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Optimizing concrete mix design with a high percentage of microsilica: Enhancing strength, Sustainability

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Abstract. Microsilica is a highly reactive pozzolanic material widely known for improving the strength and durability of concrete. In this study, we explored how replacing 10%, 20%, and 30% of cement with microsilica affects the performance of lightweight concrete over 7, 14, and 28 days. The concrete mixes were prepared using a blend of natural and artificial lightweight aggregates with cement content ranging from 350 to 550 kg/m^3. To ensure good workability, a 2% modified lignosulfonate-based superplasticizer was used, and water-to-cement ratios varied between 0.30 and 0.45. Along with compressive strength, we also measured the modulus of elasticity, specific weight, and water absorption under both dry and wet conditions. The results clearly showed that higher levels of microsilica led to notable gains in strength and elasticity, while also reducing the weight and water absorption of the concrete. The most effective mix combined 30% microsilica with a cement content above 500 kg/m^3, delivering excellent mechanical performance and durability. These findings highlight the potential of microsilica not only to enhance structural quality but also to reduce environmental impact by lowering cement usage. This study supports the thoughtful use of microsilica as a sustainable and performance-boosting material in modern concrete design.

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1. Introduction

Reducing the dead load of structures using concrete with lower specific weight and higher compressive strength is a key focus for engineers, especially in seismic zones where earthquake forces are proportional to structural mass [1]. Lightweight concrete not only enhances seismic performance but also reduces construction costs, energy use, and noise pollution [2]. To improve its mechanical properties, various mineral additives have been explored, among which microsilica stands out as one of the most effective. Microsilica is a highly reactive pozzolanic material with particles 50–100 times smaller than cement. It fills voids between cement grains, enhances adhesion, and reacts with calcium hydroxide from cement hydration to form a dense, gel-like compound. This reaction significantly increases concrete strength and decreases its weight, making microsilica a valuable additive in the production of high-performance lightweight concrete [3].

Extensive research has been conducted on the effect of microsilica on the properties of concrete with different percentages of cement, and the results have been collected [4]. Studies show that replacing

5% and 10% of cement with microsilica increases 28 day compressive strength by 9.6% and 24.8% respectively [5]. Additionally, for producing concrete with high strength, replacing 10% of the weight of cement with microsilica is a suitable option [6]. Previous research has shown that the use of 20% microsilica and 30% fly ash results in an increase in the flexural and compressive strength of concrete [7]. Other studies have also demonstrated that the use of microsilica can reduce sudden drying shrinkage and the likelihood of concrete cracking [8]. Incorporating microsilica in concrete can improve resistance to chemical and physical attacks [9].

Although most studies limit microsilica replacement to ≤ 20%, preliminary trials in this study suggest that a 30% replacement level may still enhance strength, provided a higher cement grade and adequate dispersion are employed. Empirical data on such high microsilica mixtures remain virtually absent from the literature.

This study aims to develop an optimized concrete mix design that delivers exceptionally high compressive strength while lowering specific weight. The mix designs combine natural and artificial lightweight aggregates with microsilica used as a partial replacement for cement.

While most previous research limits microsilica replacement to 10–20%, this work investigates the effects of a higher replacement level (30%) to assess its potential for further enhancing mechanical and durability properties. This experiment evaluates a range of cement content, water-to-cement ratios, and aggregate types to identify the optimal combination that leads to increased strength, reduced density and water absorption, and improved overall structural performance. The outcomes are intended to offer actionable insights for structural engineers and material scientists seeking to design sustainable, lightweight, and high-performance concrete systems.

2. Method

2.1. Cement

The cement used in this research is ordinary Portland cement type 2. The mechanical, physical, and chemical characteristics of the used cement are listed in Tables 1 and 2 respectively {Horkoss, 2004 #1}.

Table 1. Mechanical and physical characteristics of the used cement

3-day compressive strength	> 17 MPa	10 MPa	Min
7-day compressive strength	> 27 MPa	17 MPa	Min
28-day compressive strength	> 37 MPa	31 MPa	Min
Initial capture time	95±5	45	Min
Final capture time	150±10	360	Max
Surface smoothness	3000±50 cm^2/gr	2800	Min

Table 2. Percentage of cement components

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl-	L.O.I	L.S.F	C3A
22.00± 0.4	5±0.3	3.82± 0.2	64.00± 0.5	1.9± 0.2	1.5± 0.2	0.49± 0.2	0.25± 0.15	0.019± 0.001	1.0± 0.2	91.00± 1.0	6.5± 1

2.2. Microsilica

Microsilica is a highly soft white powder consisting of crystals with a diameter of 0.1 to 0.2 μm. Following the hydration of cement, the released calcium hydroxide accounts for about 20% of the mortar volume (Relation 1). Also, this component can be dissolved in water, move out of concrete, and weaken the mechanical properties and durability of concrete. Alkaline reactions of aggregates are also intensified by the presence of calcium hydroxide in cement paste. In this way, calcium hydroxide is a weakening part of the concrete mixture. Moreover, due to its instability, it is considered a weakness for concrete. The addition of microsilica to the concrete mixture causes its active SiO_2 to combine with the free calcium hydroxide solution $Ca(OH)_2$ in the capillary pores of the concrete and produce insoluble calcium silicate crystals (Relation 2), which ultimately causes the compaction of the cement paste structure [11]. This compaction also decreases permeability and ultimately increases the mechanical resistance of concrete [12]. Preventing the penetration of chlorine ions, sulfates, and other harmful chemicals into the concrete and enhancing its durability are the result of reducing the permeability of concrete in this chemical process [13]. This research used microsilica produced by a Chemical Construction Company in Iran.

$$\begin{aligned}&\text{OPC}\left(\text{ordinary Portland cement}\right)+\text{H}_2\text{O}\rightarrow\\&\rightarrow\text{CSH}\left(\text{Calcium silicate hydrate}\right)+\text{Ca}\left(\text{OH}\right)_2;\end{aligned}\tag{1}$$

$$\text{Ca}\left(\text{OH}\right)_2+\text{SiO}_2\rightarrow\text{H}_2\text{O}+\text{CSH}.\tag{2}$$

2.3. Superplasticizer

Due to the exceptional microsilica grains, special surfaces will have a visible enhancement. For this reason, the amount of water used for mixing will increase, causing a reduction in the strength of concrete. The use of superplasticizers in concrete containing microsilica can prevent water consumption [14]. The superplasticizer mix used (which is based on modified lignosulfonate) is manufactured by Shimi Company in Iran. In this investigation, about 2% by weight of cement was used. The technical and chemical specifications of the superplasticizer are presented in Table 3 [15].

Table 3. Mechanical and chemical characteristics of the used superplasticizer

Chloride (ppm)	Special Weight (kg/lit)	Physical state	Color	Lonic nature	Chemical mixture
max 500	1.19±0.02 at 20 °C	liquid	Brown	anionic	modified lignosulfonate

2.4. Natural aggregate

To make concrete with high compressive strength, it is inevitable to use grains with small dimensions. In this research, aggregates with dimensions less than 4.75 mm (0–4 sand) were used. In addition, grain consistency is one of the basic and obvious principles for the production of durable and high-strength concrete. In Fig. 1, the curve of aggregates and the permissible range of granularity according to the standard ASTM C404 [16] are shown.

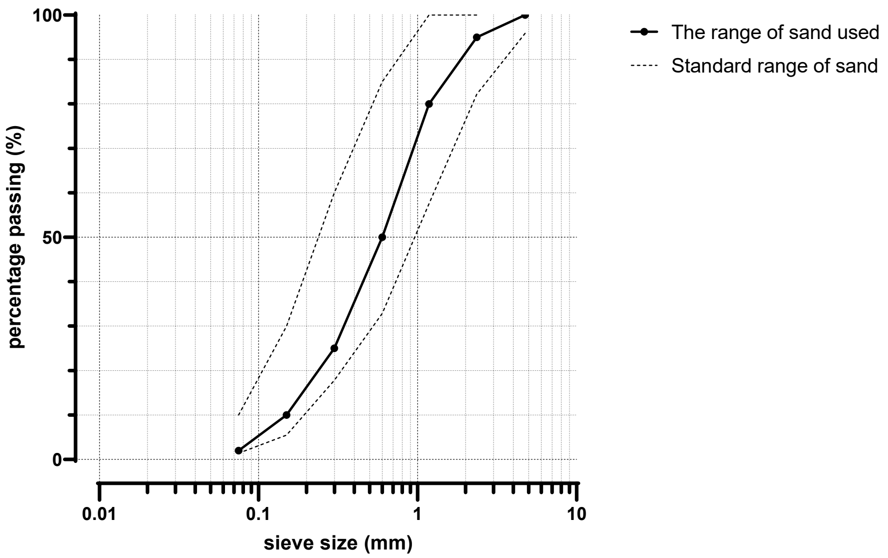

Figure 1. Granulation curve of the used sand.

2.5. Artificial aggregate

To make concrete with low specific weight, lightweight expanded clay aggregate (LECA), an artificial aggregate has been used in some concrete mix designs. Similar to the grading of natural aggregates, the dimensions of artificial aggregates are less than 4.75 mm. These grains are obtained from the expansion of clay in rotary furnaces with a temperature of about 1200 degrees Celsius. Microscopically, the outer surface of the seeds has small brown pores and the inner part of the seeds has black cell tissue [17]. A combination of desirable properties such as light weight, low thermal conductivity, effective noise attenuation, fire resistance, durability, and chemical stability has broadened the range of applications for these artificial aggregates across building construction, infrastructure projects, agriculture, environmental works, road construction, and more [18, 19].

2.6. Mix designs

To achieve the objectives of the project, 15 concrete mix designs containing natural aggregate and 7 concrete mix designs containing different artificial aggregates were examined according to ACI 211-77 [20], by Tables 4 and 5. In the aforementioned concrete mix designs, five different amounts of cement, 350, 400, 450, 500, and 550 kg/m^3 were used. Moreover, 10%, 20% and 30% microsilica (containing 2% superplasticizer based on modified lignosulfonate) were utilized as a replacement for cement. Additionally, the water-to-cement ratio was varied to 0.30, 0.35, 0.40, and 0.45. Compressive strength was evaluated on 50 mm cube specimens prepared in accordance with ASTM C109 [21]. The details of concrete mix designs can be seen in Tables 4 and 5. The letters A, B, C, D, and E indicate cement contents of 350, 400, 450, 500, and 550 kg/m³, respectively.. Also, the letters L, M, and H indicate 10, 20, and 30% of microsilica consumption, respectively, and the numbers after them indicate the water-to-cement ratio used in the design.

Table 4. Details of concrete mix designs containing natural aggregate

Mix designs	Cement content (kg/m^3)	Microsilica (%)	Cement-Microsilica paste (gr)	Water (gr)	Aggregate (gr)
AL35	350	10	160.4	56.2	680.5
AL40	350	10	160.4	64	672.5
AL45	350	10	160.4	72.2	664.5
AH45	350	30	189.6	85.3	622.2
BH30	400	30	216.6	65	616.6
BH45	400	30	216.6	97.5	582.5
CL45	450	10	206.25	92.8	597.2
CM45	450	20	225	101.25	570
CH45	450	30	243.75	109.7	542.8
D045	500	0	208.3	93.75	598
DL35	500	10	229.1	80.2	588.5
DH45	500	30	270.8	121.8	503
EL45	550	10	252	113	530
EM45	550	20	275	123.75	496.9
EH45	550	30	298	134	463.5

Table 5. Details of concrete mix designs containing artificial aggregates

Mix plans	Cement content (kg/m^3)	Microsilica (%)	Cement-Microsilica paste (gr)	Water (gr)	Aggregate (gr)	Artificial aggregate (%)
BH30'	400	30	216.6	65	616.6	50% No. 16 50% No. 30
BH30'	400	30	216.6	65	616.6	50% No. 16 50% No. 30
DL35'	500	10	229.1	80.2	588.5	30% No. 30
DM30'	500	20	250	75	572.9	15% No. 8 15% No. 16
DM35'	500	20	250	87.5	560.4	15% No. 16 15% No. 30
DH35'	500	30	270.8	94.8	532.3	15% No. 16 15% No. 30
DH35'	500	30	270.8	94.8	508.6	100% No. 16 100% No. 30

2.7. Curing

In each concrete mix design, to measure the compressive strength of concrete at the ages of 7, 14, and 28 days, three cubic samples with dimensions of 50 mm (total of 9 concrete samples in each mix design) were molded and cured. After staying in the mold for one day, the samples were transferred to a water tank at a temperature of 23–25 °C for 6, 13, and 27 days. To prevent moisture loss, the concrete samples in the molds are covered by a plastic membrane immediately after concreting [22].

3. Results and Discussion

3.1. Compressive strength

The results of the compressive strength tests for various concrete mix designs are presented in Tables 6 and 7. The progression of compressive strength development at different ages is illustrated in Figs. 2 and 3. Initial analysis of the data suggests that the 28-day compressive strength of the concrete samples increases with higher percentages of microsilica and higher cement content. Mix designs incorporating 10% microsilica exhibit a steady and consistent increase in strength up to their ultimate value. However, this trend diverges in mixes containing 30% microsilica.

Table 6. Compressive strength of concrete containing natural aggregate

Mix plans	Ccompressive strength (MPa) at		
	7 days	14 days	28 days
AL35	24.2	34.8	39.5
AL40	23	28.3	38.9
AL45	21.3	27	35.7
AH45	34.4	29.6	43.2
BH30	37	48.5	53.6
BH45	36.8	45.1	42.5
CL45	34.4	47.6	54
CM45	39.4	51	49.6
CH45	40.8	50.4	45.4
D045	40.4	52.6	60.2
DL35	43.8	53	62.4
DH45	49.2	62.8	63.3
EL45	38.6	53.3	59.7
EM45	37.3	49.7	60.7
EH45	40.8	45.2	65.2

Table 7. Compressive strength of concrete containing artificial aggregates

Mix plans	Ccompressive strength (MPa) at		
	7 days	14 days	28 days
BH30'	36.5	47	44.2
BH30'	35.2	45.8	44
DL35'	40.2	49.5	60
DM30'	42.5	51	61.8
DM35'	40.8	51	62.1
DH35'	46	61.7	60.5
DH35'	42.6	55	56.6

In mix designs containing 30% microsilica and cement content of 350 kg/m^3, a decline in strength is observed at the 14-day mark. Similarly, a reduction in 28-day strength is evident in mixes with 30% microsilica and cement content of 400 and 450 kg/m^3. Nonetheless, this declining trend appears to be stabilized in the mix with 20% microsilica and cement content of 450, as well as in the mix with 30% microsilica and cement grade 500.

Interestingly, in the mix design containing 30% microsilica and cement content of 550 kg/m^3, strength development appears normal, and the upward trend resumes. This behavior may be attributed to the higher cement content , which compensates the effects of excessive microsilica, similar to the balanced performance observed in mixes with 20% microsilica and cement content of 450 kg/m^3, and 30% microsilica with cement content of 500 kg/m^3. Excessive microsilica can disrupt the uniform rate of cement hydration, and this delayed hydration may temporarily weaken the cement matrix due to the increased presence of microsilica powder.

Also, in artificial aggregate mix designs, adding 30% microsilica alters the process of gaining strength in the same manner as in mix designs with natural aggregates. Adding LECA lowers both sample weight and compressive strength due to LECA particles being porous. This can be observed when comparing identical mix designs without adding LECA.

An increase in the water-to-cement ratio leads to a decrease in the compressive strength of the samples. In mix designs containing 30% microsilica, the irregular strength development is compensated by increasing the cement content, which counteracts the effects of excessive microsilica.

Briefly, with 10% microsilica, 28-day compressive strength increased steadily with cement grade, peaking at ≈42 % above the plain-cement control when 550 kg/m^3 cement was used. Raising the dosage to 20% produced a further boost, yielding up to ≈58 % strength gain in the C-series mix (450 kg/m^3 cement). By contrast, 30% microsilica behaved in a threshold-dependent manner:

- With 350 kg/m^3 cement, strength fell ≈12 % at 14 days and remained ≈8 % lower than the 10 % mix at 28 days.
- When cement was raised to 500 kg/m^3, the 30 % mix recovered and matched the 20 % mix at 28 days.
- At 550 kg/m^3 it exceeded all other mixes, delivering ≈18 % higher strength than its 20 % counterpart, confirming that adequate $Ca(OH)_2$ is essential for pozzolanic utilisation of such a high microsilica content.

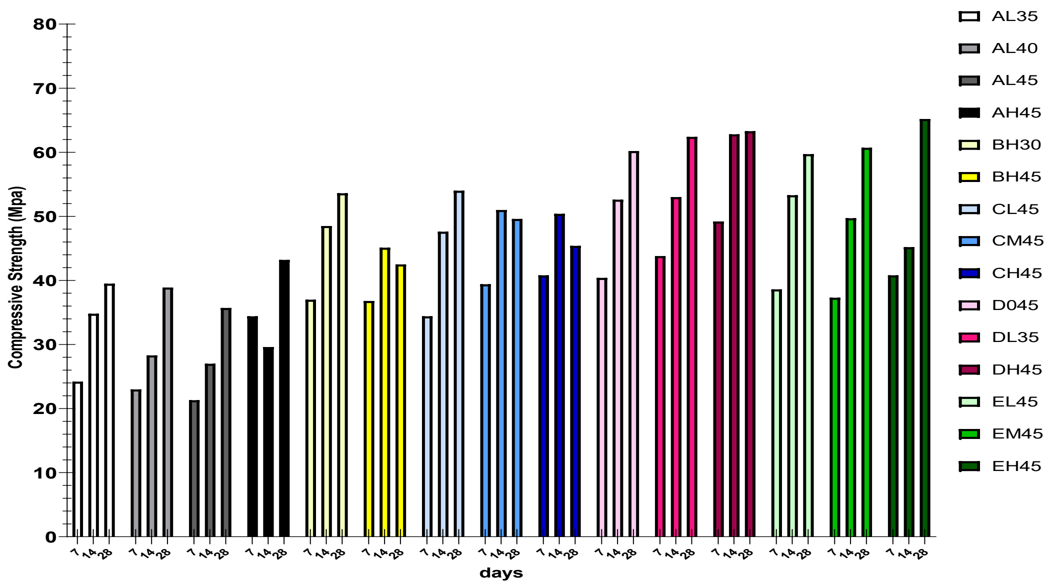

Figure 2. Strength acquisition curve of mixing designs containing natural aggregate.

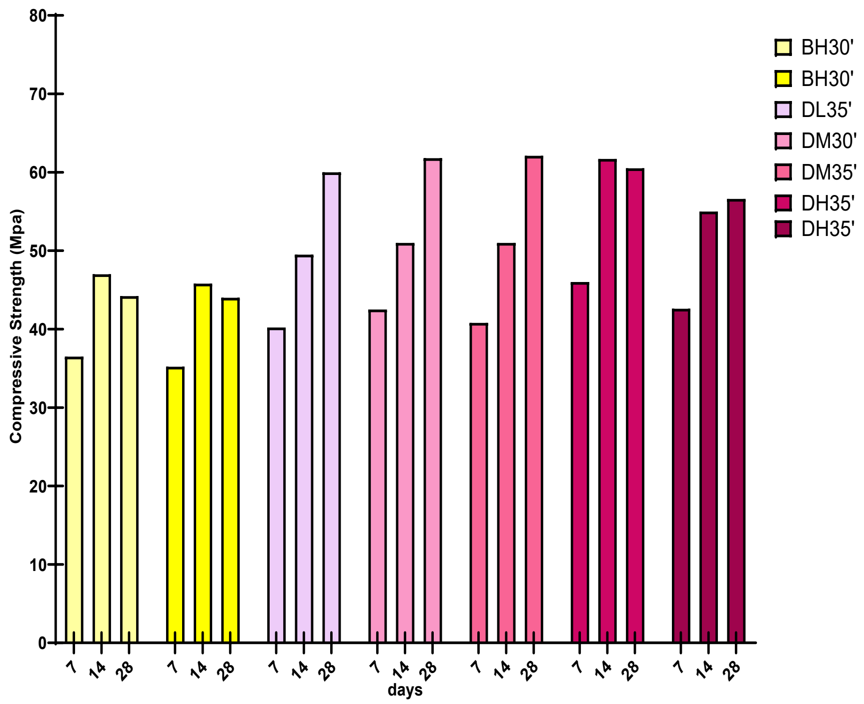

Figure 3. Strength acquisition curve of mixing designs containing artificial aggregate.

3.2. Specific weight

The progress in technology and the human need for various structures has led to extensive research on the properties and behavior of materials, which results in the creation of various types of structures and the use of various materials. Concrete can be divided into three categories in terms of specific weight: normal concrete, light concrete, and heavy concrete. However, this classification is not comprehensive and does not include the properties and applications of different types of concrete [23].

According to the definition of ordinary concrete, concrete is normally made with the ordinary type (I) to type (V) Portland cement. This concrete has a specific weight from to 2200 to 2500 kg/m^3 (usually 2400 kg/m^3). This difference is related to the type of grains and the density of the concrete. The findings indicate that the specimens have a density between 2100 and 2300 kg/m^3; despite their high compressive strength, they are still classified as lightweight structural concrete [24] (Figs. 4 and 5).

All natural-aggregate mixes fell between 2100–2300 kg/m^3, already 4–12% lighter than ordinary concrete. Substituting 50% LECA dropped density by a further ≈6 %, with only a 10–15 % reduction in strength at identical binder levels.

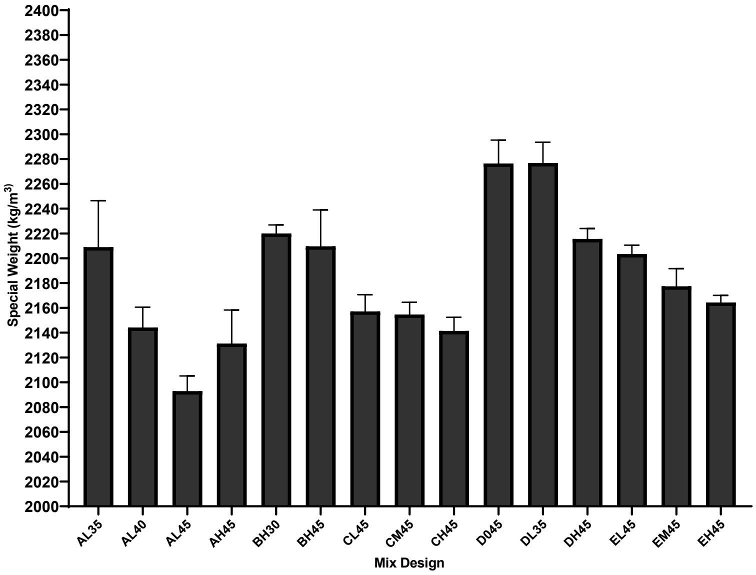

Figure 4. Specific weight of mixing designs containing natural aggregate (kg/m^3).

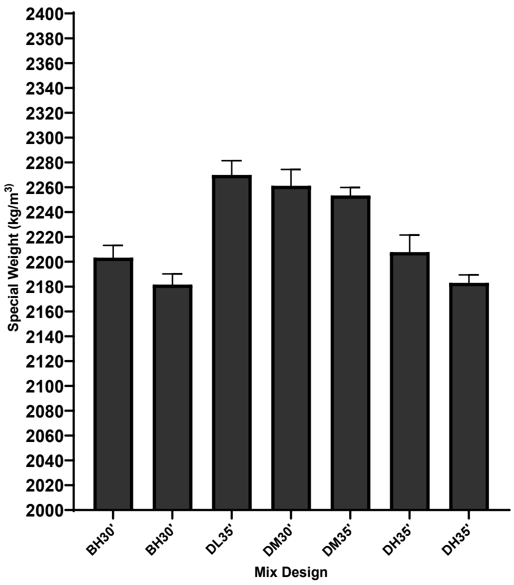

Figure 5. Specific weight of mixing designs containing artificial aggregates (kg/m^3).

3.3. Elastic modulus

One of the important parameters of concrete in the analysis and design of concrete structures is the modulus of elasticity. The modulus of elasticity is important to estimate the change in the shape of the structure under the effect of the incoming loads. Additionally, it indicates the resistance of the material to the change in shape. The modulus of elasticity is directly related to the material's hardness. The factors that can influence the value of the modulus of elasticity of concrete are aggregates, loading rate, chemical additives, curing conditions of concrete, and water-cement ratio. Since concrete is brittle, the stress-strain ratio in the elastic region cannot be used to determine the modulus of elasticity, so there are other approaches to determining concrete's static and dynamic modulus [25].

In this research, the static modulus of elasticity of concrete has been investigated. During this path, the formulas of the American code ACI-318 [26], the Canadian code [27], the European concrete regulation (EC), the Indian regulation [28], and the CEB-FIP regulation [29] were analyzed (Figs. 6 and 7).

The static modulus correlated linearly with compressive strength (R^2 = 0.92 across all 10% and 20 % mixes). Samples with 30% microsilica deviated downward by ≈15 % from this trend, attributable to their lower bulk density and the delayed clinker hydration discussed above.

1. American Concrete Code ACI-318

$$E_c = 0.043 w^{1.5} \sqrt{f_c'}$$

2. Canadian concrete code (CSA-A23.3)

$$E_c = \left(3300\sqrt{f_c'} + 6900\right)\left(\gamma/2300\right)^{1.5}$$

3. European Concrete Regulation (EC)

$$E_c = 22\left[\left(f_c'/10\right)\right]^{0.3}$$

4. Indian regulation (IS-456)

$$E_c = 5000\sqrt{f_c'}$$

5. CEB-FIP regulation

$$E_c = 21500\alpha_E\left(f_{ck}/10\right)^{\frac{1}{3}}$$

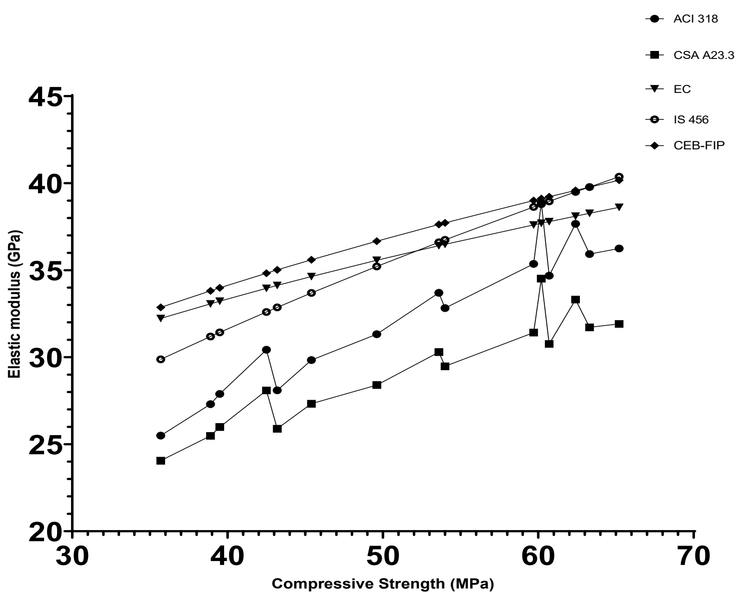

Figure 6. Comparison chart of modulus of elasticity and compressive strength of mixing designs containing natural aggregate.

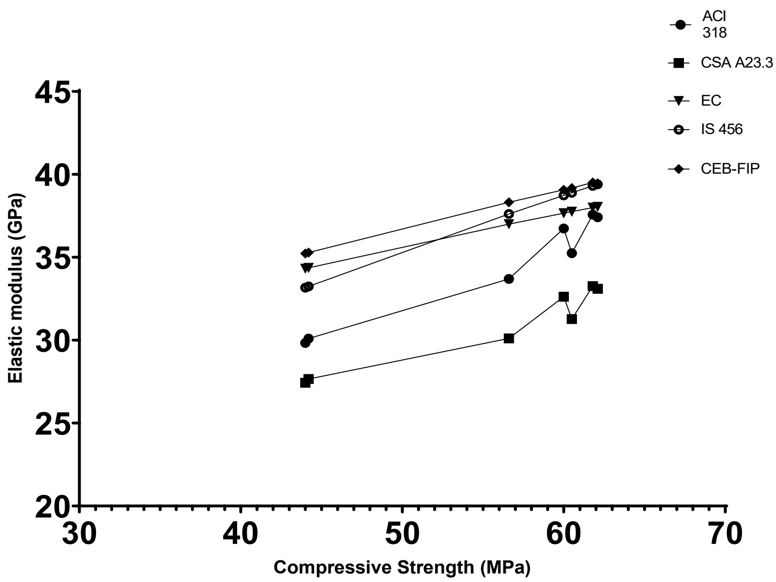

Figure 7. Comparison chart of modulus of elasticity and compressive strength of concrete mix designs containing artificial aggregate.

3.4. Water absorption

The resistance of concrete to aggressive chemical attacks is a critical factor that significantly impacts its durability. Water absorption serves as an indicator of concrete's porosity and provides insight into the volume of permeable pores and their interconnectivity. Moreover, water is a necessary component for the hydration reactions of cement. The increase in the weight of the samples depends on the effect of the water present in the pores. Depending on the environmental conditions and the thickness of the samples, gradually most of the evaporable water in the concrete is lost and the pores of the concrete become empty or unsaturated. In this research, concrete samples were placed inside the oven for 8 hours and then their dry weight was measured [30].

The results are shown in figures 8 and 9 for different mix designs. In general, with the increase in the water-to-cement ratio, the amount of water absorption of the samples also increases. The addition of microsilica strengthens the concrete’s pore structure, thereby reducing its water absorption. The difference in the amount of water absorption between the mixing design without microsilica and other mixing designs containing microsilica confirms the reason for the decrease in the amount of water absorption in the samples having microsilica.

Incorporating 10–20% microsilica reduced 24-hour water absorption by 25–40% compared to the control mix, indicating effective pore structure refinement. However, combining 30% microsilica with ≥ 500 kg/m^3 cement reversed the trend, producing an ≈18% rise in absorption. This suggests that an initial moisture deficit and agglomerated silica powder can offset the expected densification unless dispersion is improved. LECA lowered absorption by ≈10% compared with corresponding natural-aggregate mixes because of its intrinsic pore suction and internal curing effect.

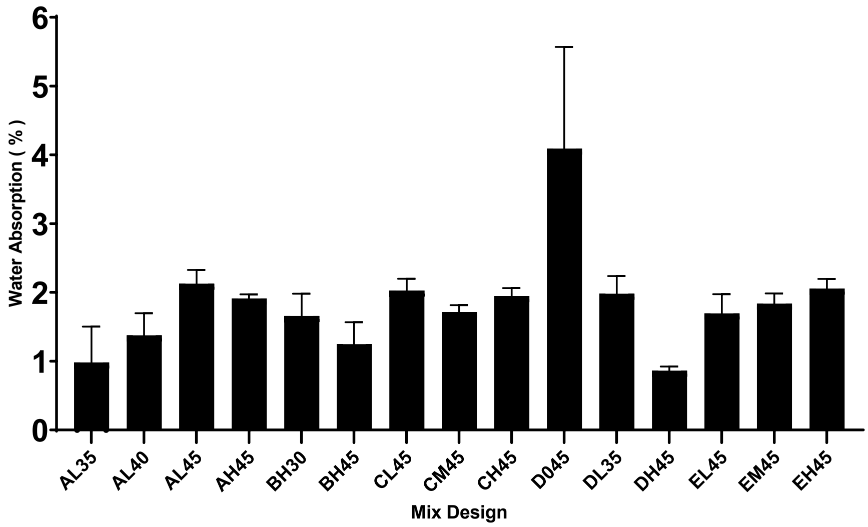

Figure 8. Water absorption percentage of mixing plans containing natural aggregate.

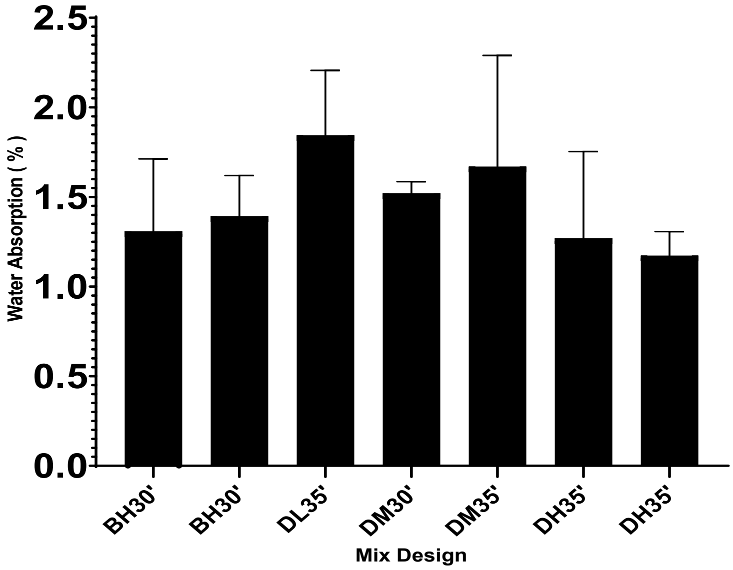

Figure 9. Water absorption percentage of mixing designs containing artificial aggregate.

4. Conclusion

Primarily, incorporating microsilica as a substitute for cement in concrete mixtures offers a dual advantage of enhancing compressive strength while also lowering the concrete's density. However, the choice of aggregate plays a critical role. Replacing natural aggregates with artificial ones (LECA) reduces compressive strength by approximately 10–15%, while simultaneously lowering water absorption.

This research demonstrates that high-microsilica lightweight concrete can attain compressive strengths exceeding 70 MPa while maintaining a specific weight below 2300 kg/m^3 when 30% microsilica is paired with ≥ 500 kg/m^3 cement and properly dispersed. An initial decline in 7–14 day strength is evident at this high microsilica percentage because agglomerated microsilica particles and a shortfall of early $Ca(OH)_2$ hamper hydration; however, higher cement content supply the needed calcium hydroxide, allowing the 28-day strength to recover and ultimately surpass that of 10% and 20% mixes.

The same dosage-and-binder balance governs other properties. The static modulus of elasticity – normally proportional to strength drops in low-density mixes that pair microsilica with LECA. Water absorption, on the other hand, improves by up to 40% when typical microsilica contents of 10–20% are used. However, it rises when 30% microsilica and high cement content are employed without extra water reducers.

Practically, achieving > 70 MPa at reduced density offers 10% mass reduction that lowers seismic demand and enables lighter lateral systems; substituting one-third of the cement with this industrial by-product trims clinker consumption and embodied carbon; and the pore-refinement induced by 10–20% microsilica enhances durability in chloride and sulfate environments. The investigation is limited to 50 mm cubes, a single lignosulfonate superplasticizer, and short-term tests, leaving long-term durability, creep–shrinkage interaction, and life-cycle cost unaddressed; as a result, future work should examine full-scale elements under field curing, trial higher range water reducers to counter high microsilica absorption, and employ response-surface methods to evaluate hybrid supplementary cementitious blends (e.g., microsilica–fly ash) that could further refine rheology, sustainability, and robustness.

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