Performance Characterisation of Sustainable Concrete Incorporating Nano Metakaolin and Manufactured Sand

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ABSTRACT

Growing environmental concerns associated with cement production and excessive river sand extraction have accelerated the search for sustainable concrete materials. This study investigates the combined use of Nano Metakaolin (0–15%) as a partial cement replacement and manufactured sand (M-sand) as an alternative fine aggregate in M20 grade concrete. Mechanical properties were evaluated through compressive, split tensile, and flexural strength tests after 7, 14, and 28 days of curing, while Schmidt rebound hammer and ultrasonic pulse velocity tests were employed for non-destructive assessment. The results revealed that 10% Nano Metakaolin produced the optimum performance, achieving 28-day compressive strengths of 33.73 MPa with river sand and 35.80 MPa with M-sand, corresponding to improvements of 28% and 29%, respectively, over the control mix. Strong correlations ($R^2 > 0.90$) were obtained between compressive strength and non-destructive test results. The study confirms that the combined use of Nano Metakaolin and M-sand is an effective approach for producing high-strength, sustainable concrete with reduced dependence on conventional cement and natural river sand.

Keywords: Nano Metakaolin; Manufactured sand; Pozzolanic reaction; Sustainable concrete; Supplementary cementitious materials.

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1. INTRODUCTION

The construction industry is under increasing pressure to reduce its environmental footprint due to the high carbon emissions associated with ordinary Portland cement (OPC) production and the depletion of natural river sand. These challenges have accelerated the search for sustainable materials that can improve concrete performance while minimizing resource consumption. Nanotechnology has emerged as a promising solution, with Nano-metakaolin (NMK) gaining attention because of its high pozzolanic reactivity, ultrafine particle size, and ability to enhance cement hydration and microstructural densification. Simultaneously, manufactured sand (M-sand) has become a viable substitute for river sand owing to its availability and consistent quality. The combined incorporation of NMK and M-sand offers a sustainable approach to producing high-performance concrete with enhanced mechanical properties and reduced environmental impact.

2. LITERATURE REVIEW

To address the environmental concerns associated with cement production, the use of supplementary cementitious materials (SCMs) has emerged as an effective strategy for reducing cement consumption while improving concrete performance. Among these materials, Nano-Metakaolin (NMK) has attracted significant interest due to its exceptional pozzolanic reactivity, nanoscale particle size, and high specific surface area, which promote cement hydration and produce a denser concrete microstructure. Nano-Metakaolin accelerates cement hydration, promotes additional C–S–H gel formation, refines the pore structure, and enhances compressive strength and durability (Zhan *et al.* 2020). The study also highlighted the importance of optimizing NMK dosage to overcome workability issues. Nano-clay materials, including Nano-Metakaolin, improve hydration kinetics, reduce shrinkage, and enhance resistance to chloride penetration and sulfate attack through pore refinement and matrix densification (Zhang *et al.* 2021). The incorporation of ultrafine metakaolin increased early- and later-age compressive strengths while significantly reducing chloride ion penetration because of the formation of additional C–S–H gel and a denser microstructure. Hybrid cementitious systems containing Metakaolin and Nanosilica improve particle packing, compressive strength, permeability, and long-term durability, making them suitable for sustainable concrete applications (Raheem *et al.* 2021). Proper dispersion of Nano-Metakaolin using Polycarboxylate-based superplasticizers minimizes particle agglomeration and maximizes its pozzolanic efficiency (Silva *et al.* (2021).

Nano-Metakaolin produces higher strength and lower permeability than conventional metakaolin because of its finer particle size and greater reactivity (Cremona *et al.* 2021 and Ali and Kadhim 2021). Incorporating metakaolin with supplementary cementitious materials such as fly ash and Nanosilica enhances compressive strength, durability, and chloride resistance while reducing the embodied carbon of concrete (Keerio *et al.* (2021) and Kumar *et al.* (2021). A comprehensive review concluded that metakaolin improves the fresh, mechanical, and durability properties of concrete, and enhances tensile performance and crack resistance in engineered cementitious composites containing Nano Metakaolin (Kazmi *et al.,* 2021 and Yao *et al.,* (2021). Nano metakaolin improves compressive, tensile, and flexural strengths while reducing chloride penetration, water absorption, and sulfate attack and the recommended optimum replacement level of approximately 10–20% by binder weight is required to achieve the best balance between workability and hardened properties (Ahmad *et al.,* (2022).

Metakaolin-based binders exhibit excellent mechanical properties, low permeability, superior chemical resistance, and significantly lower embodied carbon than conventional Portland cement systems and therefore they act as an effective material for next-generation low-carbon construction (Jindal *et al.* (2023). The combined application of metakaolin and manufactured sand has received comparatively less attention. demonstrated that replacing cement with metakaolin and river sand with manufactured sand improved compressive strength and particle packing while reducing dependence on natural resources (Rao *et al.*, 2021). However, studies investigating the combined effect of Nano-metakaolin and Manufactured Sand on concrete performance remain limited. Therefore, further research is needed to evaluate their synergistic influence on the properties of sustainable concrete. The primary objective of this experimental investigation is to systematically evaluate the synergistic effects of partial cement replacement with Nano Metakaolin and the complete substitution of river sand with manufactured sand on the mechanical properties and non-destructive characteristics of M20 grade concrete.

3. MATERIALS AND EXPERIMENTION

3.1 Constituent Materials

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:1987 was used as the primary binder. Nano Metakaolin (NMK), obtained from Aastra Chemicals, Chennai, India, served as the supplementary cementitious material. The NMK was manufactured by calcining high-purity kaolinite at 750°C and possessed a specific gravity of 2.26, an average particle size of 2.5 µm, and a specific surface area of 15,000 m²/kg. Two types of fine aggregate were employed: natural river sand and manufactured sand (M-sand). The river sand had a specific gravity of 2.65 and fineness modulus of 2.44, whereas the M-sand exhibited a specific gravity of 2.73 and fineness modulus of 2.87. Crushed angular coarse aggregate with a nominal maximum size of 20 mm and a specific gravity of 2.82 was used in all concrete mixes. Potable water free from harmful impurities was used for both mixing and curing.

3.2 Mix Proportion

The concrete mixtures were designed in accordance with the guidelines stipulated in IS 10262:2009 and is 456:2000 to achieve a target characteristic compressive strength of 20 MPa (M20 grade) at 28 days. The control mixture (Mix-1) was formulated with a cement-to-fine-aggregate-to-coarse-aggregate ratio of 1:1.9:3.2 by mass, with a water-to-cementitious materials ratio of 0.50. In the modified mixtures, OPC was partially replaced with metakaolin at mass fractions of 5%, 10%, and 15%, while maintaining the total binder content and water-to-binder ratio constant, as shown in Table 1.

Table 1: Mix proportions for concrete specimens

Mix Designation	PC (%)	NMK (%)	W/B Ratio	Fine Aggregate Type
Mix-1	100	0	0.50	River Sand / M-Sand
Mix-2	95	5	0.50	River Sand / M-Sand
Mix-3	90	10	0.50	River Sand / M-Sand
Mix-4	85	15	0.50	River Sand / M-Sand

3.3 Dimensions of the Specimen

A total of 96 concrete cubes (150 × 150 × 150 mm) were cast to determine compressive strength, with equal numbers prepared using river sand and manufactured sand for each mix proportion. In addition, 24 cylinders (100 mm diameter × 200 mm height) and 24 beam specimens (100 × 100 × 500 mm) were cast to evaluate split tensile and flexural strengths, respectively (Figs. 1–3). After 24 hours of casting, all specimens were demoulded and cured in water at 27 ± 2°C until testing at 7, 14, and 28 days.

Fig 1 Casting and Curing

Fig 2 Flexural Strength

Fig 3 Compressive and Split Tensile Strength

3.4 Methodology

Compressive strength was determined on 150 mm cube specimens in accordance with IS 516:1959 using a 2000 kN universal testing machine. The specimens were loaded continuously at a rate of 140 kg/cm²/min until failure, and the compressive strength was calculated from the maximum load sustained by each specimen.

Split tensile strength was evaluated on cylindrical specimens in accordance with IS 5816:1999 under diametral compression. Thin plywood strips (3 mm thick) were placed between the specimen and loading platens to ensure uniform line loading. Flexural strength was determined on prism specimens using the four-point loading method specified in IS 516:1959 over an effective span of 400 mm, and the modulus of rupture was calculated from the failure load.

Non-destructive evaluation included the Schmidt rebound hammer test, conducted as per IS 13311 (Part 1):1992, where the median of ten rebound readings was considered. Ultrasonic pulse velocity (UPV) measurements were carried out in accordance with IS 13311 (Part 2):1992 using a 50 kHz Pundit device in direct transmission mode.

4. RESULTS AND DISCUSSION

4.1 Characteristics of Compressive Strength

Table 2 and Fig. 4 present the compressive strength results of all concrete mixtures. The 28-day compressive strength varied from 26.35 MPa for the control mix with river sand to 35.80 MPa for the concrete containing 10% Nano Metakaolin and M-sand. All mixtures achieved strengths exceeding the characteristic strength requirement of M20 concrete. An increase in compressive strength was observed with Nano Metakaolin replacement up to 10% for both river sand and M-sand mixes, whereas further replacement to 15% resulted in a slight reduction in strength.

Table 2 Compressive strength of concrete Specimens (N/mm²)

Mix	7-day River Sand	7-day M-Sand	14-day River Sand	14-day M-Sand	28-day River Sand	28-day M-Sand
Mix-1	18.67	20.45	22.47	23.62	26.35	27.75
Mix-2	19.79	22.87	25.17	27.16	28.72	30.53
Mix-3	23.15	25.56	31.00	32.83	33.73	35.80
Mix-4	22.40	24.74	29.11	30.89	31.41	32.41

The highest compressive strength was obtained with 10% Nano Metakaolin replacement (Mix-3), recording 28-day strengths of 33.73 MPa for river sand concrete and 35.80 MPa for M-sand concrete. Compared with the respective control mixes, these values correspond to strength improvements of 28.0% and 29.0%. The enhancement is mainly attributed to the pozzolanic activity of Nano Metakaolin, which reacts with calcium hydroxide released during cement hydration to form additional calcium–silicate–hydrate (C–S–H) gel. This reaction refines the pore structure, strengthens the interfacial transition zone, and results in a denser concrete matrix. The results indicate that 10% Nano Metakaolin is the optimum replacement level for maximizing compressive strength under the present experimental conditions.

A slight reduction in compressive strength was observed when the Nano Metakaolin content was increased to 15%. This decrease is primarily attributed to the dilution effect, where the reduction in cement content outweighs the beneficial pozzolanic and micro-filling actions of Nano Metakaolin. Although NMK enhances concrete through filler effects and the formation of additional calcium–silicate–hydrate (C–S–H) gel, excessive replacement limits the availability of cement required for hydration, leading to lower strength development. Similar findings have been reported by

A.A. Ramezanianpour et al. (2012), who identified an optimum replacement level beyond which the beneficial effects diminish. At later curing ages, the strength differences between the control and NMK-modified concretes become less pronounced due to the continued hydration and stabilization of the cementitious matrix.

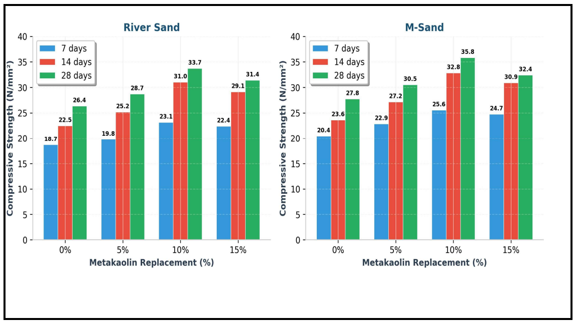

Fig 4 Compressive Strength at different replacement level

4.2 Relative Strength

To evaluate the specific influence of Nano Metakaolin (NMK) independent of the normal strength gain from cement hydration, the relative strength (RS) was determined by comparing the compressive strength of NMK-modified concrete with that of the corresponding control mix at the same curing age. The variation in RS is presented in Fig. 5. The results show that the incorporation of NMK enhanced the relative strength at all curing ages, with the maximum improvement observed at 10% replacement. The highest RS values were recorded at 14 days, exceeding 1.35, indicating that the NMK mixes developed more than 35% higher strength than the control concrete. A slight reduction in RS was observed at 28 days, which can be attributed to the gradual consumption of calcium hydroxide and the reduced rate of the pozzolanic reaction as hydration progressed (Terrence Ramlochan et al., 2000).

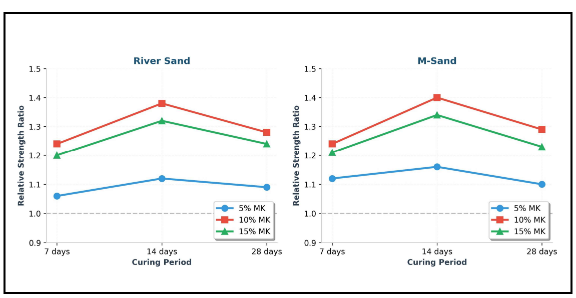

Fig 5 Relative compressive strength of Nano Metakaolin modified concretes

4.3 Flexural and Split Tensile Strength Interrelationship

The 28-day split tensile strength (fst) and flexural strength (fcr) results for all mixture combinations are presented in Table 3. Consistent with the compressive strength trends, both tensile parameters attained peak values at 10% metakaolin replacement, thereby corroborating the optimum dosage identified from compression testing.

Table 3 Flexural and split tensile strength at 28 days

Mix	Flexural Strength River Sand (N/mm^2)	Flexural Strength M-Sand (N/mm^2)	Split Tensile River Sand (N/mm^2)	Split Tensile M-Sand (N/mm^2)
Mix-1	3.62	3.74	2.06	2.38
Mix-2	3.81	3.96	2.45	2.63
Mix-3	4.14	4.25	3.22	3.46
Mix-4	4.04	4.16	2.98	3.31

The maximum split tensile strengths of 3.22 N/mm^2 (river sand) and 3.46 N/mm^2 (M-sand) were recorded for Mix-3, while the corresponding flexural strengths reached 4.14 N/mm^2 and 4.25 N/mm^2, respectively.

Regression analysis was employed to establish empirical relationships between flexural and split tensile strengths. For river sand concrete, the exponential correlation was determined as:

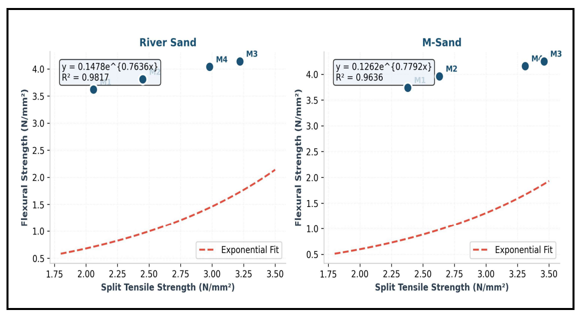

Fig 6 Exponential correlation between flexural strength and split tensile strength

$Y = 0.1478e^{0.7636x}$ with $R^2 = 0.982$ for River Sand

$Y = 0.1262e^{0.7792x}$ with $R^2 = 0.9672$ for M-Sand

The high coefficients of determination ($R^2 > 0.96$) affirm the robustness of these exponential models for predicting flexural strength from split tensile data in NMK-modified concrete systems.

4.4 Relation Between Compressive Strength and Flexural Strength

The results obtained in the present investigation were plotted to get a relation between flexural and compressive strengths for river sand and M-sand . The relation obtained is given as

$Y = 0.0723\,x + 1.7309$ with $R^2 = 0.9973$ for River Sand

$Y = 0.0615x + 2.0515$ with $R^2 = 0.9912$ for M-Sand

5. NON-DESTRUCTIVE TESTING

5.1 Rebound Hammer Test

The rebound hammer test was administered in accordance with IS 13311. The test can provide a reasonably accurate estimate of concrete compressive strength. the cube specimens were tested as per the standard guideline procedure. the test results of rebound hammer test are in accord with the compression test results. by using regression analysis, a relation has been developed between compressive strength and rebound number as shown in fig 7

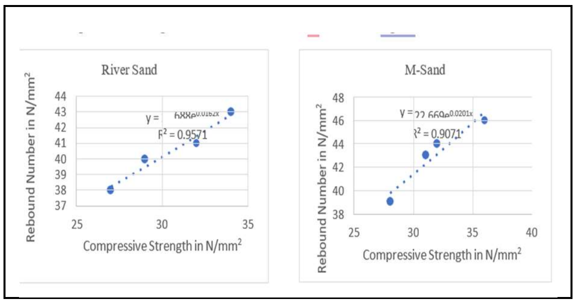

Fig 7 Relation between Compressive Strength and Rebound Number

5.2 Ultrasonic Pulse Velocity (UPV) Test

Ultrasonic Pulse Velocity (UPV) testing of concrete is based on the pulse velocity method which provides information on the concrete uniformity, cavities, defects and cracks. The pulse velocity passing through the specimen depends on its density and its elastic properties which sequentially related to the quality and the compressive strength of the concrete. Therefore, it is possible to obtain information about the properties of components by sonic investigations. The test was carried out as per IS 13311(Part 2): 1992. From this test, the strength of concrete increases as the percentage of Metakaolin increases up to 10%. The rebound hammer and ultrasonic pulse velocity tests further authorized that the modified concrete specimens although being sound and of good quality have increased strength when compared to the control concrete

6. CONCLUSIONS

The experimental investigation substantiates that the partial replacement of Portland cement with metakaolin, in conjunction with the utilization of manufactured sand as a complete substitute for river sand, yields concrete with enhanced mechanical performance and satisfactory non-destructive characteristics.

The 10% NMK replacement level (Mix-3) was identified as the optimum dosage, achieving 28-day compressive strengths of 33.73 MPa (river sand) and 35.80 MPa (M-sand), representing improvements of 28.0% and 29.0% over control specimens, respectively. These values significantly exceed the target M20 grade strength requirement.

Beyond the 10% threshold, the clinker dilution effect predominates over the pozzolanic and filler contributions, resulting in strength reductions. This finding underscores the importance of adhering to the optimum replacement level to maximize material efficiency.

The manufactured sand concrete consistently outperformed the corresponding river sand concrete across all mechanical parameters, attributed to the superior particle angularity, rougher surface texture, and enhanced mechanical interlocking of crushed fine aggregate.

Empirical correlations with high coefficients of determination ($R^2 > 0.90$) were established between compressive strength and non-destructive parameters (rebound number and UPV), validating the reliability of indirect assessment methods for quality control of NMK-modified concrete.

The incorporation of NMK as a supplementary cementitious material and manufactured sand as a sustainable fine aggregate presents a viable technical pathway for reducing the embodied carbon footprint of concrete construction while simultaneously addressing the depletion of natural river sand resources.

The findings encourage the adoption of metakaolin and manufactured sand in commercial concrete production, particularly for infrastructure applications requiring moderate to high strength with enhanced durability potential.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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