Civil Engineering and Architecture 12(2): 866-872, 2024 http://www.hrpub.org
DOI: 10.13189/cea.2024.120215

Effect of Nano-Silica on the Mechanical Characteristics of Ternary Blended Concrete

Myakala Vamshikrishna*, Ilango Sivakumar

Department of Structural Engineering, Annamalai University, Chidambaram, India

Received August 12, 2023; Revised October 23, 2023; Accepted November 14, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Myakala Vamshikrishna, Ilango Sivakumar , "Effect of Nano-Silica on the Mechanical Characteristics of Ternary Blended Concrete," Civil Engineering and Architecture, Vol. 12, No. 2, pp. 866 - 872, 2024. DOI: 10.13189/cea.2024.120215.*

(b): *Myakala Vamshikrishna, Ilango Sivakumar (2024). Effect of Nano-Silica on the Mechanical Characteristics of Ternary Blended Concrete. Civil Engineering and Architecture, 12(2), 866 - 872. DOI: 10.13189/cea.2024.120215.*

Abstract The imperative to reduce Carbon dioxide (CO_2) emissions, a principal driver of global warming and climate change, has prompted a paradigm shift in construction materials research. In this context, the utilization of mineral compounds as an innovative alternative to traditional cement is gaining increasing significance. This study introduces a novel approach to concrete production, emphasizing the environmental and sustainability advantages of replacing conventional constituents with diverse industrial by-products. Recent years have witnessed substantial interest in the integration of Supplementary Cementing Materials (SCMs) and alternative fine aggregates in concrete formulation. The core objective of this research is to investigate the compressive behaviour of ternary blended concrete incorporating nano-silica, M-sand, and fly ash as partial substitutes for cement and fine aggregate. The experimental methodology involves the development of multiple concrete compositions, wherein the nano-silica content varies while maintaining a consistent 30% fly ash and 100% M-sand ratio. The test specimens undergo a comprehensive evaluation of their compressive strength. The findings of this study reveal a significant breakthrough in enhancing the properties of ternary blended concrete through the incorporation of nano-silica. This innovative approach, blending nano-silica with other SCMs, holds the potential to revolutionize the development of high-performance, high-strength concrete. As the research suggests, further exploration is crucial to optimize ingredient proportions, curing conditions, and the long-term performance of ternary blended concrete enhanced with nano-silica. Notably, the results indicate that the addition of nano-silica substantially accelerates early-age strength development in concrete. This phenomenon can be attributed to its pozzolanic reactivity and its capacity to facilitate cement hydration. Additionally, the substitution of natural river sand with M-sand demonstrates favourable outcomes, particularly in terms of workability and strength characteristics. In sum, this study underscores a pioneering approach to sustainable concrete design, presenting the potential for substantial reductions in CO_2 emissions, while simultaneously achieving superior material performance.

Keywords Fly Ash, Ternary Blended Concrete, Colloidal Nano Silica, Cement; Admixtures

1. Introduction

In recent years, the construction industry has witnessed a growing reliance on cement as the primary raw material for concrete production [1]. This trend is driven by the ever-increasing global demand for cement, surpassing 4.3 billion tonnes annually [2]. However, the energy-intensive nature of cement manufacturing is a significant contributor to the release of CO_2 into the atmosphere [3], resulting in approximately 13.5 billion metric tonnes of CO_2 emissions [4]. Moreover, the depletion of river sand in various countries, including India, has led to strict excavation limitations [5]. Consequently, engineers are actively seeking alternative cementitious materials that can enhance fresh and hardened state properties, improve durability, and reduce reliance on both cement and natural sand in concrete [6].

The existing body of research highlights the potential of industrial by-products with pozzolanic characteristics, such as Fly ash (FA), Metakoline (MK), Granulated blast furnace slag (GGBS), Rice-husk ash (RHS), Mine waste (MW), Silica-fume (SF), Red mud (RM), among others, in enhancing fresh, mechanical, and durability properties when replacing cement in concrete, as compared to conventional methods [7]. Recent research has shown a growing interest in the application of nanotechnology, particularly nano silica (CNS), in the construction industry, owing to its high specific surface area [8]. CNS, with its significant pozzolanic properties, has demonstrated the ability to improve the physical and mechanical characteristics of concrete [9]. It's worth noting that CNS facilitates a pozzolanic reaction with unreacted calcium hydroxide crystals, leading to the production of additional C-S-H gel in concrete. Additionally, the nanoscale particles of CNS can occupy minuscule pores, thereby enhancing the density of the Interfacial Transition Zone (ITZ) in concrete [10]. CNS can be incorporated into concrete, mortar, and cement paste either as a cement substitute or an additional component [11], consistently enhancing both fresh and hardened concrete performance. As natural sand resources dwindle in many regions and environmental restrictions limit sand dredging, manufactured sand (MS) has emerged as a suitable alternative for river sand in concrete applications [12].

The current study aims to develop Ternary Blended Concrete (TBC) by replacing 30% of cement with a combination of FA and varying percentages (0%, 0.5%, 1%, 2%, and 3%) of CNS, while completely substituting natural sand with 100% MS. This research presents the results of mechanical tests conducted on TBC mixes and investigates the impact of these admixtures on the initial and long-term properties of TBC. The primary objective is to enhance TBC and explore its mechanical characteristics, ultimately contributing to the progression of sustainable construction practices. The traditional reliance on Ordinary Portland cement (OPC) and natural sand in concrete formulations has long been pivotal in ensuring the material's mechanical strength. However, the environmental consequences associated with their production have spurred the quest for more sustainable alternatives that can maintain concrete's mechanical and durability properties. While previous research predominantly focused on the combined use of FA, CNS, and MS in concrete mixes to enhance their properties, a noticeable research gap exists regarding the simultaneous utilization of multiple pozzolanic materials, particularly FA and CNS, as partial cement replacements, alongside the complete replacement of natural sand with MS. This study endeavors to bridge this gap by delving into the mechanical properties of M30 grade concrete, with a specific emphasis on how multi-material approaches can offer viable solutions for mitigating environmental pollution.

2. Materials and Nomenclature

2.1. Mix Proportions

Various mixtures were prepared using OPC of 53 grade in accordance with the BIS:12269–2013 [12] requirements. The cement exhibits a fineness modulus of 3.24%, a specific gravity of 3.14, a standard consistency of 30%, an initial setting time of 30 minutes, and a final setting time of 600 minutes. The fine aggregate used in this study consisted of locally sourced river sand that was able to pass through a 4.75 mm screen. According to the Bureau of Indian Standards BIS:383 – 2016 [13], the sand falls inside grading zone II. It has a fineness modulus of 2.79%, a water absorption rate of 1.25%, and a specific gravity of 2.47. The coarse aggregate used in this study consisted of locally sourced crushed rock that met the specifications given in BIS:383 – 2016 [13], with a particle size less than 20 mm. MS, a by-product obtained from the process of crushing granite in the industry, has a distinctive angular and coarse texture. The material exhibits a fineness modulus of 2.79, indicating that its average particle size ranges between the sieve diameters of 0.6 mm and 1.18 mm. The product adheres to the specifications specified in Zone II as indicated in BIS 383-2016 [13]. The specific gravity of the coarse aggregate is 2.6, indicating its relative density compared to water. Additionally, the fineness modulus of the coarse aggregate is 12.5%, which measures the particle size distribution. Water with a pH level ranging from 7 to 8 was used in the experiment. Furthermore, we included mineral mixes such as FA and CNS. The FA used in this study was obtained from the Dr. NTR Vijayawada Thermal Power Station (VTPS) located in Vijayawada, Andhra Pradesh. The material in concern is classified as a low calcium FA (Class F type) according to the BIS:3812 – 2013 [14] standard. It has a fineness modulus of 1.3% and a specific gravity of 1.62. The CNS solution, which consists of nanometric silica particles embedded in water, was procured from Bee-chems Chemicals located in Kanpur. In this study, the superplasticizer CONPLAST-SP430 was used. This particular superplasticizer is a mix based on sulfonated naphthalene polymer, which is free of chlorides and conforms to the specifications provided in ASTM C494-2017 [15].

2.2. Nomenclature

CM	Concrete Mix
F0M100	Concrete Mix with 100% Msand
F20M100	Concrete Mix with 20% FA and 100% MS
F30M100	Concrete Mix with 30% FA and 100% MS
F40M100	Concrete Mix with 40% FA and 100% MS
F30N1M100	Concrete Mix with 30% FA, 1% CNS and 100% MS
F30N2M100	Concrete Mix with 30% FA, 2% CNS and 100% MS
F30N3M100	Concrete Mix with 30% FA, 3% CNS and 100% MS

3. Research Methodology

3.1. Mix Proportions

For this study, the concrete mix design used was M30 grade, in accordance with BIS:10262 – 2019 [16]. The specific details of the mix design can be found in Table 1. To partially replace the cement content, a combination of FA and CNS was employed. The FA was maintained at 30%, as appropriate. A range of 0% to 3% by weight of the cement was used as the CNS content. Water and CNS were combined before being applied to the concrete. It was examined the process by which CNS affected the mechanical and durability characteristics of TBC. An average water to binder ratio of 0.43 was maintained throughout the mix formulation. Table 1 lists the mix design for TBC and standard concrete mix (CM) respectively.

Table 1. Composition ratio of mix for M30 grade of concrete

Materials	Cement	Fine Aggregate	Coarse Aggregate	Water
Quantity (kg/m^3)	375.542	670.16	1150.968	157.72

Mix Proportion = 1: 1.78: 3.06: 0.42

3.2. The Process of Casting and Curing

All concrete mixtures were prepared under atmospheric conditions at a controlled temperature of 27 ℃ ± 2 ℃. The process involved dry blending cement, FA, fine aggregate, and coarse aggregate for approximately 3 minutes. Subsequently, water, CNS, and super-plasticizer were mixed for 2 to 3 minutes before being combined with the dry mix. Cube specimens of size 150mm × 150mm × 150mm. After 24 hours, these samples were removed from their respective moulds, and kept in water curing at ambient temperature. Figure 1 represents the mixing, casting and curing of concrete specimens.

Figure 1. Mixing, Casting and Curing of Moulds

3.3. Experimental Methodology

Following the guidelines provided in the BIS publication, the compressive strength of concrete was evaluated. BIS:516 – 1959 [17] was reaffirmed in 2013. Concrete achieves almost 90% of its target compressive strength after a 28-day period, after which the rate of strength development significantly diminishes. The analysis of literature indicates that fly ash-based concrete has the potential to exhibit higher compressive strength compared to ordinary concrete over an extended time of curing. Hence, in the current investigation, compressive strength evaluation was conducted at curing periods of 7, 28, and 90 days. The cubic specimens, measuring 150mm × 150mm × 150mm, were positioned between the steel plates without any additional compaction. A continuous load increase was applied at a rate of 1.4 N/mm ^{2}per minute until the point of cube failure. The highest load recorded on the dial during this test was duly documented. For a visual representation of the compression testing process and tested specimen, as shown in figures 2 (a) and 2 (b).

Figure 2. (a) Compression test on cube specimens

Figure 2. (b) Specimen after compression testing

4. Results and Discussions

4.1. Evaluation of Optimum Percentage of FA

To find the most suitable percentage for OPC replacement with FA, we replaced cement with FA at various percentages, namely 10%, 20%, 30%, and 40%. Furthermore, we completely replaced natural sand with MS, resulting in a 100% replacement. Figure 3 illustrates the results graphically.

The graph displayed illustrates the assessment of the optimal FA proportion for substituting cement in concrete. The strength development in FA concrete primarily results from the pozzolanic reaction, with a significant increase noted after a curing period of 28 days. FA is a byproduct of coal combustion, characterized by its high silica and alumina content and the presence of separated, glassy particles [18]. When FA replaces a portion of cement in concrete, it undergoes a chemical reaction with the calcium hydroxide (lime) produced during cement hydration [19]. This pozzolanic reaction involves the interaction of silica and alumina from FA with calcium hydroxide, resulting in the formation of supplementary cementitious compounds, namely calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) [20]. These compounds play a crucial role in creating a denser and more unified microstructure within the concrete.

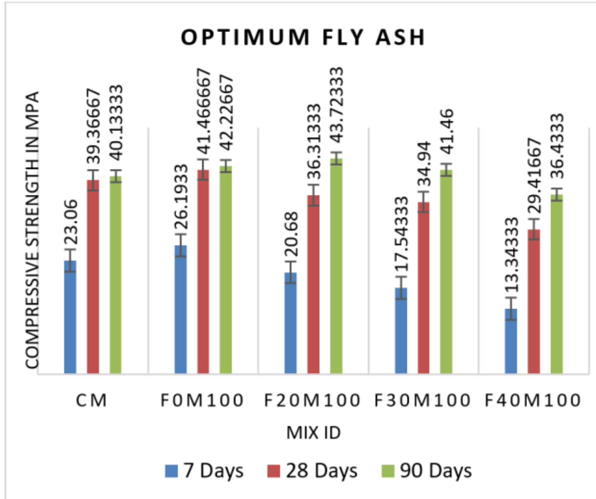

Figure 3. A graphical representation depicting the optimal proportion of fly ash content

In the initial curing stages, the strength development primarily depends on cement hydration [21]. Nevertheless, as the curing process continues, the significance of the pozzolanic reaction becomes more pronounced [22]. The continued interaction between FA and calcium hydroxide leads to a gradual strength enhancement beyond the initial curing period, resulting in improved compressive strength at 90 days and beyond, similar kind of results were observed in the experimental investigation done by A. N. Reddy et al. [7,11]. Besides bolstering the concrete's strength, the pozzolanic reaction also enhances its long-term durability and resistance to chemical attacks, making FA a valuable and beneficial addition to various concrete mixes in construction applications [24].

Noteworthy findings from our experimentation reveal that the concrete mix with a 20% FA replacement for cement demonstrates higher compressive strength during the 90-day curing period. Similarly, the mix with 30% FA content exhibits nearly equivalent compressive strength to conventional concrete at 90 days, whereas the mix with 40% FA content falls short of achieving the target strength. Consequently, the concrete mix with 30% FA content has been selected for further investigation based on these results.

4.2. Compressive Strength of Nano Silica Concrete

In order to maintain a consistent FA content of 30%, we systematically substituted the remaining cement with CNS at varying proportions of 1%, 2%, and 3%, while the remaining portion was substituted with MS. The graphical representation of these results is presented in Figure 4.

The results obtained from our experimentation provide valuable insights into the performance of TBC mixes with CNS when compared to standard concrete mixes. It is evident that the compressive strength of TBC specimens experienced a noteworthy improvement, particularly when up to 2% of the cement content was replaced with CNS, as indicated by the data presented in references [22]. This outcome underscores the positive influence of CNS on the compressive strength of the concrete.

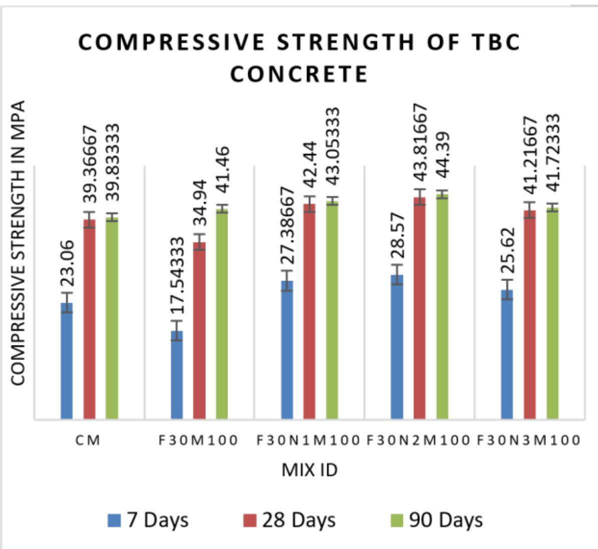

Figure 4. A graphical representation depicting the compressive strength of TBC concrete

However, it is worth noting that there was a slight decline in compressive strength when the CNS concentration exceeded this 2% threshold [21]. This observation implies that while the addition of CNS up to 2% contributes to enhanced strength, higher proportions may not yield the same benefits or may even have a diminishing effect on the concrete's compressive strength. These findings raise important considerations for optimizing the use of CNS in TBC, balancing the potential for strength improvement with the practicality and cost-effectiveness of incorporating this material in concrete production.

The observed enhancements in early-age compressive strength can be primarily attributed to the accelerated hydration process facilitated by the inclusion of CNS [22]. This trend remains consistent at both 28 and 90 days of curing. Our results consistently indicate that the addition of CNS and FA contributes to improved compressive strength compared to conventional concrete mixes [23]. In contrast to the compressive strength observed at 28 days, there is minimal change in strength after 90 days of curing. Our findings reveal that the most significant percentage increase in strength occurs after 7 days of curing, in comparison to other curing intervals [24].

These results suggest that CNS serves a dual role by acting as both a filler to increase the nanostructure density of concrete and as an activator in the hydration process. Consequently, it leads to the rapid development of early-age compressive strength in TBC [15]. However, when the addition of CNS exceeds 2%, we observe a reduction in strength. This can be attributed to an excessive leaching of CNS particles, surpassing the available liberated lime that can participate in the hydration process [22]. As a result, the bonding of pores weakens. It's worth noting that FA and CNS primarily function as cement replacements to fill voids in the matrix and contribute to density but do not substantially participate in the hydration process. In all cases considered, the incorporation of FA and CNS consistently enhances compressive strength compared to traditional concrete mixes [24]. similar kind of results were observed in the experimental investigation done by A. N. Reddy et al., and Kumar, Akash et al. [11, 23].

In conclusion, the incorporation of CNS, in tandem with FA, showcases promising results for improving the compressive strength of TBC, particularly in the early stages of curing. However, the proportion of CNS must be carefully controlled to avoid diminishing returns and maintain the integrity of the concrete structure. These findings emphasize the significance of proper material selection and proportioning in designing high-performance concrete blends for various applications. Further investigation and analysis are essential to delve deeper into the mechanisms underlying these observed effects and to optimize the use of these supplementary materials in concrete production.

5. Conclusions

Based on the results of the experimental study on Ternary Blended Concrete mixtures, the following conclusions have been derived:

- The combination of FA and CNS, along with MS, has significantly improved the particle packing and pore structure of the concrete. This improvement has led to a notable enhancement in the compressive strength of the concrete.
- Notably, the mix with 20% FA replacement for cement exhibits higher compressive strength during the 90-day curing period. Similarly, the mix containing 30% FA content shows nearly equivalent compressive strength to conventional concrete at 90 days, while the mix with 40% FA content falls short of achieving the target strength. Consequently, the mix with 30% FA content is chosen for further investigations.
- In comparison to conventional concrete mixes at all ages, Ternary Blended Concrete has enhanced properties because to the presence of Colloidal Nano Silica. Up to a 2% CNS replacement, the strength was shown to improve; beyond that, it marginally decreased but still exceeded the standard concrete mix. The development of hydrated products in the presence of colloidal nano silica in the concrete may be the cause of this increase in strength.

- It has been determined that the optimal amount of CNS is 2%, as this level enhances the pozzolanic reactivity of Ternary Blended Concrete.
- The highest compressive strength of Ternary Blended Concrete was achieved in the sample containing 30% FA and 2% CNS, totally 32% replacement for cement, along with 100% M-sand replacement for fine aggregate. The better performance is related to CNS's larger specific surface area and pozzolanic activity, which cause a considerable amount of C-S-H gel to be produced and encourage the development of a more compact concrete structure, which improves early strength development.
- The strength improvement percentage of Ternary Blended Concrete is attributed to both the pore-filling effect and the accelerated hydration of CNS particles, leading to a denser and more compacted concrete. The TBC mix with 30% FA and 1% CNS showed the highest strength enhancement percentage. It is essential to remember that CNS replacement levels greater than 2% may lead to an excess of silica, which might affect the pore structure and cause a minor loss in strength.
- The combination of FA and CNS, along with M-sand, not only enhances the concrete's performance but also contributes to eco-friendliness and sustainability.

Overall, the results of the investigation highlight the advantages of adding fly ash and colloidal nano silica to Ternary Blended Concrete mixes, encouraging increased strength and advantageous characteristics for green building techniques. Further research is essential to explore the optimal proportions, curing conditions, and long-term performance of TBC incorporating CNS.

REFERENCES

[1] Aly, M., M. S. J. Hashmi, A. G. Olabi, M. Messeiry, E. F. Abadir, and A. I. Hussain. "Effect of colloidal nano-silica on the mechanical and physical behaviour of waste-glass cement mortar." Materials & Design, vol. 33, pp. 127-135, 2012. DOI: 10.1016/j.matdes.2011.07.008.

[2] Singh, L.P., Karade, S.R., Bhattacharyya, S.K., Yousuf, M.M.and Ahalawat, S., “Beneficial role of nanosilica in cement based materials -A review”, Construction and Building Materials, vol. 47, pp. 1069-1077, 2013.

[3] Berra, Mario, Fabio Carassiti, Teresa Mangialardi, A. E. Paolini, and Marco Sebastiani. "Effects of nanosilica addition on workability and compressive strength of Portland cement pastes." Construction and Building Materials, vol. 35, pp. 666-675, 2012. DOI: 10.1016/j.conbuildmat.2012.04.132.

[4] P. Kathirvel, V. Saraswathy, S. P. Karthik and A. S. S. Sekar, “Strength and durability properties of quaternary cement concrete made with fly ash, rice husk ash and limestone powder”, Arabian journal of science and technology, vol. 38, pp. 589–598, 2012.

[5] Jalal, Mostafa, Esmaeel Mansouri, Mohammad Sharifipour, and Ali Reza Pouladkhan. "Mechanical, rheological, durability and microstructural properties of high performance self-compacting concrete containing SiO_2 micro and nanoparticles." Materials & Design, vol. 34, pp. 389-400, 2012. DOI: 10.1016/j.matdes.2011.08.037.

[6] Lincy, V., Rao, V.V.L.K. and Lakshmy, P., “A Study on Nanosilica and Microsilica Concretes under Different Transport Mechanisms”, Magazine of Concrete Research, vol. 70, no. 23, pp. 1205-1216, 2018.

[7] Reddy, A. Narender, P. Mounika, and R. Moulika. "Study on effect of alccofine and nano silica on properties of concrete-A review." International Journal of Civil Engineering and Technology, vol. 9, no. 13, pp. 559-565, 2018.

[8] Reddy, A.N. and Meena. T. “Acid Resistance of Ternary Blended Nanosilica Concrete Incorporating Fly Ash and Alccofine”, Civil Engineering and Architecture, vol. 9, no. 2, pp. 500-506, 2021. DOI: 10.13189/cea.2021.090222.

[9] Chithra, S., Senthil Kumar, S.R.R. and Chinnaraju, K, “The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate”, Construction and Building Materials, vol. 113, pp. 794-804, 2016.

[10] Riahi, Sh. and Nazari, A. “Physical, mechanical and thermal properties of concrete in different curing media containing ZnO_2 nanoparticles”, Energy Buildings, vol. 43, pp. 1977-1984, 2011.

[11] Reddy, A.N. and Meena, T. “A study on the effect of colloidal nano-silica on blended concrete containing fly ash and alccofine”, Revista Romana de Materiale, vol. 49, no. 2, pp. 217-224, 2019.

[12] BIS 12269 (2013), Ordinary portland cement 53 grade-specification, New Delhi, India.

[13] BIS 383 (2016), Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, New Delhi, India.

[14] BIS 3812 (2013), Pulverized fuel ash – specification, part 1 for use as pozzolana in cement, cement mortar and concrete, New Delhi, India.

[15] ASTM C494 (2017), Standard specification for chemical admixture for concrete, West Conshohocken, USA.

[16] BIS 10262 (2009), Concrete mix proportioning – guidelines, New Delhi, India.

[17] BIS 516 (1959), Methods of Tests for Strength of Concrete, New Delhi, India.

[18] Reddy, A.N. and Meena, T. “A study on influence of nano silica on mechanical properties of blended concrete”, Journal of Computational and Theoretical Nanoscience, vol. 16, no. 5-6, pp. 2006-2011, 2019.

[19] Raj, D.S., Ganesan, N. Abraham, R. and Raju, A. “Behavior of geopolymer and conventional concrete beam column

joints under reverse cyclic loading", Advances in concrete, vol. 4, no. 3, pp. 161-172, 2016.

[20] Zhang, M.H. and Li, H. "Pore structure and chloride permeability of concrete containing nano-particles for pavement", Construction Building Materials, vol. 25, pp. 608-616, 2011, DOI: 10.1016/j.conbuildmat.2010.07.032.

[21] Anjali, R., and G. Venkatesan. "Optimization of mechanical properties and composition of M-sand and pet particle added concrete using hybrid deep neural network-horse herd optimization algorithm." Construction and Building Materials, vol. 347, pp. 128334, 2022. DOI: 10.1016/j.conbuildmat.2022.128334.

[22] Abhilash, P. P., Dheeresh Kumar Nayak, Bhaskar Sangoju, Rajesh Kumar, and Veerendra Kumar. "Effect of nano-silica in concrete; a review." Construction and Building Materials, vol. 278, pp. 122347, 2021. DOI: 10.1016/j.conbuildmat.2021.122347.

[23] Kumar, Akash, and Gurpreet Singh. "Effect of nano silica on the fresh and hardened properties of cement mortar." International Journal of Applied Engineering Research, vol. 13, no. 13, pp. 11183-11188, 2018.

[24] Gupta, Sakshi. "Application of silica fume and nanosilica in cement and concrete-A review." Journal on Today's Ideas-Tomorrow's Technologies, vol. 1, no. 2, pp. 85-98, 2013. DOI: 10.15415/jotitt.2013.12006.