Experimental Investigation of Sustainable High-Strength Self-Compacting Concrete Incorporating Metakaolin, Micro Silica, and Manufactured Sand

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Abstract
The increasing demand for sustainable construction materials has accelerated research into eco-friendly alternatives that reduce the environmental impact of conventional concrete. This study presents an experimental investigation on the fresh, hardened, and durability properties of High-Strength Self-Compacting Concrete (HSSCC) incorporating Metakaolin (MK), Micro Silica (MS), and Manufactured Sand (M-Sand). Metakaolin and Micro Silica were used as partial replacements for Ordinary Portland Cement (OPC), while M-Sand was utilized as a complete replacement for natural river sand to promote sustainable resource utilization and minimize environmental degradation caused by excessive sand mining. The fresh properties of HSSCC were evaluated using Slump Flow, V-Funnel, and L-Box tests to assess workability, filling ability, and passing ability. Hardened concrete properties, including compressive strength, split tensile strength, and flexural strength, were determined at different curing periods. Durability performance was assessed through the Rapid Chloride Permeability Test (RCPT) to evaluate resistance against chloride ion penetration. The experimental results indicate that the incorporation of Metakaolin and Micro Silica significantly enhances the mechanical strength and durability of concrete by refining the pore structure and promoting additional pozzolanic reactions. Although higher Micro Silica content slightly reduces workability, it substantially improves compressive strength and long-term durability. Furthermore, the use of Manufactured Sand provides a sustainable and effective alternative to natural sand without compromising concrete performance. The optimized HSSCC mix demonstrates superior structural performance, improved durability, and reduced environmental impact, making it a promising material for modern infrastructure, high-rise buildings, bridges, precast elements, and other sustainable construction applications.

Keywords: High-Strength Self-Compacting Concrete (HSSCC), Metakaolin, Micro Silica, Manufactured Sand (M-Sand), Sustainable Concrete, Supplementary Cementitious Materials (SCMs), Workability, Compressive Strength, Durability, Rapid Chloride Permeability Test (RCPT), Eco-Friendly Construction.

I. Introduction

Concrete is the most widely used construction material because of its excellent compressive strength, durability, versatility, and cost-effectiveness. However, the rapid growth of the construction industry has significantly increased the demand for Ordinary Portland Cement (OPC) and natural river sand, leading to excessive consumption of natural resources and increased carbon dioxide (CO_2) emissions. Cement manufacturing alone contributes a considerable amount of global greenhouse gas emissions, making sustainable alternatives essential for modern infrastructure development. Researchers have focused on replacing a portion of cement with Supplementary Cementitious Materials (SCMs) such as Metakaolin, Micro Silica, and Fly Ash to improve both environmental sustainability and engineering performance. Similarly, Manufactured Sand (M-Sand) has emerged as an eco-friendly alternative to natural river sand due to its consistent quality and reduced environmental impact. Previous investigations have reported that Metakaolin and Micro Silica significantly enhance compressive strength, durability, and resistance to chloride penetration through pozzolanic reactions and pore refinement. These materials also improve the density of the concrete matrix, making concrete more durable under aggressive environmental conditions. Consequently, sustainable High-Strength Self-Compacting Concrete (HSSCC) has become an attractive solution for producing high-performance and environmentally responsible construction materials that satisfy modern engineering requirements while reducing ecological impacts **[1], [26]**.

Self-Compacting Concrete (SCC) is an advanced type of concrete capable of flowing, filling, and compacting under its own weight without requiring mechanical vibration. Owing to its excellent filling ability, passing ability, and resistance to segregation, SCC is particularly suitable for structures containing congested reinforcement and complex formwork. The incorporation of High-Reactivity Metakaolin and Micro Silica further enhances the performance of SCC by improving strength, reducing permeability, and increasing durability. Metakaolin reacts with calcium hydroxide released during cement hydration to produce additional Calcium Silicate Hydrate (C-S-H) gel, resulting in a denser and stronger concrete matrix. Micro Silica, because of its ultrafine particle size, effectively fills microscopic voids and improves particle packing, leading to higher compressive strength and

reduced chloride permeability. Several researchers have reported that the combined use of these mineral admixtures significantly improves the mechanical properties and long-term performance of concrete while maintaining acceptable workability through the use of superplasticizers. Furthermore, the complete replacement of natural river sand with Manufactured Sand contributes to sustainable construction by conserving natural resources and minimizing environmental degradation associated with excessive sand mining **[2]**.
The present research focuses on the experimental investigation of sustainable High-Strength Self-Compacting Concrete incorporating Metakaolin, Micro Silica, and Manufactured Sand as alternative construction materials. The study aims to evaluate both fresh and hardened properties of concrete through standard laboratory tests, including Slump Flow, V-Funnel, and L-Box tests for workability assessment, along with compressive strength, split tensile strength, flexural strength, and Rapid Chloride Permeability Test (RCPT) for durability evaluation. The combined use of Metakaolin and Micro Silica is expected to enhance strength development by promoting pozzolanic reactions and refining the concrete microstructure, while Manufactured Sand serves as a sustainable replacement for natural river sand without compromising engineering performance. The findings of earlier investigations indicate that optimized replacement levels of these supplementary materials improve mechanical strength, reduce permeability, enhance resistance to aggressive environments, and extend the service life of concrete structures. Therefore, this study contributes to the development of eco-friendly, durable, and high-performance concrete suitable for bridges, high-rise buildings, precast elements, industrial floors, and other modern infrastructure applications while supporting sustainable construction practices and reducing the environmental impact of conventional concrete production **[3], [7]**.

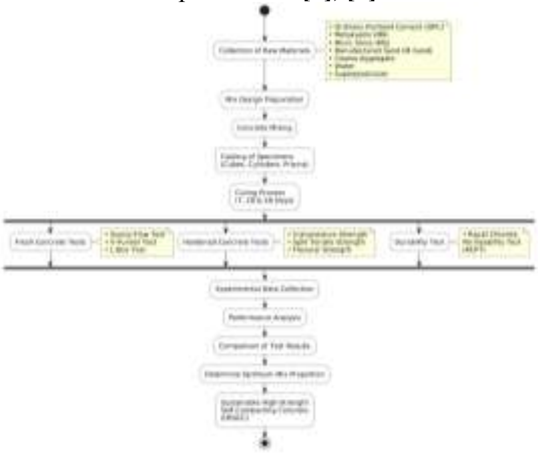

Fig1: System Architecture

Ii Survey Of Research

[1] Adel Azzawi and co-researchers conducted a comprehensive investigation on the behaviour of Ultra High Performance Concrete (UHPC) reinforced with steel fibres using both experimental testing and numerical simulation techniques. The study examined concrete mixtures incorporating Silica Fume and High-Reactivity Metakaolin with varying steel fibre contents of 1%, 1.5%, and 2%. Mechanical properties obtained through laboratory experiments were used as input parameters for finite element modelling using ANSYS software to validate structural behaviour. The results showed excellent agreement between numerical predictions and experimental observations, confirming the reliability of the simulation approach. UHPC mixtures containing Silica Fume achieved higher compressive strength than those incorporating Metakaolin, although both supplementary cementitious materials significantly improved the overall performance of concrete. The research demonstrated that combining mineral admixtures with steel fibres enhances strength, ductility, and durability, making UHPC suitable for demanding structural and infrastructure applications requiring superior long-term performance.

[2] Arunakanthi and Sudarsana Rao investigated the influence of calcium chloride on the performance of High-Performance Concrete containing 20% Metakaolin as a partial replacement for Ordinary Portland Cement. The research evaluated compressive strength and split tensile strength under different calcium chloride concentrations and curing durations. Experimental findings indicated significant improvements in both mechanical properties with increasing calcium chloride dosage and prolonged curing periods. X-ray diffraction analysis confirmed that enhanced strength development resulted from increased formation of Calcium Silicate Hydrate (C-S-H) gel and reduced Portlandite content within the concrete matrix. The presence of Gismondine compounds further contributed to improved structural performance and durability. The study concluded that Metakaolin effectively enhances hydration reactions while calcium chloride accelerates strength gain during early curing stages. These findings demonstrated that the combined use of Metakaolin and suitable chemical additives can significantly improve the engineering performance of high-performance concrete for structural applications.

[3] Beulah and Prahallada examined the durability performance of High-Performance Concrete incorporating Metakaolin under hydrochloric acid exposure conditions. The research primarily focused on evaluating compressive strength, weight loss, and resistance to acid attack at different water-binder ratios. Experimental results indicated that increasing the water-binder ratio reduced compressive strength while increasing the deterioration of concrete exposed to acidic environments. Concrete mixtures containing Metakaolin exhibited significantly better resistance to acid attack than conventional concrete due to their denser microstructure and

reduced pore connectivity. The optimum replacement level of 10% Metakaolin produced the highest residual compressive strength and minimum weight loss after prolonged acid immersion. The pozzolanic reaction between Metakaolin and calcium hydroxide generated additional Calcium Silicate Hydrate gel, which refined the pore structure and enhanced durability. The study confirmed that Metakaolin is an effective supplementary cementitious material for producing durable and sustainable concrete.

[4] Dhinakaran and co-researchers investigated the influence of Metakaolin on the compressive strength and chloride resistance of concrete prepared with different water-cement ratios. The study evaluated the effects of varying Metakaolin replacement levels on early-age strength development and long-term durability. Experimental results demonstrated that Metakaolin significantly improved compressive strength through enhanced pozzolanic reactions and pore refinement. The optimum replacement level was approximately 10% for higher water-cement ratios, whereas 15% replacement provided better performance at lower water-cement ratios. The maximum compressive strength achieved was nearly 59 MPa. Chloride permeability tests indicated a substantial reduction in chloride ion penetration, improving reinforcement protection against corrosion. The incorporation of Metakaolin also maintained the alkalinity of concrete, enhancing its resistance to aggressive environmental conditions. The research concluded that Metakaolin effectively improves both mechanical properties and durability, making it suitable for high-performance concrete applications requiring extended service life.

[5] Dinkar and colleagues investigated the development of high-strength and high-performance concrete using Metakaolin as a partial replacement for Ordinary Portland Cement. The study adopted a low water-binder ratio of 0.30 and evaluated compressive strength, split tensile strength, modulus of elasticity, permeability, and chloride penetration resistance. Experimental results revealed that concrete incorporating 10% Metakaolin achieved compressive strengths exceeding 100 MPa while exhibiting superior tensile strength and elastic modulus compared to conventional concrete. Durability assessments indicated considerable reductions in water absorption, permeability, and chloride ion penetration due to the filler effect and pozzolanic activity of Metakaolin. These reactions refined the concrete microstructure by producing additional Calcium Silicate Hydrate gel, resulting in a denser and stronger matrix. The study concluded that Metakaolin significantly enhances both mechanical and durability properties, making it an ideal supplementary cementitious material for high-strength concrete and sustainable infrastructure projects.

[6] Jibing Bai and Albinas Gailius developed statistical prediction models for estimating the consistency and workability of concrete mixtures containing Fly Ash and Metakaolin as supplementary cementitious materials. The study investigated important fresh concrete parameters, including slump, compacting factor, and Veebe time, using regression analysis and statistical significance testing. Experimental observations were compared with predicted values generated by mathematical models, demonstrating close agreement and high prediction accuracy. The proposed equations successfully estimated workability characteristics for various concrete mixtures containing different proportions of Fly Ash and Metakaolin. The research highlighted that both supplementary materials significantly influence fresh concrete behaviour and require careful proportioning to achieve optimum consistency. The developed prediction models provide practical tools for mix design optimization and quality control during concrete production. The study concluded that statistical modelling offers an efficient approach for predicting workability and improving the performance of blended cement concrete mixtures.

III. Working Methodology

The proposed methodology was developed to evaluate the influence of Metakaolin (MK), Micro Silica (MS), and Manufactured Sand (M-Sand) on the fresh, hardened, and durability properties of High-Strength Self-Compacting Concrete (HSSCC). The methodology consists of material characterization, mix proportioning, specimen preparation, curing, experimental testing, and performance evaluation. Figure 3.1 illustrates the overall workflow adopted in this research.

A. Material Selection and Characterization

Ordinary Portland Cement (OPC), Metakaolin, Micro Silica, Manufactured Sand (M-Sand), coarse aggregate, potable water, and a polycarboxylate-based superplasticizer were selected as the constituent materials. The physical properties such as specific gravity, fineness, water absorption, and particle size distribution were determined according to relevant Indian Standards before mix preparation. Metakaolin and Micro Silica were used as supplementary cementitious materials to partially replace cement, while Manufactured Sand completely replaced natural river sand to improve sustainability and conserve natural resources. The characterization of materials ensured uniform quality and compatibility among all constituents before preparing the concrete mixes.

B. Mix Design of High-Strength Self-Compacting Concrete

Concrete mix proportions were developed based on EFNARC recommendations and IS guidelines for High-Strength Self-Compacting Concrete. Different replacement percentages of Metakaolin and Micro Silica were considered while maintaining a constant water-to-binder ratio. Superplasticizer dosage was adjusted to achieve adequate flowability without segregation. Trial mixes were prepared to identify the optimum combination that satisfies both fresh and hardened concrete requirements.

The Water-to-Binder Ratio is calculated as

$$\boxed{W/B = \frac{W}{C + MK + MS}}$$

where

(W) = Water (kg)

(C) = Cement (kg)

(MK) = Metakaolin (kg)
(MS) = Micro Silica (kg)
A lower water-to-binder ratio improves compressive strength and durability by reducing concrete porosity.

C. Mixing, Casting and Curing of Specimens

All dry materials were mixed thoroughly before adding water containing the required dosage of superplasticizer. The concrete was mixed until a homogeneous consistency was achieved. Cube specimens (150 × 150 × 150 mm), cylindrical specimens (150 × 300 mm), and prism specimens were cast for compressive, split tensile, and flexural strength tests, respectively. Since the concrete was self-compacting, no external vibration was applied. After 24 hours, the specimens were demoulded and cured in clean water for 7, 28, and 56 days to ensure complete hydration and strength development.

D. Evaluation of Fresh Concrete Properties

Fresh concrete properties were evaluated immediately after mixing using EFNARC guidelines.
Slump Flow Diameter

$$\boxed{D = \frac{D_1 + D_2}{2}}$$

where
(D_1) = First diameter (mm)
(D_2) = Second diameter (mm)
The average slump flow diameter indicates the filling ability and workability of Self-Compacting Concrete.
L-Box Passing Ratio

$$\boxed{R = \frac{H_2}{H_1}}$$

where
(H_1) = Initial concrete height
(H_2) = Final concrete height
A higher passing ratio indicates better passing ability through congested reinforcement.
V-Funnel Flow Time

$$\boxed{T_v = t_2 - t_1}$$

Where
(t_1) = Initial discharge time
(t_2) = Final discharge time
Lower flow time indicates better viscosity and workability of fresh concrete.
E. Mechanical Properties of Hardened Concrete
After curing, hardened concrete specimens were tested using standard testing machines.
Compressive Strength

$$\boxed{f_c = \frac{P}{A}}$$

where
(f_c) = Compressive strength (MPa)
(P) = Maximum load (N)
(A) = Loaded area (mm²)
This equation determines the maximum compressive load sustained by concrete before failure.
Split Tensile Strength

$$\boxed{f_t = \frac{2P}{\pi L D}}$$

(P) = Failure load (N)
(L) = Length of cylinder (mm)
(D) = Diameter of cylinder (mm)
This test measures the tensile resistance of concrete under indirect loading.
Flexural Strength

$$\boxed{f_r = \frac{PL}{bd^2}}$$

where
(P) = Applied load (N)
(L) = Span length (mm)
(b) = Width (mm)
(d) = Depth (mm)
Flexural strength represents the bending capacity of concrete members.

F. Performance Analysis and Optimization

The experimental results obtained from fresh concrete tests, mechanical strength tests, and durability evaluations were compared to determine the optimum replacement percentage of Metakaolin and Micro Silica. Statistical comparisons were performed using graphical representations and tabular analyses to identify the concrete mixture exhibiting the highest compressive strength, improved workability, reduced chloride permeability, and enhanced durability. Based on the experimental findings, the optimized High-Strength Self-Compacting Concrete mix incorporating Metakaolin, Micro Silica, and Manufactured Sand was recommended for sustainable construction applications such as bridges, high-rise buildings, precast elements, industrial structures, and marine infrastructure due to its superior engineering performance and environmental benefits.

IV Results Explanations

FRESH PROPERTIES OF HIGH STRENGTH SELF COMPACTING CONCRETE

With SCC technology, the issues of maintaining concrete flow in congested reinforcement, a sloppy site, and limiting energy consumption in vibration, which are all common during the building and placement of standard weight concrete, are easily addressed. Workability decreased as the amount micro silica increases, were added to concrete although they remained well within EFNARC limits.

Slump flow

The slump flow test results are tabulated in below table-5.1. From mix M1 to M5 the flow properties shows decrement. Mix M1 and M2 shows higher flow ability compared to other mixes. From mix M3 onwards drastic decrement in slump flow was observed because of presence of Micro silica. Mix M5 shows the lowest slump flow value. According to EFNARC guidelines the limits for slump flow diameter given is 650 to 800mm.

Table 5.1 Slump flow test result

Table 1 Slump flow test result

Mix	Micro silica %	Slump flow (mm)
M1	HS SCC MS0%	668
M2	HS SCC MS 2.5%	652
M3	HS SCC MS 5%	637
M4	HS SCC MS 7.5%	623
M5	HS SCC MS 10%	592

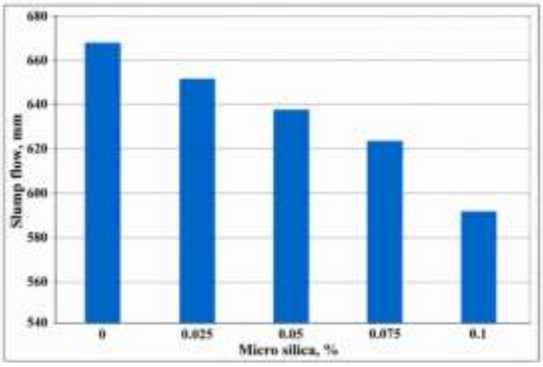

Fig 2: Slump flow test results graph

The slump flow diminishes over time as the micro silica concentration rises. This is because micro silica has a smaller particle size and a larger surface area, which makes fresh HS SCC less flowable and raises the water requirement. However, the slump flow values of all combinations are within or near the allowed SCC range (around 550-850 mm), which means that their self-compacting properties are acceptable.

V-funnel test

V-Funnel test performed to determine the segregation resistance of the concrete and also filling ability of the concrete. The V-Funnel test results are interpreted as in seconds. The test results are indicated in below table-5.2. Graph 5.2 shows the conducting V-Funnel experiment test in lab Represents the graphical representation of the test results. From the graphs we observed that after addition of micro silica that is from mix M5 the v-funnel time increases that indicates the less flow and mix M1 and M5 shows good flow property.

Table 2 V-funnel test result

Mix	Micro silica %	V-funnel (Sec)
M1	HS SCC MS0%	6.5
M2	HS SCC MS 2.5%	7
M3	HS SCC MS 5%	8.4
M4	HS SCC MS 7.5%	9
M5	HS SCC MS 10%	9.5

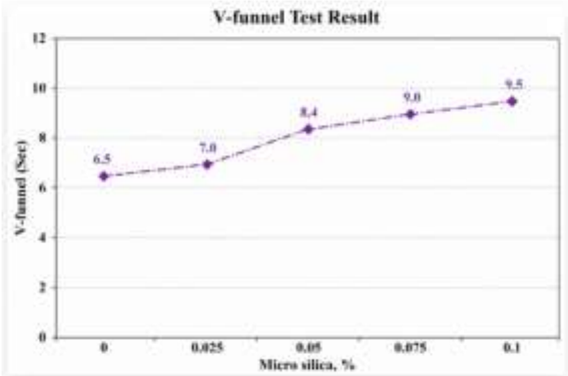

Fig3: V-Funnel Test Results

The V-Funnel Test was conducted to evaluate the viscosity, flowability, and segregation resistance of High-Strength Self-Compacting Concrete (HSSCC) containing different percentages of Micro Silica. The graph shows that the V-Funnel flow time gradually increased with increasing Micro Silica content, indicating a reduction in the flowability of fresh concrete. The control mix M1 (0% Micro Silica) recorded the lowest flow time of 6.5 seconds, demonstrating excellent workability and rapid flow through the V-funnel. When 2.5% Micro Silica was added in M2, the flow time increased slightly to 7.0 seconds, indicating a minor increase in concrete viscosity. Further increasing the Micro Silica content to 5% (M3) resulted in a flow time of 8.4 seconds, showing that the concrete became more cohesive due to the ultrafine particles of Micro Silica. The flow time further increased to 9.0 seconds for M4 (7.5% Micro Silica) and reached the maximum value of 9.5 seconds for M5 (10% Micro Silica). This increase occurred because Micro Silica has an extremely fine particle size and high specific surface area, which absorbs more water and increases internal friction within the concrete mix. Although the flowability decreased with higher Micro Silica content, all the mixes exhibited V-Funnel flow times between 6.5 and 9.5 seconds, which are within the EFNARC recommended range (6–12 seconds) for Self-Compacting Concrete. Therefore, the results indicate that the incorporation of Micro Silica improves the cohesiveness and stability of concrete while maintaining acceptable workability, making it suitable for producing durable High-Strength Self-Compacting Concrete.

L-box test

L-box test is very important in indicates the passing ability of the self compacting concrete. It has three steel rod which implicates the practical congested reinforcement situations. The values of the L-box test represents as the ratio of heights near to the test bars and the height at the ends.

Table 3 L-box test result

Mix	Micro silica %	L-box
M1	HS SCC MS0%	0.93
M2	HS SCC MS 2.5%	0.91
M3	HS SCC MS 5%	0.88
M4	HS SCC MS 7.5%	0.86
M5	HS SCC MS 10%	0.84

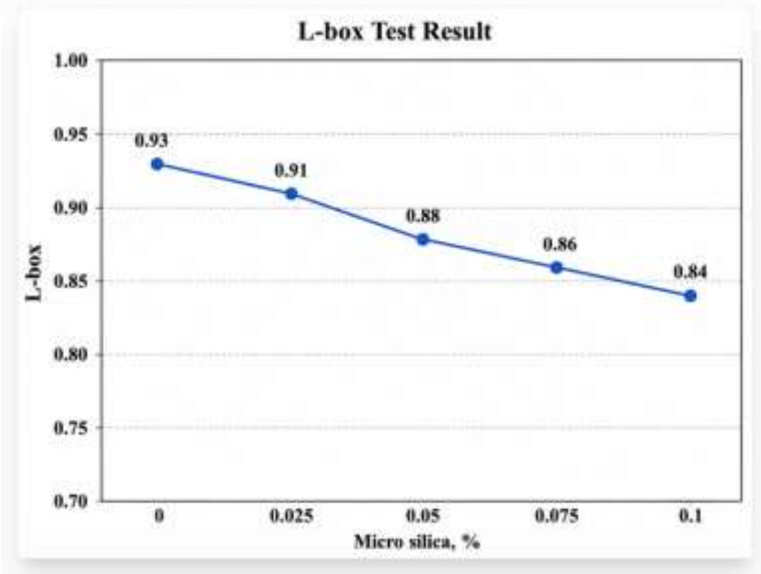

Fig3 L-box test results graph

The L-Box test conducting in the lab shows the l-box test results in a graphical form the L-box test results followed a similar trend as of slump flow and v-funnel test that mix M1 and M2 shows the good fresh properties and mix M5 showed the least value.

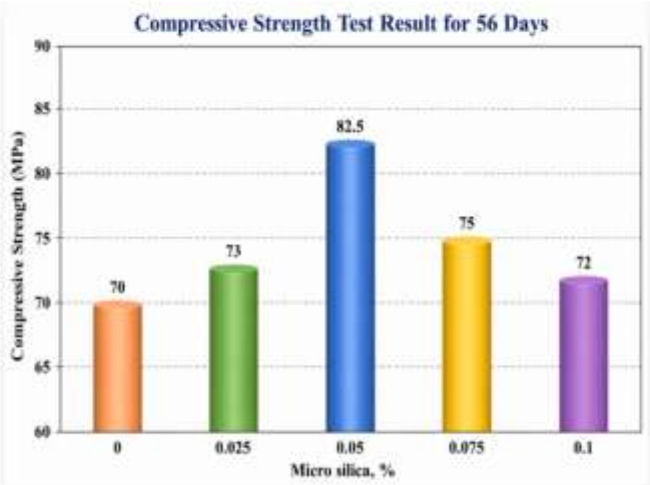

Fig4: 56days compressive strength test results graph

Compressive strength is a very important mechanical test. Above graph shows the digital compressive machine in which concrete specimen is kept and load will be applied load on the specimen will be act till it crushes. The size of the specimen used was 150x150x150mm. The test was conducted for 28, 56 days. can observe that among all the mixes mix M5 and M1 shows the least strength after addition of Micro silica from mix M3 onwards Compressive strength test results shows drastic increment in strength because this micro and micro-silica undergoes a pozzolanic reaction with calcium hydroxide present in the concrete and produces secondary CSH gels. Mix M3 which is a combination of micro and Micro silica shows the highest compressive strength among all the mixes. The highest strength observed is 71 MPa for the 28days curing.

V. Conclusion

This study successfully investigated the fresh, hardened, and durability properties of sustainable High-Strength Self-Compacting Concrete (HSSCC) incorporating Metakaolin, Micro Silica, and Manufactured Sand as eco-friendly alternatives to conventional concrete materials. The experimental results demonstrated that the combined use of Metakaolin and Micro Silica significantly enhanced the compressive, split tensile, and flexural strengths while improving the durability of concrete through reduced chloride ion permeability and a denser microstructure. Although higher percentages of Micro Silica slightly decreased workability, the concrete maintained satisfactory self-compacting characteristics when an appropriate dosage of superplasticizer was used. The complete replacement of natural river sand with Manufactured Sand produced concrete with comparable or improved engineering properties while promoting sustainable resource utilization and reducing environmental impacts associated with river sand mining. Overall, the optimized HSSCC mix offers superior mechanical performance, enhanced durability, and improved sustainability, making it a reliable and environmentally responsible construction material for high-rise buildings, bridges, precast concrete elements, industrial structures, and other modern infrastructure applications. The findings of this research support the adoption of supplementary cementitious materials and Manufactured Sand in the development of high-performance, durable, and sustainable concrete for future construction projects.

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