Optimization of Concrete Durability in Corrosive Environments: Partial Replacement of Microsilica with Natural Pozzolan

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ABSTRACT

Structural foundations in southern Iran face significant corrosion challenges, necessitating strategies to enhance concrete strength and durability. The construction industry in this region commonly incorporates 8% microsilica by weight of cement to improve performance. However, since microsilica contributes to approximately 70% of total concrete costs, and locally available natural pozzolan is about 90% cheaper, this study investigates the feasibility of partially replacing microsilica with natural pozzolan while maintaining required durability and strength standards. To evaluate this approach, eight concrete mix designs were tested for compressive strength and durability parameters, including water absorption, freeze-thaw resistance, water permeability, chloride migration coefficient, electrical resistivity, and microstructural analysis (SEM/EDS/Mapping). The findings indicate that a mix containing 4% microsilica and 12.5% natural pozzolan achieved comparable durability and void distribution to the standard 8% microsilica mix, demonstrating its potential as a cost-effective alternative. Additionally, this study assessed water absorption testing as a site-based durability evaluation method, which aligns with regional technical specifications. A comparative analysis with other laboratory durability tests revealed a strong correlation, confirming its accuracy, reliability, and cost-effectiveness for field-based durability assessments.

Keywords: *Concrete, natural pozzolan, microsilica, site durability tests, laboratory durability tests*

1. INTRODUCTION

Currently, conventional concrete remains the predominant material used in construction, despite its relatively low performance in terms of strength, permeability, and durability [1]. However, certain applications necessitate high-strength concrete capable of withstanding demanding environmental conditions [2]. To meet these requirements, various studies have proposed the incorporation of mineral additives to enhance the properties of concrete and controlling the environmental parameters of concrete during casting and curing process [3,4]. These additives include materials such as fly ash [5], steel slag [6], limestone powder [7], natural pozzolan [8], and silica fume [9]. The integration of these mineral additives into cement can influence the kinetics of hydration, facilitating the formation of additional calcium silicate hydrate (CSH) phases. These nano-modifying admixtures play a pivotal role in contemporary concrete technology, significantly impacting rheological behavior [10], structural formation [11], property development [12], impact resistance [13], chemical durability [14], and compressive strength [15].
In this context, several researchers have evaluated the effects of natural pozzolan as a supplementary material in concrete production. This admixture, composed of volcanic powder rich in alumina and silica, has been utilized as a partial replacement for Portland cement due to its cost-effectiveness and potential to enhance durability [16,17]. Additionally, natural pozzolan contributes to pore refinement by filling capillary voids,

thereby simultaneously increasing mechanical strength and reducing drying shrinkage in concrete [18]. Moreover, some findings indicate that incorporating finely natural pozzolan up to a 25% replacement level does not result in a reduction in 28-day compressive strength [19].

Oil and gas refinery equipment and concrete structures in southern Iran are highly vulnerable to corrosion. To enhance the strength and durability of concrete, the industry typically incorporates microsilica at a dosage of 8% by weight of cement in concrete production. Consequently, approximately 70% of the concrete-related costs in refinery projects are attributed to the use of microsilica. Notably, the partial substitution of microsilica with natural pozzolan offers not only economic and environmental advantages but also improves the durability characteristics of concrete. It is estimated that the total cost of natural pozzolan used in this industry amounts to approximately 10% of that of microsilica.

Considering these aspects, in a study [20]*, the authors developed eight cost-efficient concrete mix designs by partially replacing microsilica with natural pozzolan, while ensuring compliance with the durability and strength standards required in southern Iran. this study presents the findings of comprehensive research aimed at optimizing the mix design for refinery projects. Specifically, the study explores the partial replacement of microsilica with Iran's Taftan natural pozzolan. The primary objective and novelty of this research lie in maintaining concrete strength and durability in accordance with the technical specifications of refinery construction, while achieving results comparable to those of microsilica-based mix designs.*

To achieve this goal, an initial experimental phase involved four trial mix designs, in which different dosages of Taftan natural pozzolan were tested as a complete replacement for microsilica. The mixes were evaluated for compressive strength at 7 and 28 days (in accordance with ASTM C39) and subjected to various standardized durability tests. Durability assessment included six standard evaluations: water absorption (BS-1881 PART 122), resistance to rapid freezing and thawing (ASTM C-666), water permeability (DIN-1048), chloride migration coefficient (NT BUILD-492), and energy dispersive X-ray spectroscopy (EDS).

In the second experimental phase, the most favorable mix design, based on both strength and durability from the first stage, was selected. Subsequently, three new mix designs were developed as follows: (1) a mixture containing 25% natural pozzolan from the best mix design and 75% microsilica from the refinery mix design, (2) a mixture comprising 50% natural pozzolan and 50% microsilica, and (3) a mixture containing 75% natural pozzolan and 25% microsilica. This phase aimed to determine the optimal mixture incorporating both natural pozzolan and microsilica while simultaneously evaluating the combined effect of these additives on durability and compressive strength.

The structure of this paper is as follows: Section 2 presents details regarding the physical and chemical properties of the materials used in this research. Section 3 discusses the findings, focusing on strength and permeability across the examined scenarios. Lastly, Section 4 summarizes the study's conclusions.

2. MATERIALS AND METHODS

The concrete mixtures utilized materials such as washed sand, coarse aggregates (Type-A and Type-B), Type II Portland cement from Lamerd Cement Factory, microsilica, and natural pozzolan from Taftan Mountain. Washed sand featured 1.7% water absorption (ASTM C128), 95% sand equivalence (AASHTO T176), and a fineness modulus of 3.81. Coarse aggregates were divided into Type-A (12–25 mm) and Type-B (≤12 mm), both with low Los Angeles abrasion values (27–30%). The mix also included Type II Portland cement (specific gravity: 3100 kg/m³), microsilica (98.59% SiO_2, 0.45 µm particle size), and Taftan natural pozzolan (62% SiO_2), with 7-day strength activity indices of 113% for microsilica and 88% for pozzolan (ASTM C618-03 and ASTM C311-07). A plasticizer, SP-430 from Fosroc UK, was also used.

The methodology established in this study will be conducted in two testing phases. The initial phase involves a control mix design (D_1 with 8% microsilica) alongside four alternative designs. These alternative designs maintain the same ratios of water to cement, aggregates, and other materials as the control mix but replace microsilica with natural pozzolan. Specifically, the pozzolan is incorporated at levels of 15%, 20%, 25%, and 30% of the cement content in mix designs D_2 to D_5, respectively. In the first scenario of the study, the results obtained from the mix design D_4 presented the best performance in terms of durability. From this point onward, a decision was made to introduce three new mix designs, referring to D_6 to D_8. Subsequently, three new mix designs were developed as follows: (1) a mixture containing 25% natural pozzolan from the mix design D_4 and 75% microsilica from the refinery mix design D_1, (2) a mixture comprising 50% natural pozzolan from the *mix design D_4 and 50% microsilica from the mix design D_1, and (3) a mixture containing 75% natural pozzolan from the mix design D_4 and 25% microsilica from the refinery mix design D_1. This phase aimed to determine the optimal mixture incorporating both natural pozzolan and microsilica while simultaneously evaluating the combined effect of these additives on durability and compressive strength. Table 1 presents detail information on the studying mix design.*

Table 1. Proportion of materials used in both scenarios of the investigation [20].

Mix design	Washed sand (kg)	Coarse sand type A (kg)	Coarse sand type B (kg)	Water (kg)	Cement type 2 (kg)	Micro silica (kg)	Natural pozzolan (kg)	Plasticizer (kg)
D_1	1192	446	295	114	322	28	0	2.9
D_2	1192	446	295	114	297.5	0	52.5	2.9
D_3	1192	446	295	114	280	0	70	2.9
D_4	1192	446	295	114	262.5	0	87.5	2.9
D_5	1192	446	295	114	245	0	105	2.9
D_6	1192	446	295	114	307.12	21	21.88	2.9
D_7	1192	446	295	114	292.25	14	43.75	2.9
D_8	1192	446	295	114	277.4	7	65.6	2.9

This study examines several standardized tests to evaluate the properties and durability of concrete, as this is crucial in dynamic response of buildings [21]. *In this context, various low-cost techniques have been proposed in the literature for concrete structure characterization* [22].*The compressive strength test, conducted in accordance with ASTM C39, involved cubic specimens measuring 150 × 150 × 150 mm, which were subjected to laboratory jack testing at 7 and 28 days. Water absorption was assessed using 100 × 100 × 100 mm concrete samples in compliance with BS 1881 (part 122). The resistance of concrete to rapid freezing and thawing was evaluated following ASTM C666, employing cubic specimens of 100 × 100 × 100 mm. Water permeability was tested based on DIN 1048 standards using 120 × 120 × 250 mm samples, which were exposed to a water pressure of 0.5 N/mm² for three days. The chloride migration coefficient test, adhering to NT Build-492 specifications, utilized cylindrical specimens (100 mm diameter, 50 mm thickness) to determine concrete permeability against chloride ions, a widely accepted quality control method in Iran. Additionally, electrical resistance measurements were performed using the Resipod device, a non-destructive tool equipped with a 4-point probe to evaluate electrical resistance of specimens. Standard test specimens for this analysis were cylindrical, measuring 200 mm in height and 100 mm in diameter. Additionally, a chemical analysis (EDS) was conducted by TESCAN electron microscope on the fractured area of specimens, to determine the percentages of various ions and chemical elements.*

3. RESULTS AND DISCUSSIONS

The compressive strength results of the tested concrete mixtures provide valuable insights into their performance and durability. The first group of mixtures (D_1 to D_5) exhibited a range of compressive strengths at both 7 and 28 days (figure 1). Among them, D_1, which contained 8% micro silica by weight of cement, demonstrated the highest compressive strength (18.79 MPa at 7 days and 25.06 MPa at 28 days), indicating that micro silica enhances material strength. Conversely, D_5, incorporating 30% natural pozzolan, recorded the lowest compressive strength (14.35 MPa at 7 days and 20.47 MPa at 28 days), suggesting that higher proportions of pozzolan reduce compressive strength. Similarly, the second group of mixtures (D_6 to D_8) exhibited a narrower range of compressive strengths, with D_6 containing 6% micro silica and 6.25% pozzolan demonstrating the highest strength (17.53 MPa at 7 days and 23.69 MPa at 28 days). In contrast, D_8, which *had 2% micro silica and 18.75% pozzolan, showed the lowest strength (16.33 MPa at 7 days and 22.67 MPa at 28 days). A comparative analysis reveals that increasing the pozzolan content while reducing micro silica leads to decreased strength at both time intervals. Notably, while none of the mixtures surpassed the base strength of the control sample, the compressive strength of D_7 remained close to that of D_1, suggesting that refined mix designs incorporating both components may mitigate strength reductions. Additionally, across all designs, the 7-day compressive strength was approximately 70-75% of the 28-day strength.*

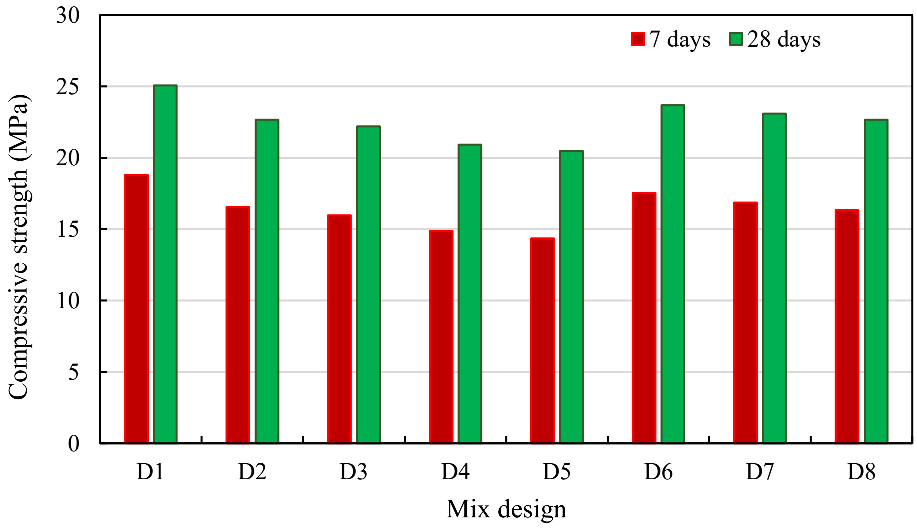

Figure 1. Compressive strength results for the proposed mix designs.

The resistance of concrete to rapid freezing and thawing was assessed across eight mix designs, with two samples tested per mixture. The results indicated a decline in compressive strength after exposure to the freeze-thaw cycle, varying from 10% to 20%. Among the tested samples, D_8 (2% micro silica and 18.75% pozzolan) showed the highest strength reduction at 20%, whereas D_4 (25% pozzolan) exhibited the lowest at 10%, suggesting that pozzolan content significantly influences durability. The trends observed among samples D_2 to D_5 confirmed that while a moderate increase in pozzolan (up to 25%) helps mitigate strength loss, exceeding this threshold negatively impacts performance. Notably, sample D_4 demonstrated better resistance than the control mix design (D_1), reinforcing the potential advantages of optimized pozzolan incorporation in improving freeze-thaw durability.

The water absorption characteristics of eight concrete mixtures (D_1 to D_8) were analyzed to assess their resistance to moisture-related deterioration, with lower absorption indicating better durability (figure 2). The results showed generally low levels of water absorption, with mix designs D_1, D_4, and D_7 exhibiting the lowest values (1.42%–1.46%), while D_8 had the highest (1.62%), suggesting greater susceptibility to water ingress. Among samples D_2 to D_5, D_2 (15% pozzolan) showed the highest absorption in the first half-hour, whereas D_4 (25% pozzolan) exhibited the lowest, indicating that pozzolan content up to 25% improves resistance but exceeding this threshold increases absorption. Similarly, in samples D_6 to D_8, D_7 (4% micro silica and 12.5% pozzolan) displayed the least water absorption, while D_8 (2% micro silica and 18.75% pozzolan) recorded the highest absorption in the same timeframe.

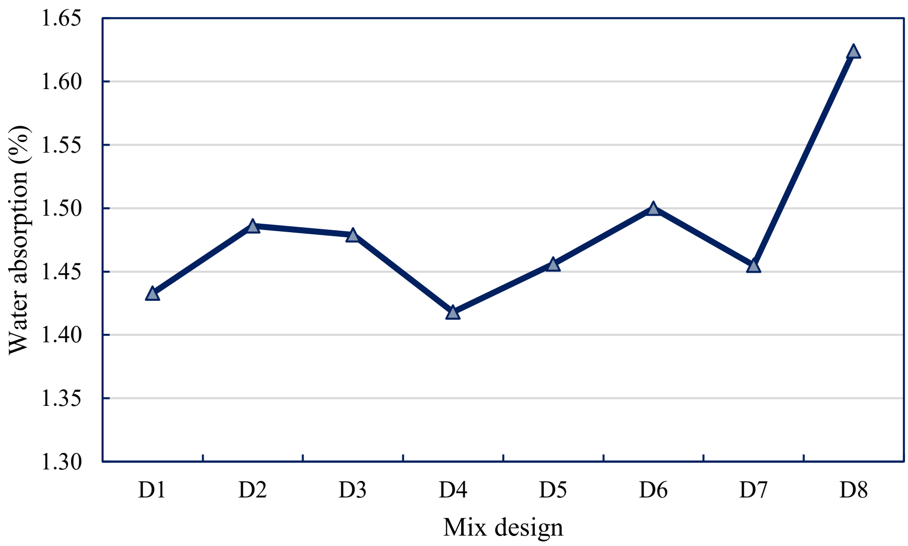

Figure 2. Results of water absorption test for design mixtures.

The water permeability of eight concrete mixtures (D_1 to D_8) was assessed, revealing relatively similar permeability values, with slight variations that could impact practical applications. The highest permeability (0.0190 m/s) was observed in D_8 (2% micro silica and 18.75% pozzolan), indicating greater susceptibility to water infiltration, while the lowest (0.0168 m/s) was recorded in D_4 (25% pozzolan), suggesting enhanced resistance. Among samples D_2 to D_5, D_2 (15% pozzolan) showed the highest permeability, whereas D_4 exhibited the lowest, demonstrating that pozzolan content up to 25% improves water resistance, but exceeding this threshold increases permeability. Similarly, in samples D_6 to D_8, D_7 (4% micro silica and 12.5% pozzolan) displayed the lowest permeability, while D_8 recorded the highest.

The chloride migration coefficient test was performed on eight mix designs, labeled D_1 through D_8, with the following recorded values: 2.30×10^{-12} m²/s, 2.38×10^{-12} m²/s, 2.36×10^{-12} m²/s, 2.28×10^{-12} m²/s, 2.34×10^{-12} m²/s, 2.37×10^{-12} m²/s, 2.34×10^{-12} m²/s, and 2.61×10^{-12} m²/s (Table 3). Analysis of the data presented in Table 3 indicates that all mix designs exhibit relatively similar chloride penetration levels, with minor variations. Among them, mix design D_4, which incorporates 25% pozzolan, demonstrates the lowest chloride ion penetration, whereas mix design D8, containing 2% micro silica and 18.75% pozzolan, exhibits the highest penetration level. Furthermore, within mix designs D_2 through D_5, mix design D_2, with 15% pozzolan, registers the highest chloride ion penetration, while mix design D_4 records the lowest. This suggests that increasing pozzolan content initially leads to reduced chloride ion penetration; however, beyond a threshold of 25%, penetration rates begin to rise again. Therefore, a reverse correlation exists between pozzolan content and chloride ion penetration up to a certain limit, beyond which additional pozzolan contributes to increased penetration. Among mix designs D_6 through D_8, mix design D_7, consisting of 4% micro silica and 12.5% pozzolan, demonstrates the lowest chloride ion penetration, whereas mix design D_8 records the highest.

The electrical resistance test results for the eight mix designs reveal distinct trends and variations in their electrical properties (Figure 3). In the first group, encompassing samples D_1 through D_5, the average electrical resistance is approximately 45.6 KΩ-cm, indicating relatively uniform electrical characteristics with minimal fluctuation among the samples. As shown in Figure 4, sample D_2, containing 15% pozzolan, exhibits the lowest electrical resistance, whereas sample D_4, incorporating 25% pozzolan, demonstrates the highest resistance. In contrast, the second group, comprising samples D_6 through D_8, displays a significant decrease in average *electrical resistance to approximately 43.9 KΩ-cm, marking a notable deviation from the first group's properties. This subgroup exhibits greater variability, with sample D_7, which includes 4% micro silica and 12.5% pozzolan, registering the highest electrical resistance at 45.8 KΩ-cm, while sample D_8, composed of 2% micro silica and 18.75% pozzolan, records the lowest resistance at 40.8 KΩ-cm.*

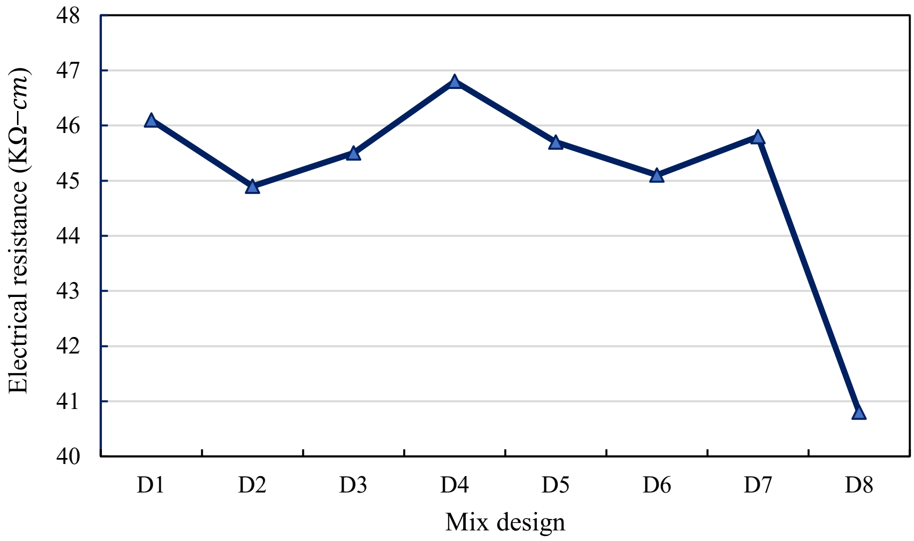

Figure 3. Results of the electrical resistance tests for design mixtures.

The final phase of the study involved assessing the permeability of eight mix designs following four months of exposure to a saltwater solution. Chemical analysis of chloride and sodium ions was performed using Energy Dispersive Spectroscopy (EDS) at three randomly selected points on each sample. Figures 5 and 6 illustrate the chloride and sodium ion concentrations in the samples, determined as the average of the values obtained from EDS evaluations.

The results reveal substantial variations in chloride and sodium ion levels among the different concrete mixtures. Chloride ion concentrations range from 556 to 3683, while sodium ion concentrations vary between 393 and 2333. These significant discrepancies are likely attributable to the randomness inherent in the EDS testing process and the heterogeneous nature of the concrete sample environment.

Among the tested models, mix design D_8 exhibits the highest average chloride ion concentration (3683), indicating the greatest permeability and susceptibility to saltwater intrusion and potential long-term degradation. In contrast, mix design D_4 demonstrates the lowest average chloride ion concentration (556), suggesting enhanced resistance to saltwater-induced damage. As can be seen in figure 4, similarly, mix design D_8 records the highest average sodium ion concentration (2333), reinforcing the notion of increased permeability due to greater exposure to the saltwater solution, while mix design D_4, with the lowest sodium ion concentration (393), presents the potential for improved durability and resistance to saltwater-related deterioration.

Notably, the chloride and sodium ion EDS test results for mix design D_7 closely resemble those of mix design D_1, associated with the refinery project. Despite the inherent randomness of the EDS test, the observed data largely aligns with previous test outcomes across the samples, underscoring the consistency of permeability trends within the evaluated concrete mixtures.

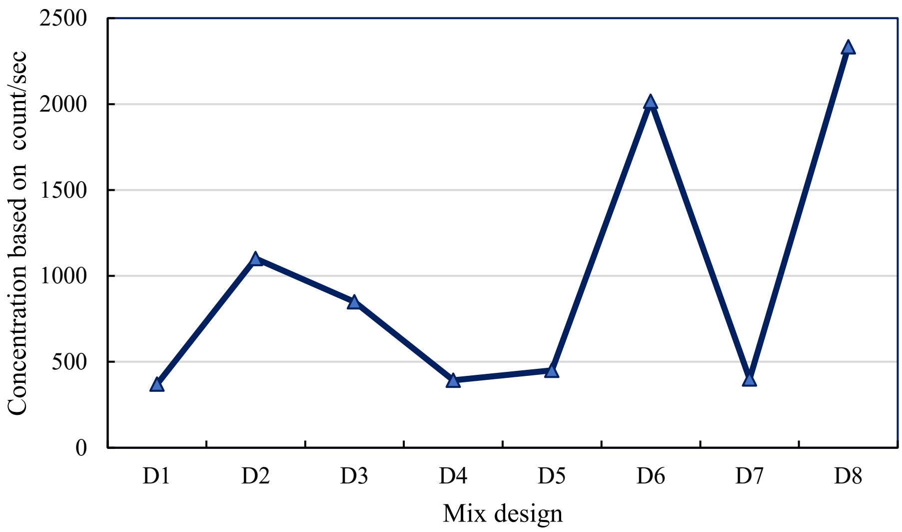

Figure 4. The Sodium ion concentration in the samples.

4. CONCLUSION

This study aimed to improve cost efficiency by partially substituting microsilica with natural pozzolan while maintaining the required durability and strength specified by the construction industry in southern Iran. The motivation behind this approach was the significantly lower cost of natural pozzolan compared to microsilica. Durability testing revealed that mix design D4, which incorporates 25% natural pozzolan, demonstrated the most favorable performance among all tested samples. Notably, even when compared to the refinery mix design containing 8% microsilica, the D4 mix exhibited superior durability characteristics. These findings suggest that increasing the natural pozzolan content up to 25% has a positive impact on the durability of reinforced concrete; however, exceeding this threshold negatively affects durability. Regarding compressive strength, the inclusion of natural pozzolan resulted in a reduction compared to concrete containing microsilica. Higher concentrations of natural pozzolan correlated with lower compressive strength at both 7 and 28 days. For instance, in mix designs relying solely on natural pozzolan, the formulation containing 30% pozzolan showed the most significant decline in compressive strength, whereas the mix with 15% pozzolan exhibited the smallest reduction. Among the samples incorporating both microsilica and natural pozzolan, mix design D7, composed of 4% microsilica and 12.5% natural pozzolan, performed exceptionally well in terms of both durability and compressive strength compared to other formulations. Notably, this blend closely resembled the refinery project mix design in durability and compressive strength, with only minor differences. Since more than 70% of concrete production costs in southern Iran stem from the inclusion of microsilica, this research proposes a financially viable alternative. By replacing 8% microsilica with a combination of 4% microsilica and 12.5% natural pozzolan in concrete formulations for projects in this region, a cost reduction of approximately 20 to 30% in concrete production can be achieved. Given the significantly lower procurement and transportation costs of pozzolan compared to microsilica, this revised mix design presents a practical and cost-effective solution for improving the economic feasibility of concrete projects in southern Iran.

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