

Compressive Strength of High-strength Concrete Incorporating Micro-silica and Quarry-dust

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Abstract

This study investigates the synergistic effect quarry dust, as a partial replacement for fine aggregate, and micro-silica, used as a partial replacement for cement, on the compressive and flexural strength of high-strength concrete (HSC), with a target grade of 80 MPa. Twenty mixes were produced using a combined percentage replacement of 0%, 5%, 10%, 15%, and 20%, across four water-binder ratios of 0.20, 0.24, 0.28, and 0.32. Compressive strength was measured at curing ages of 3, 7, 14, and 28 days, while flexural strength (modulus of rupture) was determined experimentally on prisms at 28 days and further compared against values predicted by the Eurocode 2 and ACI 318-11 code equations. Results showed that strength increased with percentage replacement up to an optimum of 10% PR, beyond which it declined, with the highest 28-day compressive strength of 73.40 MPa and highest flexural strength of 5.85 MPa both recorded at 10% PR and a water-binder ratio of 0.20, representing increases of 27.43% and 16.30% respectively over the control mixture. The Eurocode 2 equation consistently overestimated experimental flexural strength by approximately 10%, while ACI 318-11 underestimated it by approximately 17–18%. Result also revealed that combined 10% quarry dust and micro-silica replacement at a water-binder ratio of 0.20 produced the maximum strength performance and is recommended for high-end structural applications.

Keywords: Microsilica, QuarryDust, High-strength, Water Cement ratio., Compressive strength.

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1. INTRODUCTION

Concrete is the most widely used construction material in the world due to its versatility, availability, and relatively low cost (Badalyan *et al.*, 2024; ACI Committee on Silica Fume, 2010). It forms the essential framework of buildings, bridges, dams, roads, and various vital structures. With a continually expanding global population, the demand for infrastructure continues to surge, and so too does the demand for concrete. As the demand for concrete grows, so does the demand for concrete capable of withstanding high structural loads and possessing higher strength, which has driven the development of High Strength Concrete (HSC) (C. Zhang *et al.*, 2021).

High Strength Concrete (HSC) is a specialized form of concrete designed to exhibit superior mechanical performance, particularly higher compressive, tensile, and flexural strength, compared to conventional concrete (Ahmadi *et al.*, 2022; Ullah *et al.*, 2025). HSC is increasingly demanded in modern infrastructure projects such as high-rise buildings, bridges, and marine

structures, where both structural performance and durability are critical (Ng *et al.*, 2025). HSC is generally known for achieving compressive strengths above 40 to 60 MPa at 28 days, with many modern applications pushing well into the 80 to 110 MPa range and beyond. It is created using low water-binder ratios (often 0.20-0.40), high cement content, high-quality aggregates, powerful chemical admixtures such as superplasticizers, and the addition of Supplementary Cementitious Materials (SCMs), which together give HSC its characteristically high compressive strength.

Supplementary Cementitious Materials (SCMs) are admixtures, chemicals, and substances that, when used in concrete, improve concrete properties and reduce cement and fine aggregate usage. Two such materials, Quarry Dust (QD) and Micro-Silica (MS), are of particular interest to this study. Micro-Silica (MS) is a by-product of producing silicon metal or ferrosilicon alloys in smelters using electric-arc furnaces, and finds wider industrial use in aluminum and steel production, computer chip fabrication, and the production of

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silicones used in lubricants and sealants (Mazloom, 2004; Badalyan *et al.*, 2024). Quarry Dust (QD) is a by-product of aggregate crushing and production plants, comprising approximately 30% to 40% of the total output of such operations, and forms a fine-grained, grey dust that may be used as a fine aggregate in concrete, predominantly as a substitute for natural sand (Ng *et al.*, 2025; Mazloom, 2004).

Combining QD and MS in HSC has the potential to produce concrete with higher strength than either material used alone; quarry dust acts as a physical filler whose angular particles and graded fines improve particle packing density, reduce voids in the aggregate skeleton, and lower the overall cement paste demand, while micro-silica offsets any workability loss or increased water demand that results from quarry dust's angular particles and high fines content. Reported studies suggest that such combined systems can achieve compressive strengths greater than 80 to 110 MPa with optimized replacement levels, while also improving resistance to water penetration (Khan, 2011; Badalyan *et al.*, 2024). Given the growing demand for durable and high-strength infrastructure, and the comparative scarcity of research examining quarry dust and micro-silica together at high-strength grade, there is a compelling need to investigate concrete mixtures that combine mechanical strength with practical, locally sourced materials.

This research is a laboratory-based experimental case study focused on producing and assessing high-strength concrete mixes suitable for high-rise and general infrastructure applications, carried out in the Civil Engineering Laboratory of Rivers State University, Nkpolu-Oroworukwo, Port Harcourt. The study used locally sourced materials, comprising ordinary Portland cement (Grade 52.5N) from a Nigerian manufacturer, river sand and coarse granite aggregate from local suppliers, quarry dust from a nearby quarry, and densified micro-silica from an industrial supplier. The mix designs targeted an HSC grade of 80 MPa, with quarry dust and micro-silica introduced jointly as a combined percentage replacement (PR) of 0%, 5%, 10%, 15%, and 20%, tested across four water-binder ratios of 0.20, 0.24, 0.28, and 0.32, giving a total of twenty distinct trial mixes, including a control mix at 0% replacement. Superplasticizer was added where necessary to maintain workability. Specimens comprised 100 mm cubes for compressive strength tested at curing ages of 3, 7, 14, and 28 days, 100 mm x 100 mm x 500 mm prisms for flexural strength, tested at curing age of 28 days under standard moist curing conditions.

1.2 Literature Review:

High strength concrete (HSC) is commonly produced by lowering the water to binder ratio and incorporating highly reactive supplementary cementitious materials such as micro-silica to densify the matrix and improve mechanical and bond properties

(Neville, 2011; Mehta & Monteiro, 2014). In recent years, several researchers have focused on combining micro-silica and quarry dust as partial replacements of cement and fine aggregate respectively to enhance strength and sustainability of concrete (Prakash, 2017; Karthik & Chandrasekar, 2019). Most of these studies reported that appropriate levels of micro-silica and quarry dust can considerably improve compressive, tensile, flexural and bond characteristics of concrete compared with conventional mixes (Prakash, 2017; Reddy & Rao, 2020).

A number of studies within the last decade have examined the mechanical behavior of concrete when both cement and fine aggregate are partially replaced by silica fume and quarry dust. Prakash (2017) investigated high -performance concrete (HPC) with 15% silica fume as replacement of cement and partial to full replacement of fine aggregate with quarry dust and found up to about 23% increase in compressive strength due to silica fume and about 12% increase due to quarry dust, relative to control concrete. Similarly, Reddy and Rao (2018) studied M30 concrete using silica fume and quarry dust and observed that 10-15% cement replacement by silica fume and 30-40% fine aggregate replacement by quarry dust increased compressive strength and modulus of rupture compared with conventional concrete. In another experimental study, Sharma and Singh (2019) reported that combinations of 10% silica fume and 40% quarry dust produced higher compressive strength than control mixes of similar grade.

Recent work by Thomas and George (2020) evaluated the mechanical performance of M50 grade high strength concrete using silica fume as cement replacement and quarry dust as fine aggregate replacement. They found that mixes containing 10% silica fume and 50% quarry dust achieved higher compressive and flexural strengths at 28 days than reference mixes, though workability was reduced. In a related study, Kumar and Babu (2021) examined M40 concrete with 5%, 10%, and 15% silica fume and 20-40% quarry dust and reported optimum compressive strength at about 10% silica fume and 30% quarry dust. Their results indicated that excessive quarry-dust content beyond the optimum level tends to reduce workability and may hinder proper compaction.

Beyond compressive strength, several researchers have examined flexural behavior of concrete mixtures containing silica fume and quarry dust. Ali and Patel (2018) showed that for M30 concrete, a mix with 10% silica fume and 30% quarry dust exhibited an increase in flexural strength of about 15-20% over the control mix. In another study, Khan and Iqbal (2019) reported that the split tensile strength of concrete with 5% silica fume and 20% quarry dust was improved by more than 40% compared with conventional concrete. Das and Ghosh (2020) observed that the flexural strength of high-grade concrete incorporating 10% silica fume

and 25-30% quarry dust was superior to the control, attributed to improved interfacial transition zone and packing density.

Several recent studies have also considered the behavior of concrete mixes incorporating silica fume and quarry dust at early and later ages. Joseph and Mathew (2017) reported that replacement of cement with silica fume at 10-15% and sand with quarry dust up to 40% produced higher early-age strength (7 days) compared to control concrete, with strength gains continuing at 28 days. Likewise, Banerjee and Saha (2018) found that the strength gains at later ages (56 and 90 days) for silica fume and quarry dust concrete was more pronounced than in conventional mixes, which was attributed to continued pozzolanic reaction and refinement of pore structure. Similar trends were observed by Oke and Adeleke (2021), who reported that high strength concrete with 10% silica fume and 40% quarry dust showed steady strength development beyond 28 days.

In addition to mechanical properties, workability and fresh properties of silica fume-quarry dust concretes have been investigated. Prakash (2017) noted that the inclusion of silica fume tends to reduce slump due to its high specific surface area, while quarry dust further affects workability because of its angular particles. However, by using appropriate water-reducing admixtures, acceptable workability was achieved in their high-performance concrete mixes. Chitra and Rajendran (2019) similarly observed reduced slump with increasing quarry-dust content but reported that admixture usage and proper proportioning could maintain workable mixes at about 30-40% quarry-dust replacement.

While the above studies largely focused on strength and fresh properties, several recent works have explicitly considered bond characteristics and interfacial behavior in concretes containing silica fume, although often without quarry dust. Mohammed and Ibrahim (2019) investigated bond strength between reinforcing bars and silica-fume concrete using pull-out tests and found that substitution of 10% cement with silica fume significantly increased ultimate bond strength and reduced slip at failure. Similarly, Park and Lee (2020) studied bond behavior in high strength silica-fume concrete and reported improved bond stress-slip response compared to normal strength concrete, due to densification of the interfacial transition zone.

Other bond-oriented studies explored the effect of silica fume and related additives on overlay bond and repair systems. Wang *et al.* (2018) examined polymer cement mortars modified with silica fume as overlays on existing concrete substrates and reported that about 5% silica fume enhanced interfacial bond strength and changed the failure mode from pure interface failure to a composite failure pattern. Zhang, *et al.* (2022) studied the durability of silica-fume-modified overlays subjected to wetting-drying cycles and found that silica fume

improved bond performance and reduced debonding under environmental exposure. These studies, although focused on overlays, demonstrate the beneficial effect of silica fume on bond and interfacial performance.

Quarry dust has also been examined from the perspective of its influence on the mechanical behavior and microstructure of concrete. Singh and Kaur (2018) analyzed M25 concrete with 20-50% quarry dust as fine aggregate replacement and reported increased compressive and flexural strength up to about 40% replacement, with a slight reduction beyond this level. Lakshmi and Suresh (2019) reviewed the potential of quarry-dust waste as aggregate in concrete and concluded that properly graded quarry dust can be used safely up to around 40-50% replacement in many mixes without compromising strength. Their review highlighted the environmental benefits associated with reducing natural sand extraction.

More recent works have combined quarry dust with other industrial by-products and pozzolans. Rao and Prasad (2020) studied the combined effect of silica fume and fly ash with quarry dust and observed additive improvements in compressive strength when both mineral admixtures were included along with quarry dust. Adetayo and Okafor (2022) investigated high grade concrete with micro-silica and quarry dust in the presence of steel fibers and reported enhanced compressive and flexural strengths, as well as improved toughness. Although their primary focus was on fiber synergy, their results still confirm the positive role of micro-silica and quarry dust in high-performance mixtures.

A few recent studies have begun to explicitly consider both mechanical and bond performance in mixes incorporating micro-silica and quarry dust. Sahu and Patel (2021) studied M40 concrete with 10% silica fume and 30% quarry dust and evaluated both compressive strength and pull-out bond strength of deformed bars. They found that the modified concrete exhibited higher compressive strength and about 15-20% higher bond strength than the control mix. In another work, Gupta and Verma (2023) investigated the development length and bond behaviour of bars embedded in silica-fume concrete and reported reduced required development length due to improved bond, although quarry dust was not explicitly considered.

Finally, several authors have highlighted the sustainability and economic advantages of using silica fume and quarry dust. Lakshmi and Suresh (2019) and Oke and Adeleke (2021) noted that using quarry dust reduces waste disposal problems and mitigates the depletion of natural river sand, while micro-silica utilization promotes beneficial use of industrial by-products. Adetayo and Okafor (2022) further emphasized that high-performance concretes incorporating these materials can achieve superior

performance with lower overall material cost, making them attractive for developing regions.

In a Nigerian context, Animashaun *et al.* (2025) evaluated concrete in which quarry dust partially replaced cement (rather than fine aggregate) at 0%, 10%, 20%, 30%, and 40% by weight, and tracked compressive strength, durability in dilute sulphuric acid, and linear shrinkage up to 28 days. Their results showed that strength increased with replacement up to an optimum of 20% (about 27.4 N/mm² at 28 days), beyond which strength declined, while abrasion and acid resistance continued to improve at higher quarry dust contents.

Khan, Abbas, and Fares (2023) carried out comprehensive experimental research on 40 concrete mixes incorporating silica fume (8%, 10%, and 12%) and an ultrafine micro-quartz filler across water-binder ratios ranging from 0.25 to 0.40. Their results showed that the 28-day compressive strength gain from silica fume became progressively more pronounced as the water-binder ratio increased, with improvements of about 9% at a water-binder ratio of 0.25 rising to about 18% at a water-binder ratio of 0.40 for the highest silica fume dosage tested. The authors attributed this trend to the micro-filling and pozzolanic action of silica fume becoming increasingly beneficial as the matrix becomes more porous at higher water-binder ratios. This finding is directly relevant to the present study, which similarly investigates strength response over a range of water-binder ratios (0.20-0.32), and suggests that the silica-fume mixes examined here would be expected to show their largest relative strength gains at the upper end of the tested water-binder ratio range.

2. MATERIALS AND METHODS

2.1 Material

- i. **Cement:** Ordinary Portland Cement (OPC) Grade 52.5N was used as the primary hydraulic binder. The cement complied with the requirements of ASTM C150/C150M-22 (Standard Specification for Portland Cement) and BS EN 197-1:2019 (Cement - Composition, specifications and conformity criteria). It was obtained from Dangote Cement in compliance with NIS414.
- ii. **Microsilica:** Densified silica fume (microsilica) was used as a supplementary cementitious material in this study. The material met the requirements of ASTM C1240-20 (Standard Specification for Silica Fume Used in Cementitious Mixtures) and BS EN 13263-1:2005+A1:2009 (Silica fume for concrete - Definitions, requirements and conformity criteria). The microsilica was supplied in powder form and contained more than 85% silicon dioxide (SiO₂), with a specific surface area greater than 15,000 m²/kg.
- iii. **Quarry Dust:** Quarry dust (QD), a by-product obtained from granite crushing operations, was used as a partial replacement for natural river sand in this study. The material was sourced from a local quarry

in Rivers State and satisfied the physical requirements specified in BS EN 12620:2002+A1:2008 (Aggregates for concrete) and ASTM C33/C33M-18 (Standard Specification for Concrete Aggregates). Before use, the quarry dust was passed through a 4.75 mm sieve to eliminate oversized particles and any unwanted impurities.

- iv. **Fine Aggregate (Natural River Sand):** Natural River sand was used as the control fine aggregate and complied with the specifications of BS EN 12620:2002+A1:2008 and ASTM C33/C33M-18. The sand was obtained from a local supplier and thoroughly washed to remove silt, clay, and other impurities. It was graded to meet the requirements of Zone II classification. Prior to sieve analysis, the sand was oven-dried to ensure an accurate determination of its particle size distribution.
- v. **Coarse Aggregate:** Crushed granite with a nominal maximum size of 10 mm was used as the coarse aggregate in this study. The aggregate complied with the requirements of BS EN 12620:2002+A1:2008 and ASTM C33/C33M-18. It was obtained from a certified quarry in Rivers State and thoroughly washed to remove dust and fine particles. The material was also properly graded to meet the specified size requirements.
- vi. **Water:** Potable water was used for both the mixing and curing of concrete specimens. The water satisfied the requirements of BS EN 1008:2002 (Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water) and ASTM C1602/C1602M-22 (Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete). It was obtained from the municipal water supply at Rivers State University and was free from harmful substances that could interfere with cement hydration or reduce the durability of the concrete.
- vii. **Superplasticizer:** A High-Range Water-Reducing Admixture (HRWRA) based on polycarboxylate ether was used to improve the workability of the concrete while maintaining a low water-binder ratio. The admixture complied with ASTM C494/C494M-19 (Standard Specification for Chemical Admixtures for Concrete) Type F and BS EN 934-2:2009+A1:2012 (Admixtures for concrete, mortar and grout). The superplasticizer was stored and handled according to the manufacturer's instructions to ensure that its performance remained effective throughout the experimental work.

2.2 Specimen Preparation

Concrete constituent materials were sourced and test on physical properties such as specific gravity and particle size distribution were conducted to BS 812:1999 and B1377:197 respectively, Values obtained were used to compute mix design based on particle packing method as per ASTM C29. A total of 240 cubes of size 150 mm × 150 mm × 150 mm were prepared and

cast as per BS 1881:199. A total of 60 beam prisms of size 100 mm × 100 mm × 500 mm as per BS 12390-13.

2.3 Mix design of High-strength

The mix design was based on Particle packing method for proper minimization of void. The mix proportions obtained is presented in Table 2.1

Table 2.1: Mix Proportion Table for Water Binder Ratios of 0.20, 0.24, 0.28 and 0.32

Mix	Percentage replacement	Cement (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	Micro silica (kg/m ³)	Quarry Dust (kg/m ³)	Superplasticizer (%)
0.20	0%	549.48	797.55	1196.32	0	0	1.5
	5%	544.08	737.64	1167.75	34.28	40.86	1.5
	10%	510.15	697.01	1164.58	68.21	79.38	1.5
	15%	477.04	655.87	1161.40	101.32	118.40	1.5
	20%	450.54	616.87	1158.40	127.82	155.39	1.5
0.24	0%	523.00	788.64	1182.96	0	0	1.5
	5%	505.04	660.14	1203.84	31.82	142.42	1.5
	10%	473.84	719.01	1201	63.02	81.66	1.5
	15%	442.93	798.55	1197.83	94.07	122.11	1.5
	20%	412.72	617.59	1159.57	123.664	155.45	1.5
0.28	0%	500.81	780.84	1171.3	0	0	1.5
	5%	475.77	739.68	1167.92	29.68	39.85	1.5
	10%	441.81	697.03	1164.58	59.0	79.36	1.5
	15%	413.11	656.63	1162.74	87.70	118.53	1.5
	20%	385.47	615.90	1160.4	115.34	157.70	1.5
0.32	0%	459.64	787.52	1181.29	0	0	1.5
	5%	432.26	745.63	1178.78	27.38	40.22	1.5
	10%	405.42	704.03	1176.27	54.21	80.15	1.5
	15%	379.12	663.03	1173.94	80.32	119.67	1.5
	20%	353.78	621.75	1171.6	105.86	159.31	1.5

Compressive Strength Test

Compressive strength was determined using 100 mm cube specimens at curing ages of 3, 7, 14, 21, and 28 days, following the procedures outlined in BS EN 12390-3:2019 and ASTM C39/C39M-21. After casting, the specimens were demolded after 24 hours and cured in water at 23 ± 2°C until the testing age.

Before testing, the cube surfaces were dried and placed centrally in a calibrated compression testing machine with a capacity of 2000 kN. Load was applied at a constant rate of 0.6 ± 0.2 MPa/s until failure occurred. The maximum load was recorded and the compressive strength was calculated using:

$$f_c = \frac{P}{A} \quad (3.1)$$

Where:

f_c : compressive strength (MPa)

P: maximum applied load (N)

A: cross-sectional area of the specimen (mm²)

For each mixture and curing age, the reported compressive strength represents the average value of three specimens.

3. RESULTS AND DISCUSSION

The required the mix design of HSC containing quarry dust and micro-silica at 0%, 5%, 10%, 15% and 20% replacement by weight of cement, together with varying water-binder ratios, targeting a 28-day compressive strength of 80 MPa. Mixes were proportioned and cast across a percentage replacement range of 0%, 5%, 10%, 15% and 20% and water-binder ratios of 0.20, 0.24, 0.28, and 0.32. 28-day recorded the highest compressive strength compressive strength (73.4 MPa, at 10% replacement and a water-binder ratio of 0.20).

Compressive strength Result

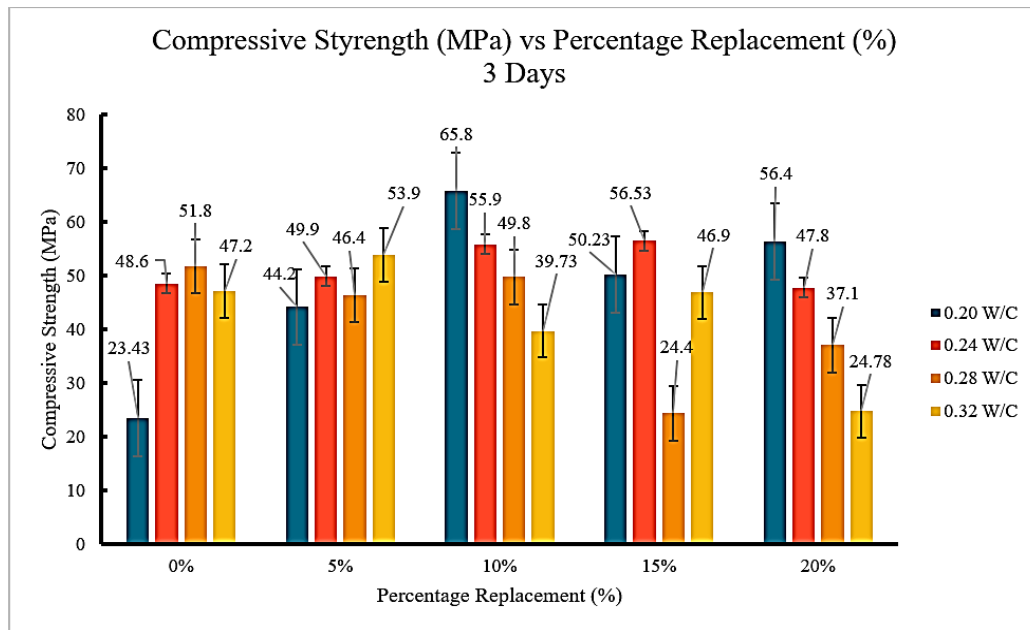


Fig. 3.1: Early age Compressive strength of 3 days for all the mixes

Figure 3.1 illustrates the strength gain with curing age at a water-binder ratio of 0.20 for all PR levels. As expected, strength increases progressively from 3 to 28 days for every mix. The 10% replacement mix shows the highest strength at every age tested and the smallest relative gain between 3 and 28 days (about 12%), indicating that a large proportion of its ultimate strength is mobilized early, consistent with the accelerated pozzolanic reactivity of micro-silica at early ages reported in the literature. In contrast, the control mix (0% PR) shows the largest relative strength gain over the same period (about 146%), reflecting the comparatively

slower, purely cementitious hydration reaction in the absence of supplementary cementitious material. This early-age pattern is also consistent with past works, which found that silica fume's pozzolanic contribution continues to add strength well beyond 28 days under favorable curing, which raises the possibility that the gap between the 10% replacement mix and the higher-replacement mixes could narrow or shift at later ages, since the additional micro-silica present in the 15% and 20% replacement mixes may still be reacting more slowly than the matrix's ability to accumulate it at 28 days.

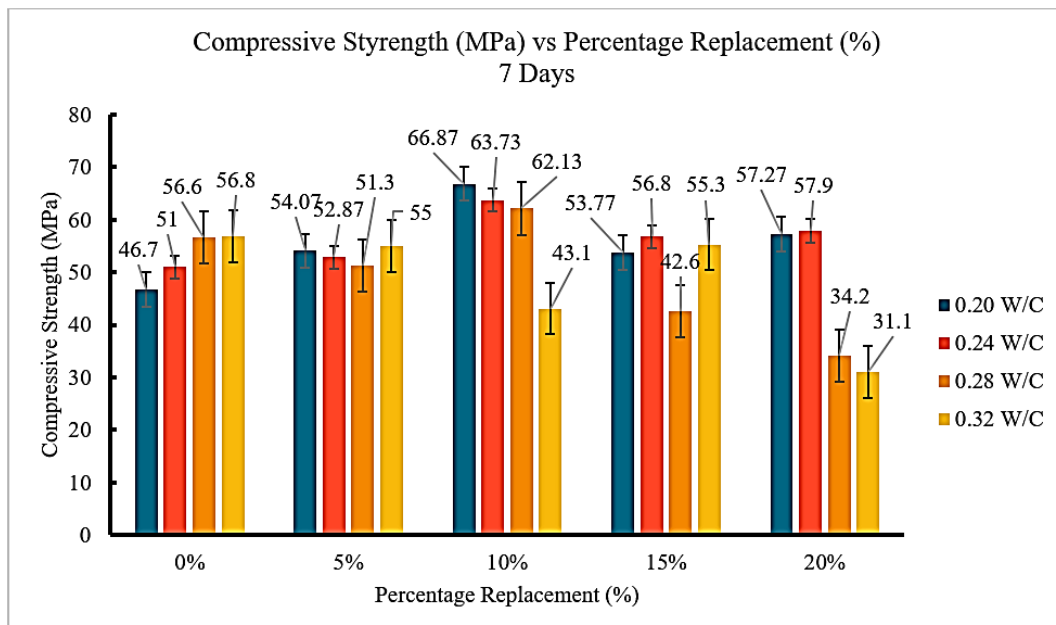


Fig. 3.2: Compressive strength of 7 days for all the mixes

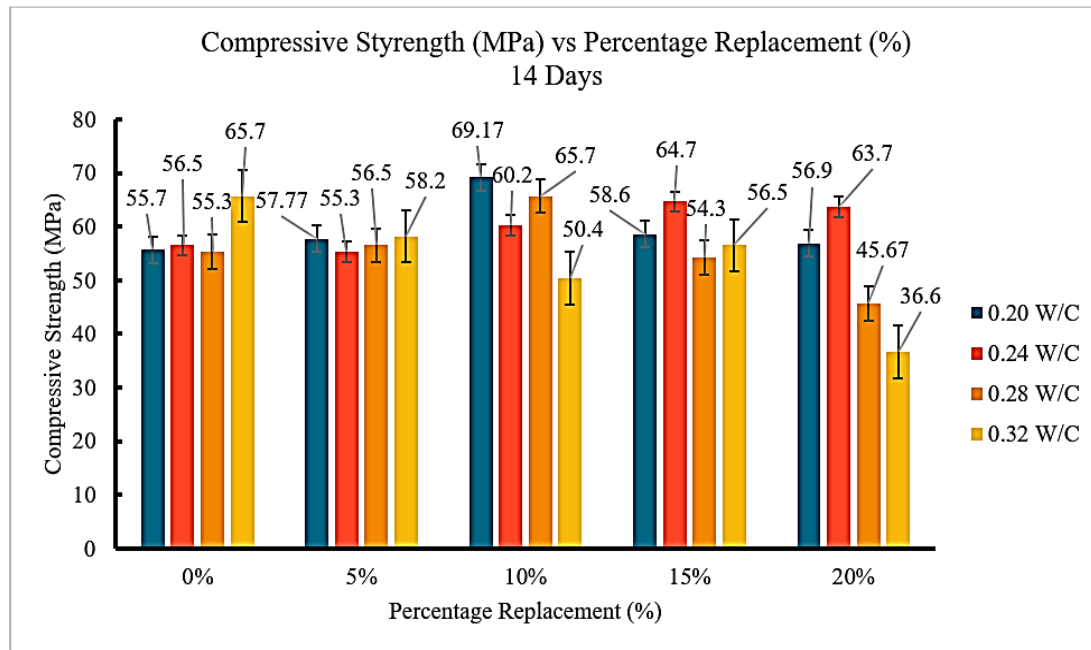


Fig. 3.3: Compressive strength of 14 days for all the mixes

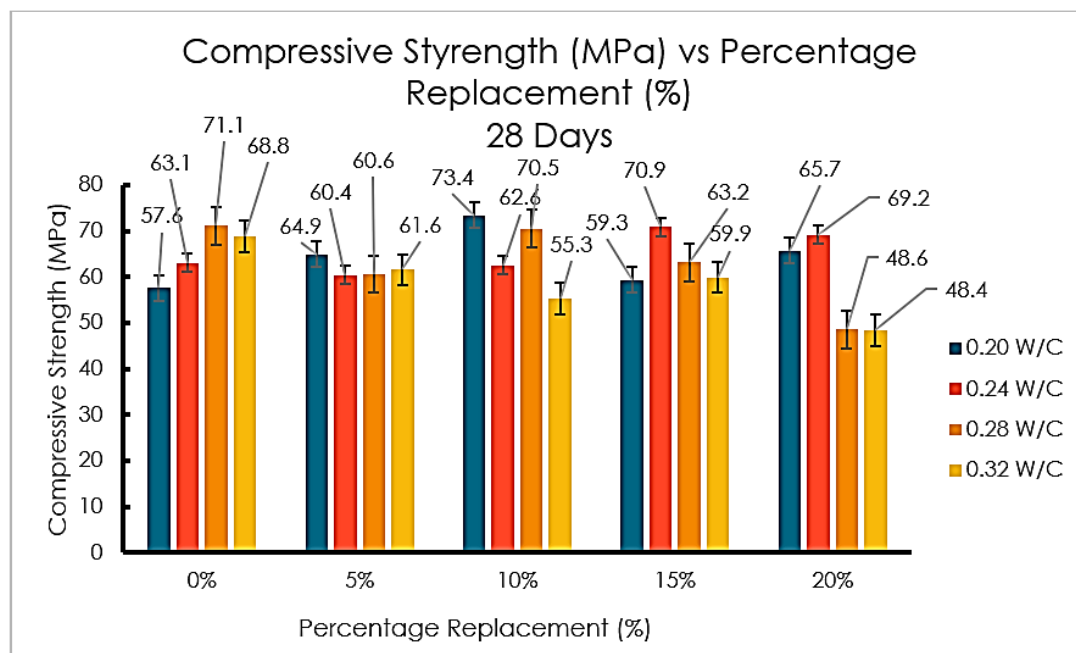


Fig. 3.4: Compressive strength of 28 days for all the mixes

Figure 3.4 shows that compressive strength generally improves with micro-silica/quarry dust replacement up to an optimum between 5% and 10% replacement, beyond which strength declines, most clearly at the higher water-binder ratios of 0.28 and 0.32. At a water-binder ratio of 0.20, the 28-day strength rose from 57.6 MPa at 0% PR to a peak of 73.4 MPa at 10% PR, an increase of about 27%, before falling back at 15% and 20% PR. This pattern is consistent with the micro-filling and pozzolanic mechanisms described in 2.1, at low-to-moderate replacement levels, micro-silica densifies the cement matrix and the interfacial transition zone while the angular quarry dust particles improve

packing of the fine aggregate skeleton, but beyond the optimum dosage, the increased fines content raises water demand and can introduce workability-related voids that offset the pozzolanic gains, echoing the dilution effect for ultrafine-filler concrete. This offers an explanation for the decline observed beyond 10% PR in the present results, particularly given that no changes to the superplasticizer dosage were made.

For the control mix (0% PR), strength increased steadily with water-binder ratio from 57.6 MPa at 0.20 to 71.1 MPa at 0.28, which is contrary to the classical inverse relationship between water-binder ratio and

strength and may reflect the difficulty of achieving full compaction in the very low water-binder, higher-viscosity control mix despite the use of superplasticizer. This is most explained by workability; at a very low water-binder ratio without the aid of supplementary cementitious material in the case of dispersion, the control mix was too stiff to achieve full compaction despite the use of superplasticizer, introducing entrapped air voids that reduced strength below what the water-binder ratio would predict.

At higher replacement levels (15% and 20%), however, the expected trend re-emerges, with strength decreasing as water-binder ratio increases from 0.20 to 0.32, most sharply at 20% replacement where strength

drops from 65.7 MPa to 48.4 MPa. This suggests that as high micro-silica and quarry dust content, workability becomes increasingly sensitive to water-binder ratio, and the benefit of a lower water-binder ratio becomes more pronounced.

Compressive strength developed over the four tested curing ages; 3, 7, 14, and 28 days across all twenty mixes, which presented this trend only for the water-binder ratio of 0.20. The Table 3.1, 3.2, 3.3, 3.4, 3.5 present the full age-development data for the water-binder ratios (0.20, 0.24, 0.28, and 0.32), alongside the overall percentage strength gain recorded between 3 and 28 days for every mix.

Table 3.1: Strength Development at w/b = 0.20

PR (%)	3 days	7 days	14 days	28 days	% Gain (3 to 28 days)
0	23.43	46.70	55.70	57.60	145.8%
5	44.20	54.07	57.77	64.90	46.8%
10	65.80	66.87	69.17	73.40	11.6%
15	50.23	53.77	58.60	59.30	18.1%
20	56.40	57.27	56.90	65.70	16.5%

Table 4.2: Strength Development at w/b = 0.24

PR (%)	3 days	7 days	14 days	28 days	% Gain (3 to 28 days)
0	48.60	51.00	56.50	63.10	29.8%
5	49.90	52.87	55.30	60.40	21.0%
10	55.90	63.73	60.20	62.60	12.0%
15	56.53	56.80	64.70	70.90	25.4%
20	47.80	57.90	63.70	69.20	44.8%

Table 4.3: Strength Development at w/b = 0.28

PR (%)	3 days	7 days	14 days	28 days	% Gain (3 to 28 days)
0	51.80	56.60	55.30	71.10	37.3%
5	46.40	51.30	56.50	60.60	30.6%
10	49.80	62.13	65.70	70.50	41.6%
15	24.40	42.60	54.30	63.20	159.0%
20	37.10	34.20	45.67	48.60	31.0%

Table 4.4: Strength Development at w/b = 0.32

PR (%)	3 days	7 days	14 days	28 days	% Gain (3 to 28 days)
0	47.20	56.80	65.70	68.80	45.8%
5	53.90	55.00	58.20	61.60	14.3%
10	39.73	43.10	50.40	55.30	39.2%
15	46.90	55.30	56.50	59.90	27.7%
20	24.78	31.10	36.60	48.40	95.3%

As shown in Figures 3.1, 3.2, 3.3, 3.4, and 3.5, and observed across the water-binder ratios tabulated in Table 3.1, 3.2, 3.3, 3.4, all twenty mixes gain strength progressively from 3 to 28 days, as expected of any hydrating cementitious system. Beyond this general pattern, however, a consistent and meaningful trend emerges specifically at the 10% PR level: at every single water-binder ratio tested (0.20, 0.24, 0.28, and 0.32), the 10% PR mix shows one of the smallest 3-to-28-day percentage gains in its respective table (11.6%, 12.0%, 41.6%, and 39.2%), and at the two lower water-binder

ratios in particular (0.20 and 0.24), its 3-day strength already represents close to 90% of its eventual 28-day strength. This means the 10% PR mix mobilizes the large majority of its ultimate strength very early in the curing process, which is consistent with the accelerated early-age pozzolanic reactivity of micro-silica already discussed in 4.2. At this replacement level, the additional supplementary cementitious materials (micro-silica and quarry dust) appear to be reacting efficiently rather than continuing to react slowly over the full 28-day period.

Two mixes stand out with unusually large 3-to-28-day gains that are better explained as experimental anomalies than as genuine slow-hydration behavior, they are; the control mix at a water-binder ratio of 0.20 (145.8% gain, driven by an unusually low 3-day reading of 23.43 MPa) and the 15% PR mix at a water-binder ratio of 0.28 (159.0% gain, driven by an equally low 3-day reading of 24.4 MPa). In both cases, the 3-day strength sits far below what the 7-day and 14-day readings for the same mix would suggest it should have been, which points to likely early-age compaction, curing, or specimen-handling variability at the 3-day test rather than a genuine feature of either mix design which is a limitation consistent with the practical batching and curing variability already acknowledged in Section 1.7. Excluding these two outliers, the remaining eighteen mixes show 3-to-28-day gains in a much narrower and more plausible band of roughly 12% to 47%.

At the higher replacement levels (15% and 20%), the strength development pattern is less consistent across water-binder ratios than at 10% replacement, at a water-binder ratio of 0.20, the 20% replacement mix shows a comparatively modest gain (16.5%), but at a water-binder ratio of 0.32, the same 20% replacement mix shows the second-largest gain in the entire dataset (95.3%), rising steadily and substantially at every age interval rather than levelling off early. This suggests that at high replacement combined with a high water-binder ratio, the additional replacement takes considerably longer to contribute their full-strength benefit, plausibly because the more porous, higher-water matrix at this combination slows the pozzolanic reaction relative to the denser, lower-water-binder-ratio mixes.

Overall, the age-development results reinforce the discussion that the 10% replacement mix is not only the maximum at 28 days across most water-binder ratios, but also the most efficient at mobilizing that strength early.

4.0 CONCLUSION AND RECOMMENDATION

4.1 Conclusion

Based on the results obtained and discussed, the following conclusions are drawn:

- i. The combined use of quarry dust and micro-silica significantly influenced the mechanical performance of the concrete. The magnitude of the response depended on both the percentage replacement and the water-binder ratio.
- ii. The results showed that moderate replacement levels produced better overall mechanical performance than higher replacement levels. Among the replacement levels investigated, 10% produced the most favourable overall response.
- iii. The highest 28-day compressive strength of 73.40 MPa was obtained at 10% replacement and a water-binder ratio of 0.20. This represented a 27.43% increase compared with the corresponding control mixture, which recorded 57.60 MPa.
- iv. The most dependable and practically attainable mix can be realized by maintaining a low water-cement ratio, moderate levels of quarry dust replacement, and an adequate curing period, with 28 days yielding the most consistent strength development. Consequently, the study concludes that the best concrete performance emerges from the interplay of mix design variables rather than their isolated contributions.

4.2 Recommendation

The research suggests that high-strength concrete mixtures which include quarry dust and microsilica should be formulated with approximately 10% quarry dust replacement, a low water-cement ratio of 0.20, and a curing period of 28 days, as this combination reliably results in the highest experimentally recorded compressive strength of about 73-74 MPa, representing the most dependable practical optimum.

It is advised that the water-cement ratio be meticulously maintained at low levels in all mix designs because it exhibited the most substantial impact on strength development while consistently influencing both compressive and bond performance through significant linear, quadratic, and interaction effects.

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