction practices aimed at minimizing environmental impact while enhancing concrete performance.

1.7 Nano Silica in Construction Materials

Nano silica, characterized by its ultrafine particle size, exhibits both pozzolanic and pozzolanic-hydraulic properties. Its incorporation into concrete has demonstrated significant improvements in strength, durability, and impermeability. In this study, 1.75% nano silica is incorporated to investigate its synergistic effects with fly ash, aiming to fully exploit the potential of these supplementary materials to enhance the mechanical properties of concrete.

1.8 Effect of Fly Ash Replacement on Concrete Properties

Previous research has demonstrated that the partial replacement of cement with fly ash can significantly enhance the properties of concrete. The interaction between fly ash and cementitious materials improves workability, reduces permeability, and increases compressive strength. Building on this foundation, the present study examines the effects of replacing 35% of cement with fly ash, combined with the addition of nano silica, to evaluate their synergistic influence on the overall performance of concrete.

1.9 Poly-Carboxylic Ether (PCE) Solutions

Poly-Carboxylic Ether (PCE) solutions are widely utilized as superplasticizers in concrete to enhance workability without compromising strength. In this study, PCE is selected for dispersing nano silica, ensuring a uniform distribution within the concrete matrix. Previous research has demonstrated the effectiveness of PCE in improving the dispersion of nanoparticles, consequently enhancing the mechanical and durability properties of concrete.

1.10 Magnetic Stirring for Nano Silica Dispersion

Achieving homogeneous dispersion of nano silica is critical for realizing its benefits in concrete. Magnetic stirring has been recognized as an effective method for dispersing nanomaterials in cementitious matrices. This section reviews studies that highlight the advantages of magnetic stirring in attaining uniform nanoparticle distribution, thereby improving the performance of nano-enhanced concrete.

1.11 Reaction Behavior

Silicon dioxide nanoparticles are chemically stable, acid-resistant, and do not react with water. Their formula, SiO_2, classifies them among acidic, glass-forming oxides. They interact with alkalis and basic oxides at elevated temperatures, indicating the material's excellent dielectric properties. Silicon dioxide nanopowders are produced through the chemical co-precipitation method, yielding ultra-stable aqueous suspensions compatible with biological buffers such as phosphate-buffered saline (PBS).

1.12 Artificial Neural Networks (ANN)

Artificial Neural Networks (ANN) are advanced computational models inspired by the human brain's network of neurons. They are capable of recognizing complex patterns and relationships within data, making them an effective tool for modeling nonlinear systems where traditional analytical methods fall short. In recent years, ANN has been increasingly applied in the field of civil engineering, particularly in predicting the properties and performance of concrete and other construction materials.

1.12.1 Working Principle of ANN

An ANN consists of an input layer, one or more hidden layers, and an output layer. Each layer contains nodes (or neurons) interconnected by weights, which are adjusted during the training process to minimize prediction errors. Learning occurs through algorithms such as back propagation, where the network iteratively updates its weights based on the error between predicted and actual outcomes.

The general steps involved in building an ANN model are:

- Data Collection: Gathering experimental data related to input parameters (e.g., cement content, fly ash content, water-cement ratio, nanosilica percentage) and corresponding outputs (e.g., compressive strength, durability indices).
- Pre-processing: Normalizing or scaling the data to ensure effective learning.
- Model Training: Feeding input data into the ANN and adjusting weights based on output error.
- Validation and Testing: Evaluating the model's performance on unseen data to avoid over fitting and ensure generalization.

1.12.2 Applications of ANN in Concrete Research

ANN models have been widely used for:

- Predicting Mechanical Properties: Such as compressive strength, split tensile strength, and flexural strength of conventional and high-performance concretes.
- Modelling Durability Characteristics: Estimating resistance to acid attack, sulphate attack, chloride penetration, and carbonation.
- Optimizing Mix Designs: Identifying optimal proportions of cementitious materials, fibers, nano-additives, and aggregates for desired performance.
- Assessing Environmental Impacts: Predicting CO_2 emissions reductions when using supplementary cementitious materials like fly ash and nanosilica.

1.12.3 Advantages of ANN in Concrete Technology

- Nonlinear Modeling: Effectively captures complex relationships between input and output variables without requiring explicit physical models.
- High Prediction Accuracy: When properly trained, ANN models can predict concrete behavior with high reliability.
- Time and Cost Efficiency: Reduces the need for extensive experimental work by providing preliminary predictions.
- Adaptability: Can be easily retrained or updated as new experimental data becomes available.

1.12.4 Limitations of ANN

- Data Dependency: Requires a large, diverse, and high-quality dataset for accurate modeling.
- Overfitting Risk: May overfit training data if not properly validated.
- Interpretability: Acts as a "black box," making it difficult to interpret how specific input variables influence the output.

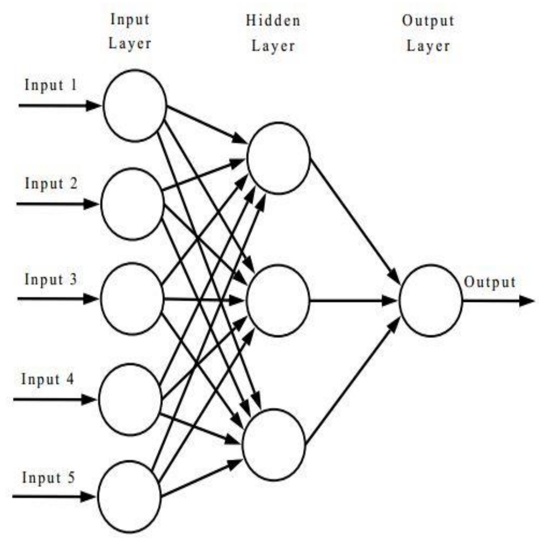

Fig. 6 ANN working model

2. LITERATURE REVIEW

Anjeza Alaj’s 2023 research affirms the viability of sustainable concrete by replacing 30% of cement with low-CaO content Class F fly ash, showcasing positive environmental and quality outcomes over 600 days of testing.

In 2023, M.C.K. Jamenraja’s experiment enhances concrete properties by incorporating polypropylene fibers (0.2–0.4%), alccofine (15%), and nanosilica (1%), resulting in improved compressive strength, modulus of elasticity, flexural strength, acid resistance, and durability. This novel material promotes ductile failure, leading to enhanced concrete durability and serviceability.

Abhishek Kumar's 2023 study demonstrates that incorporating nanosilica up to 3% improves both mechanical and durability properties of concrete, with increased compressive strength, significant pozzolanic activity, refined pore structure, and potential for reducing environmental pollution by lowering CO_2 emissions during hydration.

In 2022, Rajkumar's study highlights the effectiveness of colloidal nanosilica, with up to 3% substitution for cement, enhancing mechanical and durability properties while improving microstructure and catalyzing pozzolanic activity in high-performance concrete.

In 2021, Kanta Rao's research explores the use of fly ash as a cost-effective alternative to cement in concrete, revealing that a 30% replacement enhances compressive, split tensile, and flexural strengths by 13%, 9%, and 13%, respectively. Finer particles and pozzolanic action contribute to increased strength, especially after optimal replacement.

Abhilash's 2021 review emphasizes the environmental impact of concrete production and highlights the potential for enhanced durability by incorporating small amounts of nanosilica, which modifies the nanostructure of cementitious materials, leading to improved mechanical properties and durability.

In 2021, B. Ashwini and Vidiveli demonstrated enhanced durability properties in concrete through partial cement replacement with fly ash (20%) and incorporation of Multi-Walled Carbon Nanotubes (MWCNTs) at 0.025%, 0.05%, and 0.075%, analyzed via acid, chloride, and sulfate resistance tests.

In 2020, B. Ashwini and Vidiveli further researched incorporating MWCNTs (0.025%, 0.050%, 0.075%) and partial cement replacement with fly ash (20%), assessing mechanical properties through compression, split tensile, and flexural tests. Their 2020 study emphasized the importance of nanoparticle dispersion for enhancing the elastic modulus after 28 days of curing.

Sridhar's 2019 study reveals that incorporating 3% nanosilica by weight in high-performance concrete accelerates early-stage hydration, improves water permeability resistance, enhances microstructure, and acts as a filler material, promoting pozzolanic activity for superior concrete quality.

Mohana Sundari's 2019 project investigates the impact of nanosilica on reinforced beams, assessing compressive and flexural strength, workability, and comparing results with conventional beams, aiming to optimize material performance with supplementary cementitious materials.

B. Tiprajat's 2019 study suggests that using activated fly ash as a partial replacement for cement can improve the strength and sustainability of concrete structures.

Jaishankar's 2018 research demonstrates that adding nanosilica to M70 high-performance concrete improves mechanical strength and enhances durability, supported by positive results from alkalinity and water absorption tests, especially at higher nanosilica replacement levels.

In 2017, O.M. Suganya found that colloidal nanosilica enhanced concrete properties, even with varying levels of fly ash substitution, resulting in increased mechanical strength and improved sustainability.

Prasath's 2017 study investigates the pozzolanic nature of nanosilica and silica fume, examining their impact on mechanical properties in M30 and M40 concrete, and addressing corrosion issues through accelerated corrosion tests on columns with varying silica fume and nanosilica percentages.

C. Karthikeyan's 2017 research explores advancements in concrete technology, incorporating silica fume and nanosilica as partial cement replacements in M30 and M40 grades. The study shows improved mechanical and durability properties and tackles corrosion concerns through optimized usage of these materials.

In his 2017 review paper, Rishab Joshi investigated the effects of partial cement replacement with fly ash (0%, 10%, 20%, and 30%) on M20 grade concrete, finding that workability and durability increased with fly ash content, though compressive strength decreased, with 30% identified as the optimal replacement level.

R.D. Padhye's 2016 research explored the optimal use of fly ash as a partial cement replacement in high-grade concrete. Testing various percentages and curing periods, the study determined the best balance between strength, cost, and applicability for each grade.

In 2016, Jayanta Chakraborty extensively analyzed the effects of fly ash as a partial replacement for cement in high-grade concrete, investigating compressive strength variations at different percentages and curing durations to find the optimum, acceptable, and economical usage.

Mohd Mufasshir Alam Shah's 2016 study highlights the revolutionary use of nanomaterials, particularly nanosilica, in concrete. His findings demonstrate enhancements in compressive strength, split tensile strength, flexural strength, impact resistance, and modulus of elasticity for M50 grade concrete, offering a sustainable alternative to traditional methods.

In 2015, M. Bala Vinayag's review explored the utilization of fly ash, a major waste material from thermal power plants, as a binding material in geopolymer concrete. By incorporating nanosilica and silica fume, the study enhanced properties and real-world applications, providing an effective solution to reduce environmental impact by repurposing fly ash.

Finally, Rafat Siddique's 2003 study reveals that incorporating high volumes of Class F fly ash (40%, 45%, and 50% replacement) initially reduces short-term strength but significantly improves compressive, tensile, and flexural strengths, modulus of elasticity, and abrasion resistance after 91 and 365 days. This suggests suitability for up to 50% cement replacement in precast elements and reinforced concrete construction.

Akbarian et al. (2012) discuss the application of Artificial Neural Networks (ANN) to predict the compressive strength of concrete. The study shows that ANN models, trained with parameters like water-cement ratio, aggregate type, and curing time, can more accurately predict concrete strength than traditional regression methods, offering a promising tool for concrete mix optimization.

Bousselham et al. (2017) focus on the use of ANN to predict various concrete properties, such as compressive strength, elastic modulus, and durability factors. Their research highlights the potential of ANN to model the relationship between mix design variables and concrete performance, significantly improving the accuracy and efficiency of concrete mix design.

Kumar and Rajesh (2020) explore the use of ANN for modeling concrete durability, specifically predicting properties like chloride permeability and sulfate resistance. The study demonstrates that ANN can effectively forecast the long-term durability of concrete based on mix composition and environmental conditions, helping to optimize concrete performance in challenging environment.

3. EXPERIMENTAL INVESTIGATION

Flexural strength tests were conducted on the cured concrete prisms as per IS 516:2021 standards using a flexural testing machine. The double-point loading method was adopted to determine the flexural strength of the specimens.

Additionally, preliminary tests were carried out on individual materials before mix preparation. The standard consistency and setting time of cement were tested as per IS 4031 (Part 4 and 5), while sieve analysis of fine aggregates and coarse aggregates was conducted as per IS 2386 (Part 1). These tests ensured that the quality of materials conformed to the specifications required for high-performance concrete production

Based on the literature review, the method and quantity of concrete were finalized. The control mix, and mix with Nano silica partial replacement of cement using Class F Fly Ash to evaluate the composite properties of the concrete. The concrete specimens were cast for Flexural Strength test prisms (100mm x 100mm x 500mm) were used for the testing. The flexural testing of the prisms was carried out using a flexural testing machine. The tests were conducted in accordance with the relevant codal provisions. Figures7 illustrate the casting of concrete prism.

After the testing of specimens, the results were computed based on the conventional procedure. The Flexural strength for the prisms were computed with codal formula. The figure 8 shows the shows the Flexural Testing results of Prism specimens.

Fig. 7 Casting of Prism

Fig. 8 Specimens under Curing

Table 1 Comparison of Experimental and ANN Results of Flexural Strength

% of Nano Silica	Experimental Results (MPa)	ANN Results (MPa)
0.15	9.8	9.7
0.25	10.1	10.0
0.35	10.3	10.2

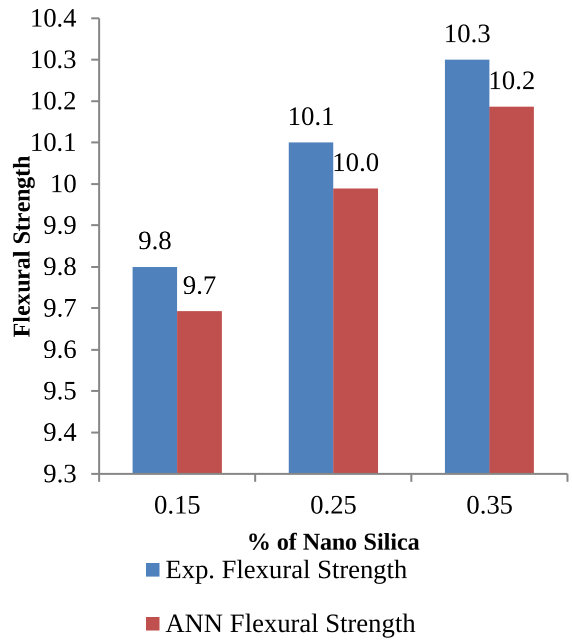

Fig. 9 Comparison of Flexural Strength

4. CONCLUSIONS

- A significant enhancement in concrete strength was observed with the incorporation of Nano Silica.
- The strength increase was gradual, corresponding to the increase in nanosilica content in the concrete.
- The mix with 0.35% of Nano silica exhibited the most promising results, showing the highest values in flexural tests.
- It was noted that the strength improved as the void content in the concrete decreased.
- The results obtained in the Artificial Neural Networking were observed much closer to the experimental results.

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