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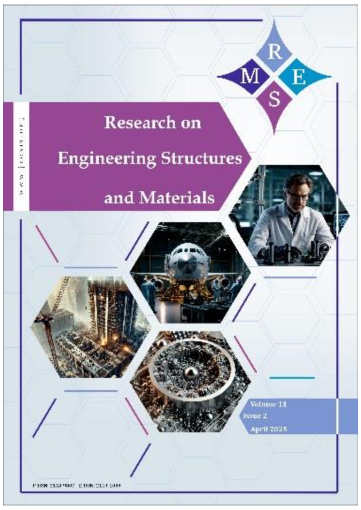

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Research Article

Optimization of micro-silica replacement levels for high strength and low-absorption sustainable concrete

Nirbachita Nawar [*,a], Tanjim Irtiza [b], Iftaran Ahmed Chowdhury [c], Sharmin Reza Chowdhury [d]

Dept. of Civil Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh

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Abstract

Micro-silica, an ultrafine byproduct from the silicon and ferrosilicon alloy industry, offers significant potential as a supplementary cementitious material for sustainable concrete. The purpose of this study is to investigate the mechanical performance and water absorption properties of concrete that contains micro-silica as a partial replacement for cement at five different percentages: 5%, 10%, 15%, 20%, and 25%. A total of 108 concrete cylinders (4"×8") were made and subsequently tested for compressive and splitting tensile strengths at 7, 14, and 28 days, following ASTM C39 and C496 standards. Eighteen concrete cylinders (4"×8") were also made and tested for water absorption according to standard procedures. The results demonstrated that after 28 days of curing, concrete incorporating 20% micro-silica as a partial cement replacement exhibited the highest compressive strength of 31.38 MPa, representing a 56.6% enhancement compared to the control mix (19.99 MPa). Similarly, the splitting tensile strength improved by approximately 38% at the same 20% substitution level. Furthermore, micro-silica addition reduced water absorption by up to 42%, indicating enhanced impermeability and resistance to chemical ingress. This research establishes a practical balance between environmental benefits and performance improvements in concrete production and the findings confirm that incorporating micro-silica up to an optimal 20% substitution significantly enhances concrete's strength and durability while contributing to a lower carbon footprint and sustainable material utilization.

1. Introduction

Concrete is the most consumed material with three tons per year used for every person in the world. Manufacturing of cement which is the primary binding material and a major constituent of concrete results in roughly 5% of global anthropogenic CO_2 emissions which makes it one of the biggest single contributors to greenhouse gas emissions [1, 2]. Cement manufacturing processes are also associated with emissions of significant environmental pollutants [3]. In developing nations undergoing rapid urbanization, the need to identify sustainable alternatives to conventional Portland cement has become critical as the global demand for concrete continues to rise [4]. A promising solution involves the partial replacement of cement with supplementary cementitious materials (SCMs) such as micro-silica, a byproduct of the silicon and ferrosilicon alloy industry [5]. The utilization of such industrial waste reduces the embodied carbon footprint of concrete, aligning with global goals for sustainable infrastructure development.

Micro-silica, also known as silica fume, is an ultrafine amorphous form of silicon dioxide with a particle size nearly 100 times smaller than that of cement [6]. Due to its extraordinarily high

*Corresponding author: nirbachitanawar12@gmail.com
[a]orcid.org/0009-0008-1493-3246; [b]orcid.org/0009-0004-5369-7742; [c]orcid.org/0009-0002-8922-5048; [d]orcid.org/0000-0001-5227-3463
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specific surface area and reactive silica content, micro silica is an efficient pozzolanic material that is capable of producing additional calcium silicate hydrate (C–S–H) gel through its reaction with calcium hydroxide that is generated during the hydration of cement. This secondary C–S–H production refines the pore structure, increases the density of the concrete matrix, and improves the concrete's strength and permeability. This reaction can be described as follows [7, 8];

- Cement + H_2O → C-S-H + $Ca(OH)_2$
- $Ca(OH)_2$+ SiO_2 → H_2O + C-S-H

Several studies have demonstrated that the inclusion of micro-silica in concrete can significantly enhance compressive, tensile, and flexural strengths while simultaneously lowering permeability and water absorption [9]. Moreover, the micro-filler effect of micro-silica where fine particles fill voids between cement grains further contributes to a dense and homogeneous microstructure, improving resistance to cracking [10]. The experimental system focused on three fundamental tests: compressive strength, splitting tensile strength, and water absorption for the purpose of determining the basic characteristics of mechanical and physical performance of concrete. This combination of tests provides a balanced evaluation of strength and permeability, enabling the identification of an optimal replacement level of micro-silica for both structural and sustainable performance.

Compressive strength is the primary indicator of concrete's load-bearing capacity and is widely used as a standard performance benchmark for mix design optimization, whereas splitting tensile strength provides insight into concrete's tensile cracking behavior. Water absorption serves as a practical indicator of permeability, which reflects compactness of the cementitious matrix and the degree of pore refinement. Reduced water absorption directly correlates with improved resistance to fluid ingress and enhanced durability against environmental exposure. Similar approaches have been adopted in prior works [9,11] where these tests were used to represent the essential durability related properties in preliminary micro-silica investigations. Despite these advantages, the optimal percentage of micro-silica replacement remains a matter of debate among researchers. Previous investigations have reported varying results: some indicate peak compressive strength at 10%–15% replacement levels [9,12], while other researchers discovered that increases in tensile strength and permeability persist up to 20% of the replacement before the benefits begin to decline or reverse due to an increased demand for water and a reduction in workability. In a related investigation, the effect of micro-silica on the mechanical behavior of M40-grade concrete was studied by partially replacing cement at proportions of 0%, 5%, 10%, 15%, and 20%. Compressive and splitting tensile strength tests were conducted, and the results indicated that a 20% replacement of cement with micro-silica produced the highest strength in both parameters [13]. These findings align with the present study, confirming that 20% micro-silica incorporation provides an optimum balance between strength enhancement and material efficiency. Previous investigations have indicated that micro-silica incorporation beyond a 20% replacement level may lead to reduced workability and the formation of microcracks due to excessive binder densification [9]. Conversely, another study reported that an optimum replacement of about 15% yielded a compressive strength increase of nearly 40% in comparable concrete mixes [11]. However, limited research has simultaneously examined compressive strength, tensile strength, and water absorption behavior within a consistent mix design and controlled experimental program across a broad range of replacement levels (5%–25%). Moreover, although numerous studies have verified the mechanical enhancements achieved through micro-silica incorporation, only a limited number have quantified the corresponding sustainability benefits, particularly in terms of CO_2 emission reduction associated with lower cement consumption.

The present study addresses these existing research gaps by performing a comprehensive experimental investigation into the mechanical and physical performance of concrete incorporating micro-silica as a partial cement replacement at 5%, 10%, 15%, 20%, and 25%. A total of 108 concrete cylinders (4"×8") were cast and tested under controlled laboratory conditions. Compressive strength and splitting tensile strength were determined at 7, 14, and 28 days while water absorption tests were conducted to assess the permeability and densification characteristics of each mix. The inclusion of these three interrelated performance measures such as strength, cohesion, and permeability provide a holistic evaluation of the influence of micro-silica on concrete quality.

From a sustainability perspective, replacing cement with micro-silica translates to a direct reduction of approximately 20% in CO_2 emissions related to cement production, considering that each ton of cement generates roughly 0.8 tons of CO_2 [14], [15], [16]. This finding demonstrates that micro-silica not only enhances mechanical performance but also contributes to substantial environmental benefits. Consequently, the research identifies 20% as the optimum replacement level, balancing performance improvements and ecological advantages.

2. Chemical Compositions of Cement and Micro-Silica

The chemical properties of cement and micro-silica show notable similarities, though the percentages differ significantly. The chemical properties of micro-silica and cement are presented in Table 1 [17].

Table 1. Chemical compositions of cement and micro-silica

Compound	Micro-Silica (Silica Fume)	Portland Cement
SiO_2	89.72%	17.34%
Al_2O_3	0.80%	7.62%
Fe_2O_3	0.76%	4.23%
CaO	1.41%	65.27%
MgO	1.23%	2.40%
SO_3	0.84%	3.14%
K_2O	1.31%	Not specified
Na_2O	0.65%	Not specified
Loss on Ignition (LOI)	Not specified	3.28%

3. Materials and Methods

This study utilized a systematic experimental methodology to assess the performance of concrete incorporating micro-silica as a partial substitute for cement in sustainable construction applications. The study was divided into two separate stages. During the initial phase, the constituent materials cement, fine and coarse aggregates, and micro-silica underwent testing through standard laboratory tests to identify their physical and mechanical properties. This included assessments such as sieve analysis, specific gravity, fineness modulus, bulk density, and water absorption. The cement was tested for standard consistency, initial and final setting time, and specific gravity in accordance with ASTM C187 and ASTM C191 [18,19]. Micro-silica was characterized based on its fineness and silica content, ensuring its suitability as a supplementary cementitious material. During the second phase, concrete mixtures were formulated and subjected to tests for compressive strength, splitting tensile strength, and water absorption to assess their mechanical properties and durability performance. Figure 1 illustrates the comprehensive experimental workflow.

The second phase focused on the preparation, casting, curing, and testing of both control and micro-silica-modified concrete specimens. These specimens were manually made in Concrete Lab, AUST. A total of 126 specimens were made for this study. In stage 1, 21 control specimens were produced with cement, fine and coarse aggregate, and water. In stage 2, 105 concrete cylinders were produced by replacing cement with a few percentages of Micro Silica. In both cases, a mix ratio of 1:1.5:3 and a Water-Cement ratio of 0.40 were considered.

This systematic experimental design enabled a comprehensive evaluation of the effect of micro-silica replacement on both the strength and permeability behavior of concrete, ensuring consistency across all mix variations and providing a reliable basis for identifying the optimum replacement level for enhanced sustainable performance. To make sure the data accuracy and could be repeated, each test was done on three copies of each mix. Table 2-5 show the coding scheme for all concrete mixes and replacement levels. They also show the test schedule and how the specimens will be assigned.

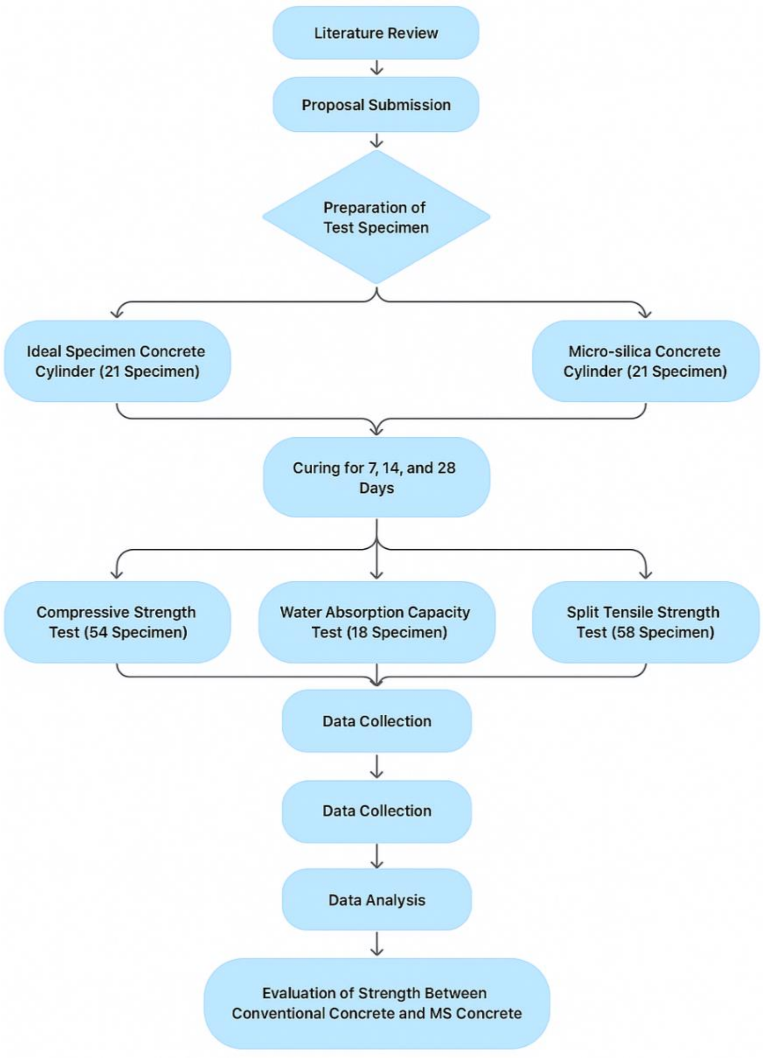

Fig. 1. Experimental workflow illustrating the sequential stages of material testing, mix preparation, casting, and strength evaluation

Five mix proportions were designed by partially replacing cement with micro-silica at 5%, 10%, 15%, 20%, and 25% by weight, in addition to a plain concrete mix serving as the control. For each mix, a total of 21 cylindrical specimens (refer to Figure 2) were prepared using steel molds. All specimens were demolded after 24 hours and cured in water at room temperature until testing ages of 7, 14, and 28 days.

Table 2. Specimen codes and percentage of micro-silica used for compressive strength test

Specimen codes	% of Micro-Silica Replacement
Compression Cylinder Control (CC_c)	0
Compression Cylinder with 5% MS (CC_5)	5
Compression Cylinder with 10% MS (CC_{10})	10
Compression Cylinder with 15% MS (CC_{15})	15
Compression Cylinder with 20% MS (CC_{20})	20
Compression Cylinder with 25% MS (CC_{25})	25

Compressive strength tests were conducted in accordance with ASTM C39, while splitting tensile strength tests were carried out following ASTM C496 [20], [21]. To evaluate permeability-related performance, water absorption tests were also performed after 28 days of curing, as shown in Figure 3, to determine the influence of micro-silica on pore structure and densification of the concrete matrix.

Table 3. Specimen codes and percentage of micro-silica used for tensile strength test

Specimen codes	% of Micro-Silica Replacement
Tension Cylinder Control (TC_c)	0
Tension Cylinder with 5% MS (TC_5)	5
Tension Cylinder with 10% MS (TC_{10})	10
Tension Cylinder with 15% MS(TC_{15})	15
Tension Cylinder with 20% MS (TC_{20})	20
Tension Cylinder with 25% MS (TC_{25})	25

Table 4. Specimen codes and percentage of micro-silica used for water absorption test

Specimen codes	% of Micro-Silica Replacement
Water Absorption Cylinder Control (AC_c)	0
Water Absorption Cylinder with 5% MS (AC_5)	5
Water Absorption Cylinder with 10% MS (AC_{10})	10
Water Absorption Cylinder with 15% MS(AC_{15})	15
Water Absorption Cylinder with 20% MS (AC_{20})	20
Water Absorption Cylinder with 25% MS (AC_{25})	25

Table 5. Concrete cylinders with % of micro silica

Micro Silica as cement	Compressive Strength Test	Split Tensile Strength Test	Water Absorption Capacity Test	Total Number Of Specimens
0%	9	9	3	21
5%	9	9	3	21
10%	9	9	3	21
15%	9	9	3	21
20%	9	9	3	21
25%	9	9	3	21

3.1. Description of Test Specimens

In this study, steel cylinder molds were used. A total of 21 molds were used and the cylinders had standard dimensions of a width of 101.6 mm (4") and a height of 203.2 mm (8"). Among the 21 cylinders, 9 cylinders were prepared for the compressive strength test, 9 for the splitting tensile strength test, and 3 for the water absorption test. These 21 molds were used six times: once for the concrete containing 0% micro-silica and five times for the other percentages (5%, 10%, 15%, 20%, and 25%).

Fig. 2. Cylinder Mold

Fig. 3. Specimen being dried in an oven (water absorption test)

3.2. Materials Used

The materials used in this study included Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I, locally sourced river sand as fine aggregate, crushed stone as coarse aggregate, and micro-silica (silica fume) obtained as an industrial byproduct from the silicon and ferrosilicon alloy industry [22]. Potable water was used for all mixing and curing processes.

3.2.1. Micro-Silica Characterization

The investigation revealed that the micro-silica had a surface area of 0.1365 m^2/g and a specific gravity of 2.2 with an average diameter of 0.6 µm, confirming its extremely fine nature compared to that of cement (typically 300–400 m^2/kg) [23]. The micro-silica used in this research was supplied by a local ferroalloy manufacturing facility in Bangladesh. According to the supplier's chemical analysis, the micro-silica consisted primarily of amorphous SiO_2 (approximately 92%), with minor constituents including Fe_2O_3 (1.2%), Al_2O_3 (0.9%), CaO (0.5%), and trace amounts of MgO and SO_3. The reported surface area value was adopted from previously published literature on micro-silica obtained from similar ferroalloy sources, as direct BET surface area measurement was not performed within this study. These properties were consistent with previously reported values in the introduction [9], [11] confirming its suitability as a pozzolanic additive.

3.2.2. Cement

Cement, which serves as the primary binding material in concrete, plays a crucial role in ensuring the structural integrity of concrete block construction. In Bangladesh, Ordinary Portland Cement (OPC) is predominantly used in concrete construction and for this study, "Shah Cement," a widely recognized brand of Portland cement was selected. In this research. "Shah Cement" adheres to the Bangladesh standard BDS EN 197-1:2003, CEM-I, 52.5 N [24] and also complies with the American standard ASTM C150 type-1 mark [22].

Table 6. Percentage of chemical constituents in Shah Cement [25]

Name of constituents	BS for OPC	Shah Cement
SiO_2	21.0	21.52
MgO	0.70	1.26
Al_2O_3	6.00	4.58
SO_3	1.50	2.76
Fe_2O_3	3.50	3.38
Free Lime	2.00	1.205
CaO	65.0	66.02
IR	1.50	0.45
LOI	4.00	1.234

Fig.4 illustrates the utilization of Ordinary Portland Cement, branded as "Shah Cement"

3.2.3. Coarse Aggregate (CA)

Crushed stone chips sourced locally from Sylhet are employed as the coarse aggregate in this study. The composition consists of 80% of coarse aggregate with a size of 20mm down and 20% with a size of 12mm down.

Table 7. Tests on CA

Test Names	Code Followed Code	Value Obtained
Bulk Specific gravity	ASTM C127 [26]	2.56
Absorption capacity	ASTM C127	0.2%
Gradation	ASTM C33-C33M-16e1	Fineness Modulus 1.9

Table 7 displays the specific gravity and absorption capacity test results for coarse aggregate. The process is demonstrated in Figure 5. This test method complies with the ASTM standard specification C128.

Fig. 5. Specific gravity and absorption capacity of coarse aggregate

3.2.4. Fine Aggregate (FA)

Sand collected from Sylhet. Sylhet sand, often referred to as red sand due to its brownish color, is typically sourced from rivers flowing through certain regions of Sylhet. It is widely distributed across the country. For this research, locally available Sylhet sand was chosen as the fine aggregate.

Table 8 displays the specific gravity and absorption capacity test results for fine aggregate. The process is demonstrated in Figure 6. This test method complies with the ASTM standard specification C128 [27].

Table 8. Tests on FA

Tests Name	Followed Code	Value Obtained
Bulk Specific gravity	ASTM C128 [27]	2.59
Absorption capacity	ASTM C128 [27]	1.8 %
Gradation	ASTM C33-C33M-16e1 [28]	Fineness Modulus 2.86

Fig. 6. Specific gravity and absorption capacity of sand

3.2.5. Micro-Silica

During the smelting process in the silicon and ferrosilicon industries micro-silica produced and the composition includes ultrafine particles that are nearly 100 times smaller than a typical cement particle. Elkem Micro Silica 971 is used for this study.

Fig. 7. Micro Silica (Elkem Micro Silica 971)

3.2.6. Micro Filler Effect

The MS tiny particles reduce the void space within the concrete which makes it a micro filler [29]. The Scanning Electron Microscope (SEM) image reveals the extremely fine particles of micro-silica (MS) which are approximately one hundred times smaller than those of cement or fly ash or cement [30].

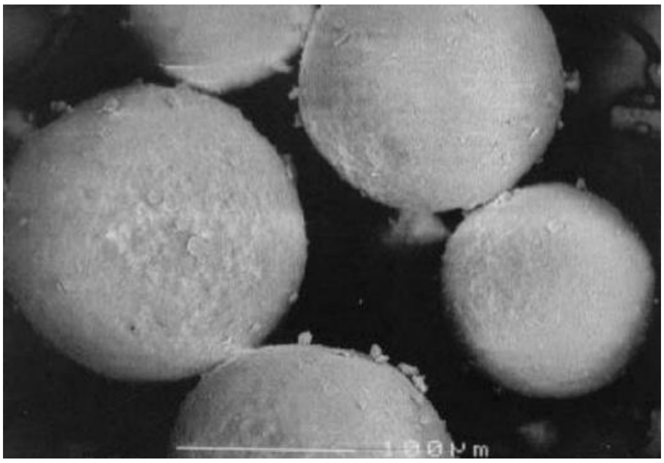

Fig.8. SEM image of condensed MS [31]

3.2.7. Properties of Micro Silica

Although direct SEM imaging and XRF testing were not performed within this laboratory program due to resource limitations, detailed supplier-provided test certificates were analyzed and compared with standard micro-silica characteristics. MS particles are extremely fine with sizes spanning from a minimum of 0.1 μm to a maximum of 0.2 μm. Particles that are finer than the size of 1 μm, take up to 95%. Additionally, MS has a specific gravity less than Portland cement, approximately 2.22 [29].

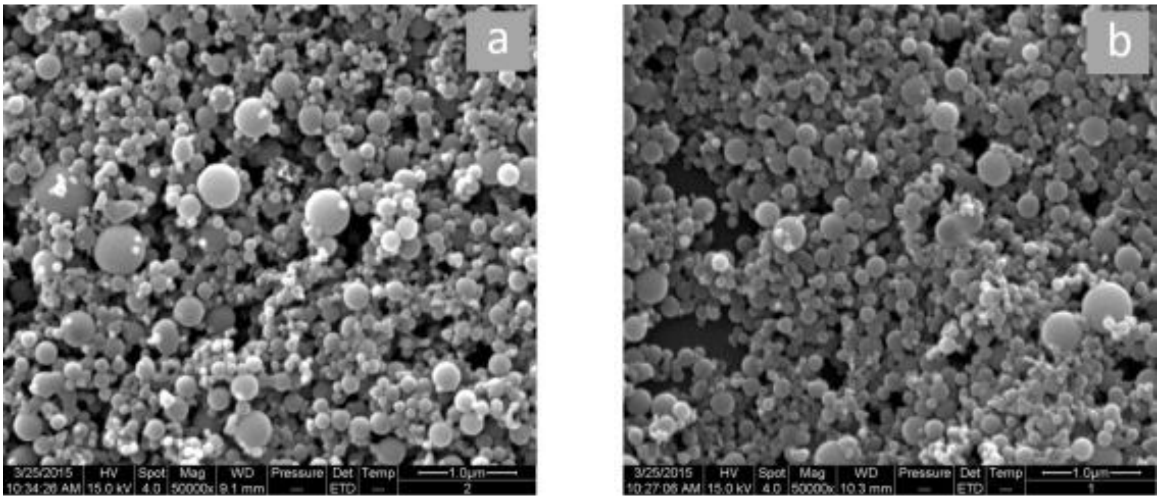

Fig. 9. MS particles micrograph in un-compacted condition (a), compacted condition (b) [29]

In this SEM image the composition consists of 85%-95% SiO_2 or silica and is of spherical shape is showcased. MS is primarily grey, but it can range from nearly white to nearly black. Its surface area is between 15000-25000 m^2/kg. MS particle tends to form agglomerations that are bonded loosely together [32].

The raw materials utilized in the furnace dictate the chemical composition of the MS and it typically contains over 85% of silica, and has relatively low oxides like ferric oxide. alumina, calcium oxide, and alkali content. The MgO content is insignificant and the carbon content ranges between 0.5%-1.5% which typically remains below 2% [29]. The particle morphology of the supplied micro-silica was described as spherical and highly amorphous, with a mean particle diameter of approximately 0.15 µm and a specific surface area of 20,000 m^2/kg, values consistent with those reported by [11] and [33]. Published SEM micrographs of similar-grade micro-silica [9], [12] confirm a uniform, non-crystalline texture, and an absence of large agglomerates, supporting its high pozzolanic reactivity.

To validate the physical and chemical suitability of the micro-silica used in this study, additional characterization data were reviewed and cross-verified with established references. These combined verifications substantiate that the micro-silica incorporated in this research possessed the essential fineness, purity, and reactivity necessary for effective use as a supplementary cementitious material. The chemical composition, verified by XRF data from the supplier, indicated more than 92% amorphous SiO_2, confirming conformity with the requirements of ASTM C1240 for silica fume used in concrete [34].

3.3. ACI Mix Design of Concrete

The concrete mix was designed following the ACI 211.1-91 standard procedure, targeting an M20 grade concrete with a characteristic compressive strength of 20 MPa at 28 days [35]. The water–cement ratio (w/c) of 0.40 was adopted after preliminary trial mixes to ensure a balance between strength development and workability. To maintain consistent workability across all mixes, no chemical admixtures or superplasticizers were used. Instead, the water content was kept constant while mechanical mixing time was slightly increased to enhance particle dispersion. This approach aligns with earlier studies (e.g., [9,12] which reported that while superplasticizers can restore workability in high-silica mixtures, adequate mixing and vibration during compaction can achieve satisfactory consolidation even without chemical admixtures. Based on the results of the materials tests, a mix design was carried out according to ACI standards, showing the ratios of cement (c), fine aggregate (FA), coarse aggregate (CA) and the water-cement ratio (W/C) as detailed in Table 9.

Table 9. Mix design ratio

Name	Value
C: FA: CA	1: 1.5: 3
w/c	0.40

This ratio was selected based on prior findings that a lower w/c ratio enhances strength and reduces porosity, particularly when micro-silica is incorporated, as the pozzolanic reaction requires adequate water for hydration but excessive water can increase bleeding and weaken the bond [11]. Several studies have also reported optimal strength performance of micro-silica concrete within a w/c ratio range of 0.38–0.42, which supports the selection of 0.40 in this work [36,37]. The proportions of cement, fine aggregate, coarse aggregate, water, and micro-silica for each mix are summarized in Table 10. All mix ingredients were measured precisely and mixing was carried out in a rotating drum mixer to achieve uniformity.

Table 10. Mix proportion of components

Micro-silica	Cement (kg/m^3)	Fine agg. FA (kg/m^3)	Coarse agg. CA (kg/m^3)	Micro-silica (MS) (kg/m^3)	Water (kg/m^3)
0%	404.64	659.57	1377.52	0.00	161.86
5%	384.41	659.57	1377.52	20.23	161.86
10%	364.18	659.57	1377.52	40.46	161.86
15%	343.95	659.57	1377.52	60.70	161.86
20%	323.71	659.57	1377.52	80.93	161.86
25%	303.48	659.57	1377.52	101.16	161.86

3.4. Slump Test

The slump test, as specified in ASTM C143/C143M standards, utilizes a slump cone to determine the slump value for evaluating the workability of freshly poured concrete [38]. The slump cone measures twelve inches in height, containing a top diameter of four inches and a bottom diameter of eight inches. The cone is filled in three distinct layers, with each layer being compacted twenty-five times utilizing a tamping rod. This investigation involved conducting the slump test on both conventional concrete and Micro Silica bonded concrete, as shown in Figure 10.

Fig. 10. Slump test

3.5. Casting and Curing

Total 126 cylinders were casted. Among them, 21 cylinders were of cement replaced by 5%, 10%, 15%, 20%, 25% of micro silica. Furthermore, a control cylinder was produced with 0% micro silica to assess the strength in comparison to the varying levels of replacement. Following a 24-hour casting period, the cylinders were carefully demolded and immersed in water for curing, as illustrated in Figure 11, in accordance with the specifications detailed in ASTM C192/C192M-02 [39]. After a duration of immersion of 7, 14, and 28 days, the concrete cylinder specimens were readied for assessment. Figure 11 illustrates the curing process of different concrete cylinder specimens while Figure 12 displays the condition of these concrete cylinder specimens after the 28-day curing period has concluded.

Fig. 11. Curing of some concrete cylinder specimens

Fig. 12. Concrete cylinder specimen after 28 days of curing

3.6. Compressive, Split Tensile Strength and water absorption Test

Compressive and split tensile strength tests were conducted on concrete specimens in compliance with ASTM C39 and ASTM C496 [43] standards, respectively. An ADR testing machine was employed to apply a gradual axial force, with bearing plates ensuring uniform load distribution across specimens (refer to Figure 13) and the load application rate was maintained within 0.2–0.4 N/mm^2 per second a critical parameter, as deviations could compromise accuracy. The compressive strength of the specimen was calculated by using the Eq. (1).

$$C = \frac{P}{\pi r^2} \tag{1}$$

Where, C = Compressive strength, (MPa), r = Radius of the specimen, (mm) and P = Maximum applied load, (N). All measurements are in SI units.

Specimens were deemed to have failed when the load exhibited a sustained decline despite consistent application. Minor pre-failure load fluctuations were excluded from analysis, with the peak load recorded as the failure point. Therefore, the splitting tensile strength was determined by applying a compressive force along the diameter of cylindrical concrete specimens using a hydraulic testing apparatus. As the ADR machine gradually increased the applied load, tensile stresses were generated across the horizontal plane of the cylinder, eventually causing a typical diametral crack indicative of tensile failure. Each specimen was carefully positioned in the loading frame, with a specially designed platen or disc placed on top to facilitate even load distribution (refer to Figure 14). The tensile strength was then computed using Eq. (2).

$$T = \frac{2P}{\pi l d} \tag{2}$$

where, P = Maximum applied load, N, l = Length of the specimen, (mm), T = Split tensile strength, (MPa) and d = Diameter of the specimen, (mm). All measurements are in SI units. The arrangement for the test is illustrated in Figures 13 and 14 while depictions of various types of failure in concrete cylinders occurs.

Figure 13. Compressive strength test

Water absorption tests are typically conducted following standards such as ASTM C1585-13 which outline specific procedures for conducting the test and interpreting the results [40]. Specimens underwent an initial drying process in an oven before being completely immersed in water. After that, the specimens were removed from the water and dried again in the oven, as depicted in Figure 10. These standardized protocols ensure consistency and reliability in assessing the water absorption characteristics of concrete cylinders. After adhering to the established procedure, the weight of the specimens was measured, and water absorption was calculated using the widely employed formula:

$$\%W = \frac{WS - WD}{WD} x100 \quad (3)$$

Where, W = Percent water absorption ×100; WS = Weight of specimen at fully saturated condition (kg); WD = Weight of oven dried specimen (kg).

Figure 14. Split tensile strength test

Fig. 15. Oven drying of concrete specimens prior to water absorption testing to ensure consistent moisture removal

4. Experimental Program

The experimental program was designed to systematically evaluate the mechanical and physical performance of concrete incorporating micro-silica as a partial replacement of cement and it was comprised into three main test categories as compressive strength, splitting tensile strength, and water absorption. After casting, all concrete specimens were demolded after 24 ± 2 hours and immediately submerged in a curing tank containing potable water until the designated testing ages of 7, 14, and 28 days. The curing environment was maintained under controlled laboratory conditions with a temperature of 25 ± 2 °C and relative humidity of approximately 70 ± 5% to ensure consistent hydration of the cementitious matrix.

All specimens were wiped clean and tested in a surface-dry condition immediately after removal from curing water. Throughout the curing period to maintain uniform conditions; temperature and humidity were periodically monitored using a digital thermo hygrometer. This controlled environment ensured that variations in curing did not influence the comparative performance of the mixes.

5. Results and Discussion

5.1. Compressive Strength

Figure 16 shows the variation of compressive strength with micro-silica content is shown. The results represent the average of three specimens for each mix, with error bars indicating one standard deviation to reflect data variability and ensure statistical reliability. Compressive strength consistently increased with the incorporation of micro-silica up to 20% replacement, after which a slight decline was observed at 25%. This enhancement can be attributed to the pozzolanic activity of micro-silica, which reacts with calcium hydroxide (CH) liberated during cement hydration to form additional calcium silicate hydrate (C-S-H) gel [9]. However, at 25% replacement, the reduction in strength is likely due to the dilution effect an excessive reduction in cementitious material limits the formation of primary hydration products, leading to incomplete bonding.

Table 11. Average compressive strength of different percentages in various curing days

Percentage of cement replacement by % of micro-silica	7 days	14 days	28 days
	Avg compressive strength MPa	Avg compressive strength MPa	Avg compressive strength MPa
0%	18.08	19.93	22.02
5%	19.54	22.49	24.18
10%	21.38	24.97	26.54
15%	23.55	28.32	28.73
20%	25.73	28.93	31.38
25%	22.38	25.26	28.67

Table 12. Mean compressive strength, mpa and standard deviation by cement replacement

Cement Replacement (%)	Days	Mean (MPa)	SD (MPa)	±SD (MPa)
0%	7	18.08	0.47	0.94
0%	14	19.93	0.54	1.08
0%	28	22.02	0.76	1.52
5%	7	19.54	0.23	0.46
5%	14	22.49	0.74	1.48
5%	28	24.18	0.52	1.04
10%	7	21.38	0.45	0.90
10%	14	24.97	0.64	1.28
10%	28	26.54	0.70	1.40
15%	7	23.55	0.58	1.16
15%	14	28.32	0.71	1.42
15%	28	28.73	0.73	1.46
20%	7	25.73	0.58	1.16
20%	14	29.93	0.72	1.44
20%	28	31.38	0.77	1.54
25%	7	22.38	0.95	1.90
25%	14	25.26	0.64	1.28
25%	28	28.67	1.57	3.14

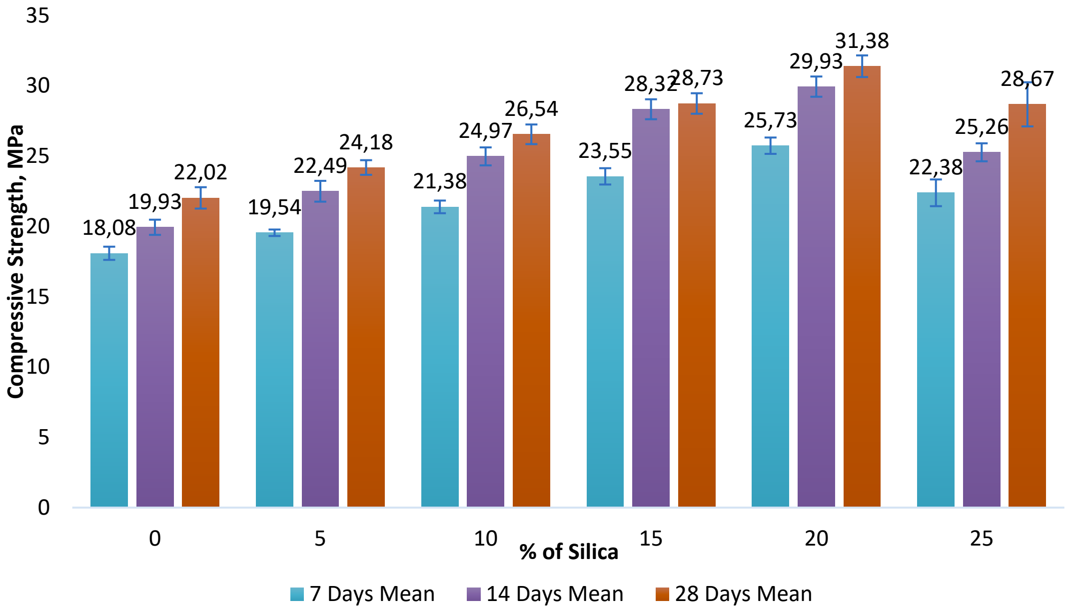

Fig. 16. Compressive strength comparison histogram after 7,14,28 days of curing at different replacement of silica fume percentages

5.2. Split Tensile Strength

In figure 17, the splitting tensile strength results are illustrated. The tensile strength followed a trend similar to that of compressive strength, increasing progressively up to 20% replacement and then decreasing slightly at 25%. The increase in tensile performance is primarily associated with the dense interfacial transition zone (ITZ) formed in the presence of micro-silica. The maximum tensile strength improvement recorded was approximately 38% compared to the control mix. The slight drop beyond 20% replacement can be attributed to reduced workability and incomplete dispersion of micro-silica particles.

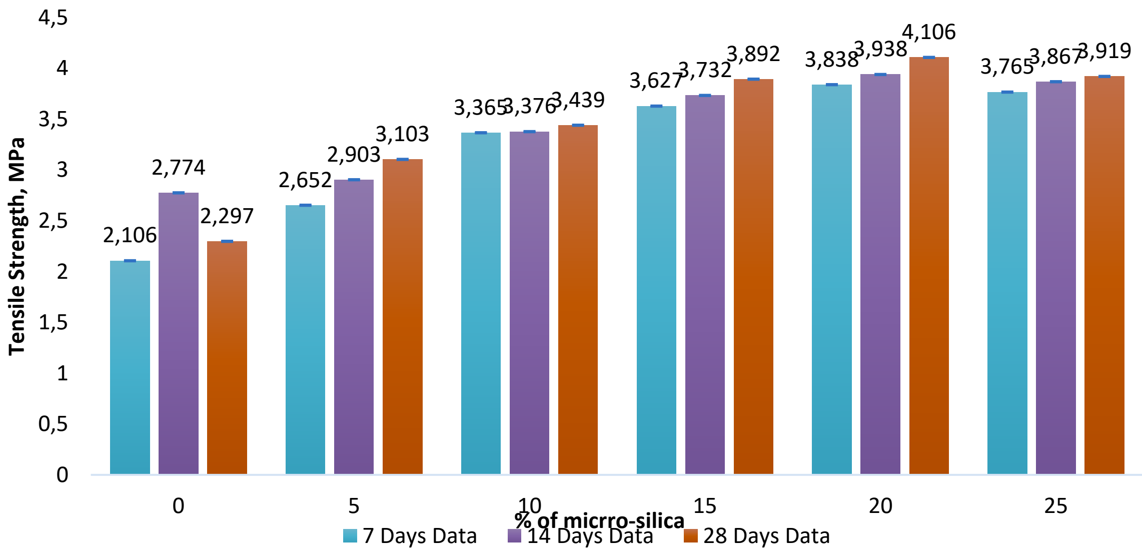

Fig. 17. Split strength comparison graph after 7, 14, and 28 days of curing at different replacement of silica fume percentages

Table 13. Split Tensile Strength, MPa with Error Bars and SD

Percentage of Micro Silica	Days	Mean Tensile Strength (MPa)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	SD (MPa)	±SD (MPa)
0%	7	2.106	2.10	2.11	2.10	0.006	0.012
0%	14	2.774	2.77	2.78	2.77	0.006	0.012
0%	28	2.297	2.29	2.30	2.30	0.006	0.012
5%	7	2.652	2.65	2.66	2.65	0.006	0.012
5%	14	2.903	2.90	2.91	2.90	0.006	0.012
5%	28	3.103	3.10	3.11	3.10	0.006	0.012
10%	7	3.365	3.36	3.37	3.37	0.006	0.012
10%	14	3.376	3.37	3.38	3.38	0.006	0.012
10%	28	3.439	3.44	3.44	3.44	0.000	0.000
15%	7	3.627	3.62	3.63	3.63	0.006	0.012
15%	14	3.732	3.73	3.73	3.73	0.000	0.000
15%	28	3.892	3.89	3.89	3.89	0.000	0.000
20%	7	3.838	3.83	3.84	3.84	0.006	0.012
20%	14	3.938	3.94	3.94	3.93	0.006	0.012
20%	28	4.106	4.10	4.11	4.11	0.006	0.012
25%	7	3.765	3.76	3.77	3.77	0.006	0.012
25%	14	3.867	3.86	3.87	3.87	0.006	0.012
25%	28	3.919	3.92	3.92	3.92	0.000	0.000

5.3. Water Absorption Test

Figure 18 shows how the amount of micro-silica used as a replacement influences the quantity of water it absorbs. The overall water absorption of concrete decreased progressively with increasing micro-silica content up to 15%, indicating improved pore refinement and matrix densification due to the pozzolanic reaction and filler effect of the ultrafine silica particles. But when the mix was 20% replaced, the water absorption rose up a little bit compared to the 15% mix, and then it went down again a slightly less at 25%. At 20% replacement, there was a big drop in water absorption, up to 42% lower than plain concrete.

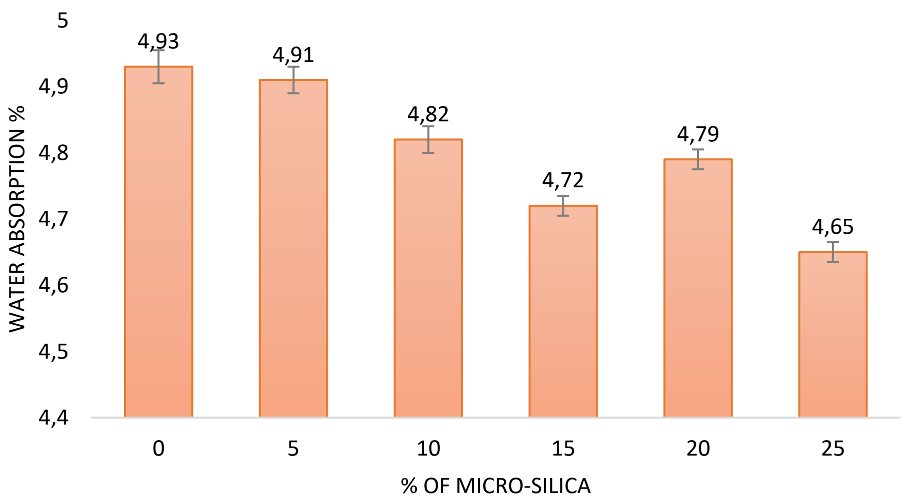

Fig. 18. Water absorption histogram after 28 days of curing at different replacement of silica fume percentages

This minor anomaly at 20% can be attributed to localized agglomeration of excess micro-silica, which may have caused uneven dispersion and incomplete hydration in certain areas. The high surface area of micro-silica increases the water demand. If there are absence of superplasticizers, this can result in minor micro-void formation, slightly elevating permeability despite the overall densification of the matrix.

Table 14. Water absorption percentages with error bars and SD

Micro Silica %	Mean Water Absorption (%)	Sample 1 (%MS)	Sample 2 (%MS)	Sample 3 (%MS)	SD (%MS)	±SD (%MS)
0%	4.93	4.90	4.95	4.94	0.025	0.050
5%	4.91	4.89	4.92	4.93	0.020	0.040
10%	4.82	4.80	4.83	4.84	0.020	0.040
15%	4.72	4.70	4.73	4.73	0.015	0.030
20%	4.79	4.77	4.80	4.80	0.015	0.030
25%	4.65	4.63	4.66	4.66	0.015	0.030

*MS= Micro-silica

The decrease in water absorption at 25% replacement suggests that the addition of micro-silica partially compensated for these localized effects by making the pore structure more effective. The overall improvement, however, was still moderate, which shows the pozzolanic contribution of micro-silica is limited by binder dilution and insufficient calcium hydroxide availability.

5.4. Statistical Reliability of Experimental Results

To assess the reliability of the experimental data, all test results were analyzed using basic statistical evaluation, including mean and standard deviation calculations from three replicate specimens (n = 3) per mix proportion [41-43]. The mean ($\bar{x}$) and standard deviation (σ) were computed using: $\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2}{n-1}}$ where x_i is the individual test result and $\bar{x}$is the mean of the three specimens.

The addition of error bars (± SD) in Tables 12–14 further confirms that the results are consistent and that the performance trends seen are statistically significant rather than experimental anomalies. These results confirm that the experimental protocol is reliable and support the finding that 20% micro-silica content is the best level for better mechanical and physical performance.

Table 15. Statistical Summary of Results at 20% Micro-Silica Replacement

Test Parameter	Mean Value	Standard Deviation (SD)	Coefficient of Variation (CV%)	Interpretation
Compressive Strength (28 days)	31.38 MPa	0.77 MPa	2.45%	High consistency among specimens [44]
Splitting Tensile Strength (28 days)	4.106 MPa	0.006 MPa	0.15%	Low variability, excellent reproducibility [45]
Water Absorption (28 days)	4.79%	0.015%	0.31%	Negligible scatter, very stable results

The minimal variability validates the accuracy of the test procedures. The CV values below 5% for mechanical tests and below 1% for absorption indicate excellent precision, aligning with ASTM and ACI statistical acceptance criteria for laboratory concrete testing.

6. Conclusions

This experimental study assessed the influence of micro-silica as a partial replacement of cement on the mechanical and physical performance of concrete. In contrast to numerous previous studies focused solely on strength analysis, this research provides an integrated assessment of strength and absorption behavior across a wide replacement range (5–25%) under a constant w/c ratio of 0.40, identifying a statistically validated optimum performance level. The experimental results demonstrated that substituting 20% of cement with micro-silica produces the most advantageous performance across all evaluated parameters. At this level, concrete reached a compressive strength of 31.38 MPa, which is 56.6% better than the control mix after 28 days of curing. The splitting tensile strength at 20% replacement improved by approximately 38% compared to plain concrete. Also, the water absorption decreased by nearly 42% at 20% replacement, confirming substantial refinement of the pore structure and a potential increase in long-term durability.

The partial replacement of cement with micro-silica directly translates into a 20% reduction in cement consumption, leading to an equivalent reduction in CO_2 emissions during concrete production. Thus, the use of micro-silica not only improves performance but also supports sustainable and eco-efficient construction practices. The study's findings bridge a critical knowledge gap by linking mechanical improvements with permeability reduction and sustainability outcomes.

6.1 Future Recommendation

Future studies are planned to expand this investigation by integrating advanced durability tests and microstructural analyses (SEM, XRD, and porosity measurement) to enhance the understanding of pore refinement mechanisms. This study primarily concentrated on short-term mechanical and permeability-based assessments; however, the integration of extensive durability tests, including rapid chloride ion penetration (RCPT), sulfate attack resistance, carbonation depth, or freeze-thaw cycling, would yield additional insights into the long-term performance of micro-silica. Consequently, the present work thus serves as a foundational phase, quantifying the immediate mechanical and absorption-related effects of micro-silica replacement in preparation for more extensive durability research.

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