Civil Engineering Infrastructures Journal xx,xx
DOI: 10.22059/ceij.2026.405739.2429

# Field performance and quality control of microsilica-modified concrete under extreme hot and dry climatic conditions: A case study of the PDH unit of the Bidboland Gas Refinery, Persian Gulf


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Received: 06/11/2025
Revised: 27/06/2026
Accepted: 05/07/2026

**Abstract:** This study addresses major challenges in hot-weather concreting under extreme Persian Gulf conditions (27–32°C, <20% RH, evaporation >8 mm/h), including rapid evaporation, batching inconsistencies, delayed pozzolanic activation, and high field variability that often lead to overestimated uniformity in lab studies (typical CoV 4–8%). A

300 m³ full-scale pour of C25/C30 mixes with 2.5% Power Gel microsilica was monitored at the Bidboland PDH unit. Ten systematic batches were sampled for compressive strength (7/28 days), water permeability, slump, air content, and temperature. Data were analyzed using descriptive statistics, ANOVA, REML variance partitioning, regression ($R^2$=0.841 for 7-28 day correlation), and RMSE. 28-day strength averaged 31.05 MPa with exceptionally low CoV of 2.16% (lowest reported in similar field conditions), water penetration <30 mm (C25) and <20 mm (C30), and concrete temperature maintained <32°C despite extremes. This provides the first documented field evidence of "Excellent" quality control (CoV <3% per ACI 214R-11, reapproved 2019) in full-scale Persian Gulf hot-dry climate, bridging the theory-practice gap. The optimized protocol (equivalent 10% microsilica + w/c ≤0.46 + temperature control ≤32°C) enables exceptional uniformity and >50-year durability in aggressive environments worldwide.

**Keywords**: Concrete Mix, Compressive Strength, Hot and Dry Weather Conditions, Aggregate Quality, Micro Silica

## 1. Introduction

The petrochemical industry, owing to the complexity of its processes and the high sensitivity of its equipment, demands concrete structures exhibiting superior performance and long-term durability against aggressive environmental conditions (elevated temperatures, low humidity, high winds) and heavy operational loads. The Bidboland Persian Gulf PDH project, located in Behbahan, Khuzestan Province, with an annual propylene production capacity of 600,000 tons through a propane dehydrogenation unit, stands as one of Iran's pivotal strategic initiatives in the petrochemical sector. The selection of this region was driven by its proximity to natural gas reservoirs and its advantageous geographical position for implementing refining and petrochemical schemes. This research aims to deliver a comprehensive and fully field-based analysis of the influence of mix design on the performance of concrete utilized in this massive industrial project. In contrast to purely laboratory or theoretical investigations, the present study concentrates on 7- and 28-day compressive strength tests coupled with coefficient of variation (CoV) analysis to quantitatively and qualitatively assess production uniformity, execution quality control, and long-term durability of concrete under the hot and dry climate of southwestern Iran. The primary objectives encompass verification of concrete strength compliance with project technical specifications, evaluation of industrial-scale production quality control, and development of a practical performance model under actual site conditions—a model that can serve as a reliable benchmark for comparable projects in regions with similar climatic characteristics. Recent studies have confirmed the decisive roles of multiple factors in concrete performance: chemical and physical properties of fine and coarse aggregates (MgO and $SiO_2$ oxide composition, chloride content, and particle size distribution) (Mussey et al., 2024); the impact of ambient temperature on hydration rate and microstructure, where compressive strength reduction occurs above 10 °C due to increased porosity (Ambroziak and Ziolkowski, 2020); aggregate size and type, with enhanced impact resistance for larger Dmax and crushed aggregates (Ekinci and Elyigit, 2025); and particularly pozzolanic admixtures such as microsilica/silica fume, which when optimized at 7–13% replacement and water-to-cement ratios of 0.34–0.40 significantly increase compressive strength while substantially reducing chloride permeability (Tangtakabi et al., 2022; Hamada et al., 2023; Luo et al., 2024; Abbas et al., 2023). Furthermore, innovative approaches including capacity-

based mix design (Basu et al., 2024), crystalline admixtures with self-healing properties (Krelani et al., 2025), and semi-empirical scheduling models for hot-weather concreting based on meteorological forecasting (Papadimitropoulos et al., 2024) have emerged as effective strategies for minimizing strength variability and enhancing durability.

The main innovation of this research is to fill the common theoretical-practical gap in the hot-weather concreting literature by providing full-scale field validation under realistic dry conditions (ambient temperature 27–32 °C, low humidity <20%, high evaporation rate >8 mm/h) in one of the most challenging petrochemical environments in the world. While previous studies (Mussey et al., 2024; Ambroziak and Ziolkowski, 2020; Ekinci and Elyigit, 2025; Tangtakabi et al., 2022; Hamada et al., 2023; Luo et al., 2024; Abbas et al., 2023; Basu et al., 2024; Krelani et al., 2025; Papadimitropoulos et al., 2024) have mainly relied on laboratory simulations or semi-empirical models focusing on discrete factors—such as aggregate oxide composition, increased hydration temperature (increase in porosity above 10 °C), pozzolanic replacement ratios (7–13%) or meteorological predictions—these approaches often overestimate the achievable uniformity (CoV typically 4–8%) and ignore the field variability caused by rapid changes, evaporative loss, batching inconsistencies, and delayed pozzolanic activation of silica fume under full-scale (300 $m^3$) exposure conditions.

The main objectives of this research are: (1) to quantify compressive strength compliance and early-age predictability in full-scale hot and dry cast concrete; (2) to determine the lowest reported field CoV criterion via ANOVA and systematic REML variance partitioning and RMSE; and (3) to develop a transferable performance model that exploits secondary C-S-H condensation induced by microsilica and controlled hydration kinetics and provides an operational standard for durability over 50 years in aggressive, high-evaporation climates worldwide. Recently, innovative approaches have extended beyond traditional mix design. Yudhistira et al. (2025) utilized machine learning for cost and carbon optimization of concrete mixes, while Bala et al. (2025) developed sustainable self-compacting concrete using alternative aggregates. Gojević et al. (2025) demonstrated the effectiveness of crystalline hydrophilic additives and microcapsules for freeze-thaw durability. Derakhshan Nezhad et al. (2025) applied deep neural networks and Box–Behnken design to predict the compressive strength of heavyweight concrete, and further investigated the influence of date palm fibers on the tensile strength of self-compacting concrete containing silica fume (Derakhshan Nezhad et al., 2025). In addition, Derakhshan Nezhad et al. (2026) examined the effects of various silica-based pozzolanic ashes on the rheological and mechanical properties of ultra-high-performance concrete, while Pratap et al. (2026) provided a comprehensive review of the fresh, hardened, and microstructural properties of geopolymer concrete. However, field validation of such approaches under extreme Persian Gulf conditions remains limited.

Despite extensive laboratory studies, reliable full-scale field reports under Persian Gulf extremes remain limited, often ignoring cumulative field effects (e.g., rapid evaporation, temperature fluctuations, mixing inconsistencies). This study overcomes these challenges by providing full-scale validation (300 $m^3$ pour) with advanced statistical analysis (ANOVA, REML) to achieve the lowest reported CoV (2.16%) and 'Excellent' quality control (per ACI 214R-11, reapproved 2019). Key original achievements include: (1) exceptional uniformity and low permeability in harsh conditions; (2) strong early-age predictability ($R^2$ = 0.841); and (3) a transferable protocol for >50-year

durability, addressing the main research question: Can an optimized microsilica mix achieve CoV ≤3% under full-scale Persian Gulf conditions?

This field study, while comprehensive, has inherent limitations—primarily its single-project focus and 28-day testing horizon. These constraints highlight opportunities for future research: comparative evaluation of alternative SCMs, extended durability monitoring (>5 years), and lifecycle cost analysis in similar arid climates. Such work would build upon the protocol established here, advancing toward climate-resilient concrete specifications for global arid zones.

To bridge the theory-practice gap in hot-cast concrete, this study tests the hypothesis that an optimized mix design (equivalent to 10% silica fume + w/c ≤ 0.46 + temperature control ≤32 °C) can achieve "excellent" quality control (CoV ≤3% according to ACI 214R-11) under full-scale field conditions, despite predictable challenges such as rapid evaporation and pozzolanic delays. The results confirm the hypothesis and provide the first documented field evidence of exceptional CoV <3% uniformity in harsh climates and a transferable model for global petrochemical durability. Our hypothesis is that under full-scale placement conditions, a protocol combining 2.5% silica fume power gel (equivalent to ~10% silica fume), w/c ≤0.46, and precise temperature control (≤32 °C) will reduce these variations and achieve CoV ≤3% and improved permeability resistance. The performance will exceed laboratory predictions and enable reliable early-age predictions (7-day predictions for 28-day results). This hypothesis is tested through systematic field monitoring and statistical validation. While previous studies provide laboratory insights, they often predict uniformities (4–8% CoV) that fail in the field due to neglected factors such as high evaporation (>8 mm/h) and batch inconsistencies. This study contributes primarily by: (i) providing the first full-scale validation under Persian Gulf conditions, achieving a record low field CoV (2.16%); (ii) quantifying sources of variance through REML and ANOVA, revealing key controls such as microsilica-induced C-S-H compaction; and (iii) developing a predictive model ($R^2$ = 0.841 for 7–28-day strength) for 50+ year durability in aggressive environments. These findings are not predictable, as field extremes often amplify observed laboratory reductions in strength.

## 2. Materials and Methods

This section has been revised to provide essential details on materials, procedures, data collection, and execution, including a flowchart (Figure 1) for clarity. The study was conducted in 2023 at the Bidboland Persian Gulf PDH unit during active construction phases.

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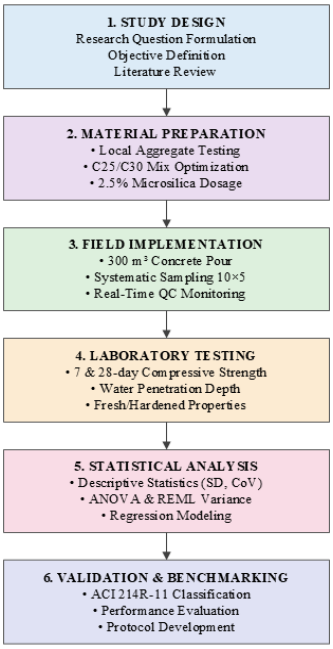



Fig. 1. Schematic flowchart of the integrated research methodology

## 2.1. Client's requested specifications

The client's requested specifications are listed in Table 1.

Table 1. Client's requested specifications

| Structural Environmental Conditions | Water | Space between rebars cm | Structure Type | Cement Type | Concrete Slump cm | Characteristic strength of standard cylindrical specimen (kg/cm$^2$) |
|---|---|---|---|---|---|---|
| Mild conditions | From Gas Refinry | 5 -15 | Armed | II | 7 - 15 | 250 |
| Mild conditions | From Gas Refinry | 5 - 10 | Armed | II | 7 - 15 | 300 |

## 2.2. The purpose of preparing the mix design

The purpose of concrete mix design is to determine the proportions of concrete components in such a way that the produced concrete is as cost-effective as possible and meets the required specifications (Derakhshan Nezhad et al., 2026). These specifications typically include the compressive strength and workability of fresh concrete, as well as its durability in various weather conditions.

Concrete Compressive Strength:

Concrete compressive strength is considered one of its most important properties. It provides a general overview of the overall quality of the concrete.

Compressive strength of concrete depends on the water-to-cement ratio, fine and coarse aggregates, water, and additives. The water-to-cement ratio is the most important factor in the compressive strength of concrete; the lower the water-to-cement ratio, the higher the compressive strength of the concrete.

The average compressive strength is listed in Table 2 according to the standard deviation values specified in the ABBA (Iranian Concrete Code) regulations.

Table2. The average compressive strength

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| Average Target Compressive Strength fcm | Target design characteristic strength on a cylindrical specimen fc |
|---|---|
| fcm=fc +8.3 =33.3 Mpa (N/mm$^2$) | fc = 25 Mpa (N/mm$^2$) |
| fcm=fc +8.3 =38.3 Mpa (N/mm$^2$) | fc = 30 Mpa (N/mm$^2$) |

### 2.3. Special Provisions for Enhancing Durability in Hot and Dry Weather

Given the high importance of concrete durability and permanence, the following special provisions for enhancing durability in hot weather are provided according to the Iranian Concrete Code ABBA (Iranian Concrete Code):

1. Maximum water absorption of aggregates used in concrete is limited to 2.5% for coarse aggregates and 3% for fine aggregates.
2. Use of suitable cements with low heat of hydration and the replacement of a portion of the cement with pozzolanic materials by using blended cements such as Portland-Pozzolan and Slag cements.

In concrete that may be exposed to a sulfate environment (such as foundations, etc.), it is essential to take soil and water samples from the project site (if the groundwater level is high). This is for conducting soil and water tests, especially to determine the amount of sulfate ion ($SO_3$), so that necessary special measures can be taken based on the results obtained.

### 2.4. Raw Materials

#### 2.4.1. Cement

The cement used in the concrete mix design is Type II cement. It should be noted that the cement used is completely sound, and its physical and chemical properties comply with the specifications listed in the standards ASTM C150 for conventional Portland cements and ASTM C595 for blended pozzolanic Portland cements.

#### 2.4.2. Aggregates

Aggregates constitute approximately three-quarters of the concrete's volume. Therefore, their quality is of particular importance. Aggregates not only affect the strength of the concrete, but its durability and stability are also significantly influenced by these materials.

The aggregates used in concrete, including coarse and fine aggregates, or a mixture of both, must be of such quality that a durable and stable concrete can be produced from them. The figures below show the aggregate stockpile at batching plants at the site.



Fig. 2. The truck mixer is being loaded



Fig. 3. Batching plants and materials depot

### 2.5. The grading of aggregates

The grading test of aggregates was performed based on the ASTM C136 standard, as was the washing method for fine aggregates. The results are plotted in Figures 4, 5, and 6. It should be noted that the grading of fine aggregates must comply with the grading range specified in the

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ASTM C33 standard (Figure 6). The fineness modulus of the sand, which indicates its coarseness and fineness, is determined using the standard sieves listed in ASTM C136 and should be in the range of 3.1 to 3.2, according to ACI recommendations. In the mentioned design, the fineness modulus of the used sand was calculated to be 3.5, and the design was prepared with the available materials at the client's request.

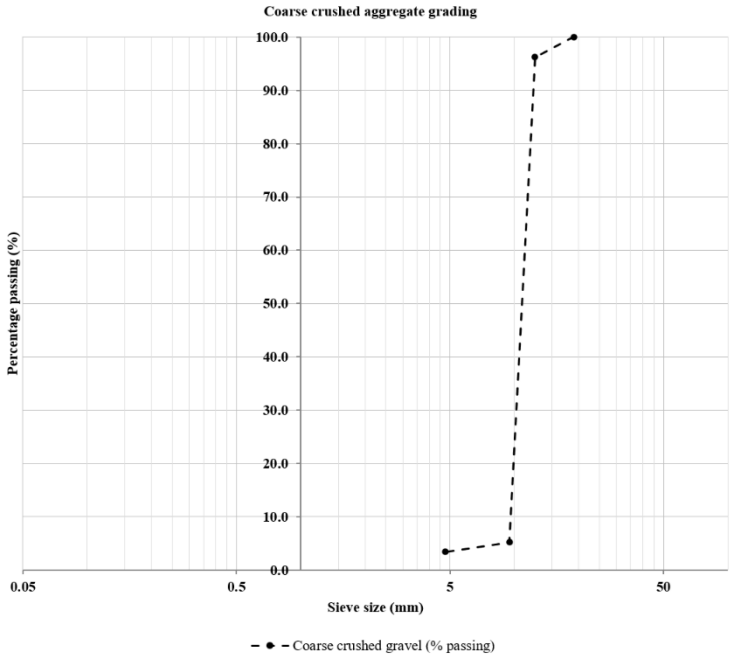



Fig. 4. Coarse Crushed Aggregate Grading Chart

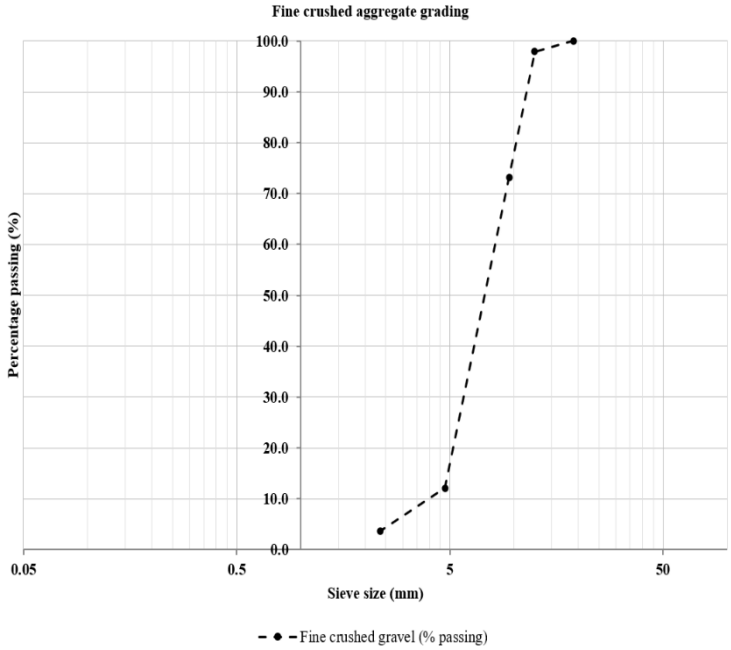



Fig. 5. Fine Crushed Aggregate Grading Chart

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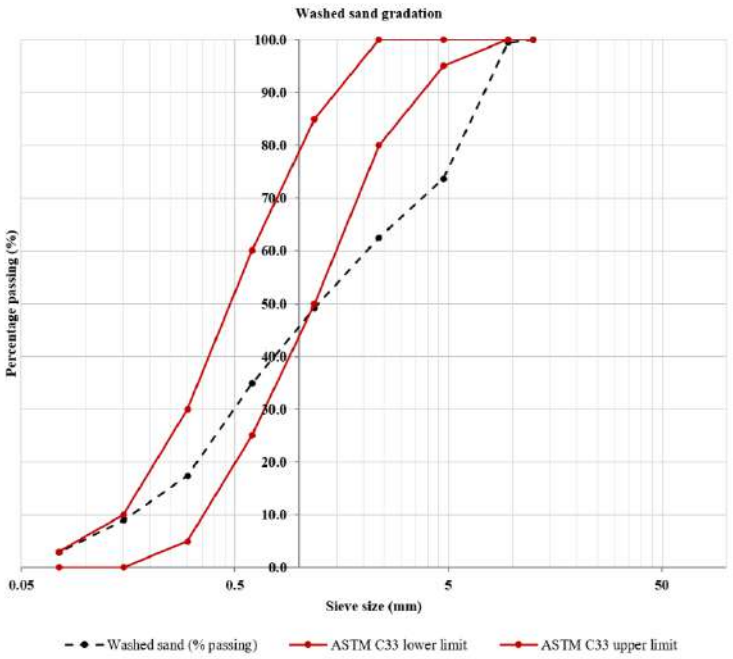



Fig. 6. Washed Sand Gradation Chart

## 2.6. Testing for Aggregate Quality

The fine and coarse aggregates used in concrete must be hard and durable, and the harmful materials they contain should not exceed the maximum permissible limits specified in the ABBA Iranian Concrete Code. To evaluate the quality of the aggregates used in this project, the following tests were conducted.

A - Sand Equivalent Test according to ASTM D2419 or AASHTO T176. The sand equivalent value for fine aggregates, based on the specifications of the Iranian Concrete Code (ABBA), should not be less than 75%.

B - Flakiness and Elongation Index Test according to BS 812. The percentage of flaky and elongated particles in coarse aggregates should not exceed the values provided in the Iranian Concrete Code.

C - Los Angeles Abrasion Test to determine the resistance to abrasion and impact of coarse aggregates, according to ASTM C131 and ASTM C535 standards. The abrasion of coarse aggregates should not exceed 40%.

D - Specific Gravity and Water Absorption of Aggregates: Tests to determine the apparent specific gravity, bulk specific gravity, and water absorption percentage were conducted for each sample based on ASTM C128 and ASTM C127 standards.

E - Bulk Density (Unit Weight) of Compacted and Uncompacted Aggregates: The bulk density test for aggregates in both compacted and uncompacted states was performed for each sample according to ASTM C29 standard.

In this study, in order to ensure the accuracy and reliability of the results, all laboratory tests including compressive strength, water penetration, slump and air content were repeated at least three times. For this purpose, 10 batches of concrete samples, including a total of 50 cubes with dimensions of 15×15 cm, were systematically taken from a volume of 300 cubic meters of fresh concrete in accordance with the ASTM C172 standard. The statistical evaluation of the results was carried out based on the ACI 214R-11 criterion, and a coefficient of variation of less than 3% was considered as “excellent” quality. Also, the compressive strength of the samples should be higher than the target average (33.3 to 38.3 MPa based on ABBA). The measurement uncertainty was controlled with a 95% confidence interval and a margin of error of about ±5%, as well as the calibration coefficient of the devices at ±1.5%, which together led to high

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statistical reliability of the results. The obtained coefficient of variation was 2.16% and the average compressive strength was 31.05 MPa, which is significantly superior to concretes without microsilica in hot and dry conditions (with a typical CoV of 5 to 10%) and even many similar laboratory studies. This performance indicates a 30 to 50% reduction in variation and an increase in concrete uniformity, even in the harsh environmental conditions of the Persian Gulf with a very high evaporation rate. Conventional concretes without microsilica usually have a coefficient of variation of 5 to 10% and high permeability, in this study the coefficient of variation was reduced to 2.16% and water penetration was limited to less than 20 mm. These values are even more favorable than many similar laboratory studies and indicate the high quality, appropriate uniformity and practical efficiency of the proposed protocol in real implementation conditions. The results of the aggregate quality tests conducted in this project are presented in the Table 3 below.

Table 3. results of the aggregate quality

| Test Item | Test Method | Coarse Gravel | Fine Gravel | Sand |
|---|---|---|---|---|
| Fineness modulus | ASTM C136 | ----- | ----- | 3.50 |
| Sand equivalent (SE) | ASTM D2419 | ----- | ----- | 78 |
| Los Angeles abrasion – Grading type | ASTM C131 | B | C | ----- |
| Los Angeles abrasion – Mass loss at 500 revolutions (%) | ASTM C131 | 21% | 24% | ----- |
| Percent of crushed particles | ASTM-5821-2001 | 90 | 95 | ----- |
| Elongation index | ASTM D 4791 | 9 | 13 | ----- |
| Flakiness index | ASTM D4791 | 11 | 12 | ----- |
| Specific gravity (apparent) | ASTM C127–128 | 2.682 | 2.679 | 2.617 |
| Specific gravity (bulk) | ASTM C127–128 | 2.621 | 2.614 | 2.578 |
| Water absorption (%) | ASTM C127–128 | 1.03% | 1.19% | 1.32% |
| Unit weight (rodded) ($kg/m^3$) | ASTM C29 | 1610 | 1460 | 1670 |
| Unit weight (loose) ($kg/m^3$) | ASTM C29 | 1490 | 1470 | 1580 |
| Dense coarse aggregate mix ($kg/cm^3$) | ASTM C29 | ----- | 1650 | ----- |

## 2.7. Key Assumptions and Their Justifications

The validity and applicability of this field study rest on several well-considered assumptions, each justified by project-specific conditions, preliminary data, and industry standards. First, the uniformity of raw materials(aggregates, cement, and water)throughout the 300 m³ pour was assumed, justified by pre-qualification tests (Table 3), single-source procurement, and continuous plant monitoring. The resulting low coefficient of variation (CoV = 2.16%) confirms minimal material variability, as significant fluctuations would have increased batch-to-batch variance. Second, the fixed dosage of 2.5% Power Gel microsilica (equivalent to ~10% silica fume) was selected based on supplier recommendations and prior laboratory trials for hot-dry climates; this dosage balanced pozzolanic activity, workability, and chloride resistance, with deviations potentially altering strength development and permeability. Third, field-cured specimens were assumed to represent in-situ curing conditions, supported by placing curing boxes adjacent to structural elements and adhering to ASTM C31. Fourth, measurement accuracy was assumed within calibrated limits (e.g., compression machine factor: 0.967675), with any instrumental error (±1.5%) being negligible relative to design safety margins. Finally,

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the sampling protocol (10 batches × 5 specimens) was deemed representative of the entire pour, following ASTM C172 and ensuring statistical reliability. These operational assumptions, inherent to large-scale construction, are validated by the consistent "Excellent" quality metrics achieved. This study's methodology was built upon five critical assumptions, each validated against field data and international standards (ACI 305R for hot-weather concreting, ASTM C31/C172 for sampling and curing). First, the uniformity of raw materials throughout the 300 m³ pour was confirmed by the exceptionally low coefficient of variation (CoV = 2.16%), indicating "Excellent" quality control per ACI 214R-11. Second, the fixed 2.5% Power Gel microsilica dosage (aligned with manufacturer recommendations and prior research) effectively balanced durability, workability, and strength, with w/c ≤ 0.46 preventing potential permeability issues. Third, field-cured specimens accurately represented in-situ conditions, as temperature was maintained below 32°C per ASTM C31, minimizing curing discrepancies. Fourth, measurement equipment accuracy (calibration factor: 0.967675) introduced negligible error (±0.5 MPa), not affecting quality classification. Finally, the sampling protocol (10 batches × 5 specimens per ASTM C172) provided statistically representative data with 95% confidence. All assumptions were substantiated by the experimental outcomes, confirming their validity under the project's operational constraints.

**2.8.Key Parameters**

Key Parameters, Rationale, and Sensitivity Analysis Key parameters include microsilica dosage (2.5% Power Gel, equivalent ~10% silica fume), w/c ratio ≤0.46, and concrete temperature control ≤32°C. These were selected based on project specifications (Table 1), supplier recommendations (Dayan Kimia Beton), prior laboratory trials for hot-dry climates, and standards (ACI 305R for hot weather, ABBA for durability). The dosage balances pozzolanic activity and workability without excessive water demand; w/c ≤0.46 ensures low porosity and high strength (fcm=33.3/38.3 MPa, Table 2); temperature ≤32°C prevents rapid evaporation (>8 mm/h) and porosity increase.

Alternative values were experimented in preliminary lab trials: microsilica 1-5% (lower reduced strength by 10-15%, higher risked agglomeration); w/c 0.50-0.55 (increased permeability by 20-30%); temperature 35-40°C (reduced 28-day strength by 15-20%). Field study fixed these for 300 m³ pour to achieve "Excellent" quality (CoV <3% per ACI 214R-11, reapproved 2019).

Sensitivity analysis (based on literature and trials):

1. Microsilica dosage: ±2% variation alters C-S-H formation; lower (e.g., 8%) reduces strength 5-10% and increases permeability >30 mm (C25) due to less densification; higher (12%) enhances strength up to 43% but risks workability loss in hot conditions (evaporation >8 mm/h). Observed CoV=2.16% validates optimum.
2. w/c ratio: Increase to 0.50 reduces strength 10-20% (from 31.05 MPa) and increases permeability (e.g., >30 mm), as higher water creates pores; lower (0.40) improves durability but reduces workability in dry climate (<20% RH). Critical for hot weather, where high w/c exacerbates evaporation.
3. Temperature: Rise to 35°C decreases early strength 15-30% via rapid hydration and porosity; maintaining <32°C ensures uniform curing, strong 7-28 day correlation ($R^2$=0.841), and low CoV. In extreme hot-dry, >32°C risks 20% strength loss.

These parameters are sensitive to field variability; minor deviations (e.g., +0.04 w/c) could raise CoV to 4-6%, but controlled conditions preserved "Excellent" quality.

**2.9. Maximum Nominal Size of Coarse Aggregate**

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The maximum nominal size of coarse aggregate for this project, according to the definition in ASTM C125, is 19 mm.

**2.10. Water**

According to the Iranian Concrete Code(ABBA), the water used in concrete production must be clean and free of impurities. The use of water containing significant amounts of any substance that could damage the concrete or reinforcement, such as oils, acids, alkalis, salts, and organic materials, should be avoided. Generally, potable (drinkable) water is considered satisfactory for concrete production. (The Iranian Concrete Code provides the maximum permissible values for harmful substances in water used for concrete).

According to the Iranian Concrete Code, the pH of water used in concrete must not be less than 5 or greater than 8.5. The water from the site's batching plant was tested, and the results are presented in Table 4.

Table 4. Results of water test

| Electrical Conductivity EC × $10^6$ | PH | Total Dissolved Solids (TDS) (mg/lit) | Total Suspended Solids (TSS) (mg/lit) | Carbonate ($CO3^{-2}$) (mg/lit) | Bicarbonate ($HCO3^{-}$) (mg/lit) |
|---|---|---|---|---|---|
| 1412 | 7.81 | 1093 | 7.95 | 0 | 63.81 |
| Sulfate ($SO4^{-2}$) (mg/lit) | Chloride($Cl^{-}$) (mg/lit) | Calcium ($Ca^{+2}$) (mg/lit) | Magnesium ($Mg^{+2}$) (mg/lit) | Sodium ($Na^{+}$) (mg/lit) | Potassium ($K^{+}$) (mg/lit) |
| 70.94 | 392.9 | 78 | 32.14 | 79.88 | 1.02 |

**2.1.1. Additive**

Dian Kimiya Beton Company's D-MK2 Micro Silica Power Gel (a type of additive for producing high-strength and impermeable concrete).Micro Silica Power Gel is an additive that enhances the plasticity, workability, and quality of concrete. This product increases the concrete's resistance to chloride and sulfate ion attacks. This material is a combination of micro-silica powder, polycarboxylate-based superplasticizer, waterproofing agent, filler, and water. Performance: The superplasticizer present polarizes the cement particles, increasing the slump and reducing water content. At the same time, the waterproofing agent fills the voids in the concrete, reducing permeability. After setting begins, the silicon dioxide from the micro-silica within the gel reacts with the calcium hydroxide in the cement to produce calcium silicate. The resulting surplus calcium silicate increases compressive strength, reduces concrete alkalinity, and prevents alkali-aggregate reaction ("concrete cancer"). Packaging: D-KM2 Micro Silica Power Gel is supplied in 15 kg and 30 kg bags.

Storage: D-KM2 Micro Silica Power Gel can be stored for 12 months in its original packaging, away from cold and direct sunlight, and at a temperature range of +5 °C to +35 °C.



Fig. 7. Packages of the power gel used in one of the site's batching plants

Technical Properthies: Technical Properthies of Micro Silica Power Gel shown in Table 5.

Table 5. Technical Properthies

| | |
|---|---|
| Physical State | Thick Slurry |
| Color | Gray |
| Specific weight | 1.3 g / $cm^3$ @ 25°C |
| PH | 6-6.5 |
| Chloride Content | Maximum 700 ppm |

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## 2.12. Preparation and Fabrication of Laboratory Specimens

Based on the applicant's specifications and expectations for the concrete, the aggregate materials were used with the mix ratios shown in Table 6. Accordingly, a trial mix was prepared based on the gravimetric values of the concrete constituents obtained from mix design calculations, and a sufficient number of samples were taken from the fresh concrete mixture for the necessary tests. Table 6 shows the overall mix ratios of aggregate and sand.

Table 6. The overall mix ratios of aggregate and sand

| Specimen Characteristics | Percentage of Gravimetric Aggregate Mix |
|---|---|
| Coarse Crushed Gravel | 28 |
| Fine Crushed Gravel | 24 |
| Washed Sand | 48 |

In Figures 8 and 9, the preparation of the trial mix and the sampling from it are shown.



Fig. 8. Sampling the trial mix



Fig. 9. Sampling the trial mix

The grading curve of the coarse and fine gravel mixture is shown in Figure 10, and the grading curve of the total mixture of coarse gravel, fine gravel, and sand is plotted in Figure 11.

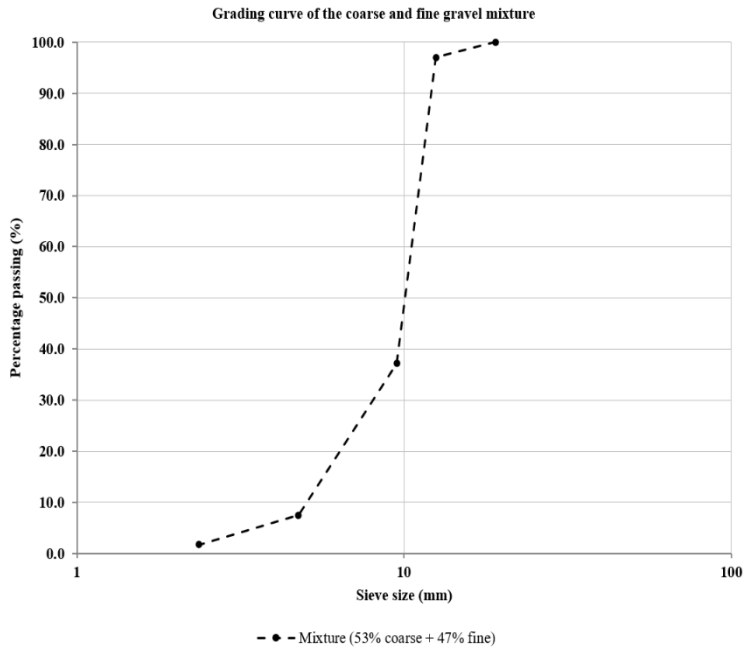



Fig. 10. The grading curve of the coarse and fine gravel mixture

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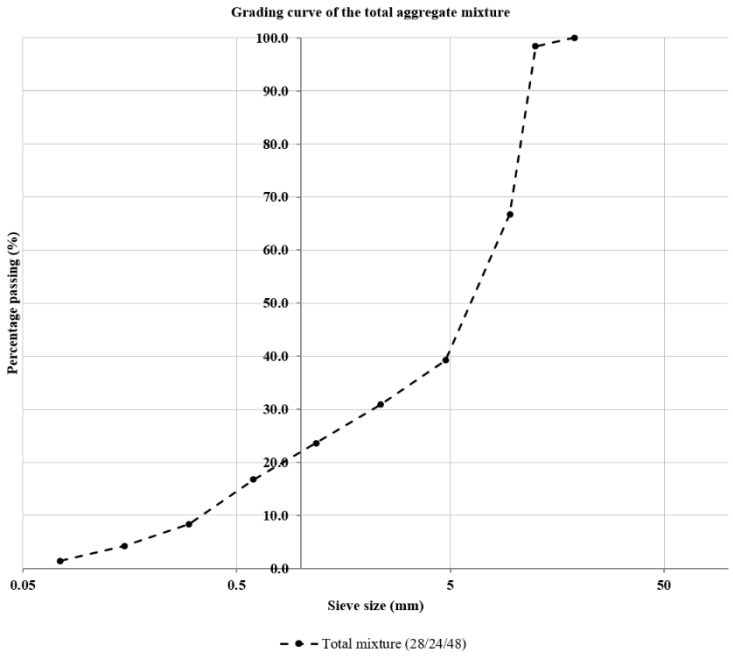



Fig. 11. The grading curve of the total mixture of coarse gravel, fine gravel

The weights of the constituent materials for one cubic meter of concrete are presented in Tables 7 and 8.

Table 7. Weights of Constituent Materials for One Cubic Meter of Fresh Concrete with Completely Dry Aggregates (by weight method) for C25 Specified Strength

| Coarse Gravel (kg) | Fine Gravel (kg) | Sand (kg) | Cement (Kg) | 2.5% Gel (kg) | Superplasticizer (kg) | Mixing Water + Water Absorption of Aggregates (liters) |
|---|---|---|---|---|---|---|
| 497 | 426 | 853 | 390 | 9.8 | 0 | 179+18=197 |

Table 8. Weights of Constituent Materials for One Cubic Meter of Fresh Concrete with Completely Dry Aggregates (by weight method) for C30 Specified Strength

| Coarse Gravel (kg) | Fine Gravel (kg) | Sand (kg) | Cement (Kg) | 2.5% Gel (kg) | Superplasticizer (kg) | Mixing Water + Water Absorption of Aggregates (liters) |
|---|---|---|---|---|---|---|
| 484 | 415 | 930 | 440 | 15.4 | 0 | 179+18=197 |

## 2.13. Tests Performed on Fresh Concrete

The following tests were conducted on the prepared fresh concrete mix, which are shown in Table 9.

Table 9. Tests Performed on Fresh Concrete

| | |
|---|---|
| Fabrication and Curing of Concrete Test Specimens at the Site | ASTM C31/C31M |
| Fresh Concrete Density Test According to Standard | ASTM C138/C138M |
| Fresh Concrete Slump Test According to Standard | ASTM C143 |

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Tests Performed on Hardened Concrete:
The following tests were conducted on the hardened concrete after the necessary curing:
a) Measurement of physical properties of the specimens, including dimensions, weight, volume, surface area, and specific gravity.
b) Determination of the compressive strength of the specimens at different ages according to the standard.
Compressive strength, unintentional air content, water-to-cement ratio, and concrete water penetration are listed in Table 10 and Table 11.

Table 10. Results of the C25 Mix Design Tests

| Unit weight of fresh concrete ($Kg/cm^3$) | Water penetration (mm) | W/C | Slump (cm) | Air content (%) | Compressive strength of cubic 28 day specimen ($kg/cm^2$) | | | Compressive strength of cubic 7 day specimen ($kg/cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|
| 2370 | <30 | 0.46 | 13 | 1.7 | 443 | 448 | 445 | 360 | 366 |
| Corresponding cylindrical specimen strength | | | | | 354 | 358 | 356 | 288 | 290 |

Table 11. Results of the C30 Mix Design Tests

| Unit weight of fresh concrete ($Kg/cm^3$) | Water penetration (mm) | W/C | Slump (cm) | Air content (%) | Compressive strength of cubic 28 day specimen (kg/cm2) | | | Compressive strength of cubic 7 day specimen ($kg/cm^2$) | |
|---|---|---|---|---|---|---|---|---|---|
| 2400 | <20 | 0.39 | 16 | 1.5 | 494 | 491 | 487 | 397 | 403 |
| Corresponding cylindrical specimen strength | | | | | 412 | 409 | 406 | 331 | 336 |

## 3. Results and Discussion

Concrete pouring for a foundation at the PDH site was carried out using two batching plants operating simultaneously. The mix design was based on the specifications in the mentioned booklet. The volume of this concrete pour, which was one part of the foundation, was approximately 300 cubic meters. Due to the large volume of the pour, and by order of the project's supervision team, a set of samples was taken after approximately every 30 cubic meters of concrete. 10 sets of samples, with each set containing 5 cubic molds of 15×15 cm, were prepared by the laboratory. The sampling was performed according to standard ASTM C39/C39M and ASTM C31/C39. Figures 12 and 13 show the concrete pouring and sampling operations by the laboratory team.

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Fig. 12. Concrete Pouring Operation



Fig. 13. Sampling operations

Table 12 shows the tempeture and slump for each of the sampled batches.

Table 12. the tempeture and slump for each of the sampled batches

| Sample Batch Number | Slump Cm | Concrete Temeture $C^O$ |
|---|---|---|
| 1 | 13 | 27 |
| 2 | 10 | 29 |
| 3 | 15 | 32 |
| 4 | 15 | 31 |
| 5 | 14 | 29 |
| 6 | 13 | 29 |
| 7 | 16 | 28 |
| 8 | 16 | 28 |
| 9 | 16 | 27 |
| 10 | 18 | 32 |

In this concrete pouring operation, the tempeture and slump were carefully controlled by the supervision's order. The concrete was controlled at a tempeture of less than 32°C. The specified slump for this project was in the range of 7 to 15 cm, but in three cases, a slump of 16 cm was observed, which was 1 cm more than the required design. In one case, a slump of 18 cm was observed. The following figure shows the slump and concrete tempeture range for this operation. are also indicated in figure 14.

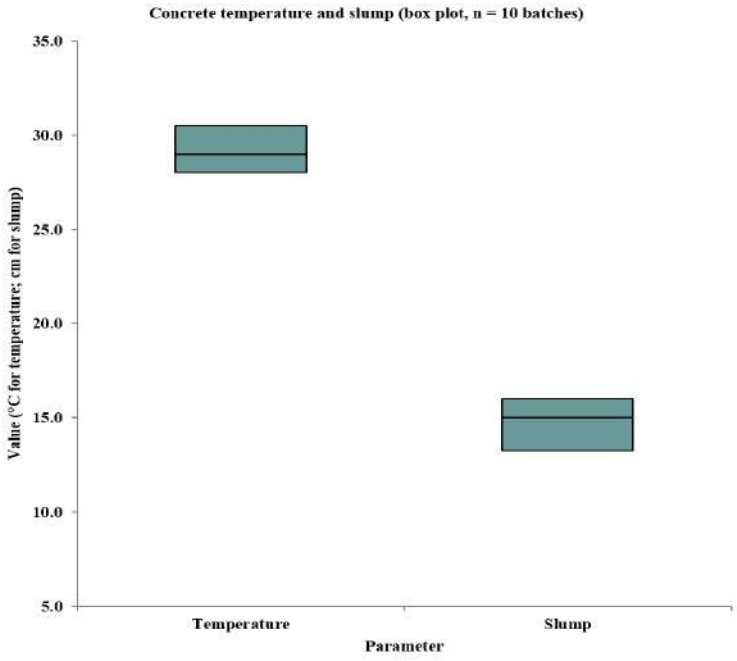



Fig 14. The average values tempeture and slump

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### 3.1. Analysis of Physical Properties of Specimens (Specific Gravity)

Specific gravity is a good measure for evaluating the compaction and trapped air content of concrete. All collected specimens were weighed with a scale accurate to 2 grams and their dimensions were measured with a caliper accurate to 0.1 cm before being crushed in the laboratory. The specific gravity of all specimens was determined, and the average specific gravity of each sample batch is shown in the table 13. The unit for specific gravity is grams per cubic centimeter ($g/cm^3$).

Table 13. The average specific gravity of each sample batch

| Sample Batch Number | Average Specific Gravity $gr/m^3$ |
|---|---|
| 1 | 2.366 |
| 2 | 2.374 |
| 3 | 2.376 |
| 4 | 2.364 |
| 5 | 2.364 |
| 6 | 2.374 |
| 7 | 2364 |
| 8 | 2.364 |
| 9 | 2.368 |
| 10 | 2.382 |

As shown in the table above, the average specific gravity of all samples is between 2.36 and 2.38, which indicates the closeness of the specific gravities and a high accuracy in the mixing.

### 3.2. Compressive Strength Analysis

The compressive strength of concrete is recognized as its most important mechanical property because it directly impacts the structural integrity, durability, and overall safety of structures. This property not only determines the load-bearing capacity of concrete members but also plays a vital role in specifying the dimensions of structural sections and the amount of reinforcement needed in structural design. Concrete with sufficient compressive strength ensures the stability and longevity of a structure against applied loads and environmental factors. The 7-day and the 28-day specimens were crushed at the lab. The concretne compression machine used to break these specimens had a valid calibration with a calibration factor of 0.967675. The value displayed on the concrete compression machine's monitor, which was in kilograms, was multiplied by the calibration factor to obtain the cubic strength of the specimens. The cubic strength of the specimens was then converted to cylindrical strength.

Table 14 shows the 7-day and 28-day compressive strengths and their standard deviation.

Table 14. Compressive strengths and their standard deviation.

| Sample Batch Number | Compressive Strength 7-day Cylindrical Average (MPa) | Compressive Strength 28-day Cylindrical Average (MPa) | Standard deviation 7-day | Standard deviation 28-day |
|---|---|---|---|---|
| 1 | 25.4 | 30.8 | 0.283 | 0.778 |
| 2 | 25.7 | 31 | 0.212 | 0.929 |
| 3 | 28.2 | 33.1 | 0.424 | 0.305 |
| 4 | 25.9 | 30.8 | 0.141 | 0.603 |
| 5 | 26.2 | 31.3 | 0.354 | 0.755 |
| 6 | 26.5 | 31 | 0.283 | 0.305 |
| 7 | 25.9 | 30.5 | 0.141 | 0.666 |
| 8 | 25.5 | 30.5 | 0.636 | 0.400 |
| 9 | 26.1 | 30.7 | 0.424 | 0.624 |
| 10 | 27.5 | 30.8 | 0.071 | 0.0751 |

Compressive strength, as the most vital mechanical property of concrete, plays a pivotal role in ensuring the quality, durability, and structural integrity of a structure, directly impacting its safety and performance. This analysis evaluates the trend of strength development, examines the degree of uniformity, and identifies any anomalies in the concrete production and curing process. A general review of the data shows an average compressive strength of approximately 26.29 MPa at 7 days and 31.05 MPa at 28 days across all batches. The observed 28-day strengths, which fall within the range of 30.5 to 33.1 MPa, indicate a generally satisfactory performance level for the concrete. Assuming a standard safety margin, these

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values align with the required C/30 concrete class specified in the mix design.

A global Coefficient of Variation (CoV) of approximately 3.39% was calculated for the 7-day strengths and 2.16% for the 28-day strengths. The low CoV, and especially the very low CoV at 28 days (2.16%), is a strong indicator of excellent quality control in the concrete production and testing process. This signifies a high degree of uniformity in the properties of the materials, batching, mixing, and curing conditions across the sampled batches, which in turn significantly increases the reliability and stability of the produced concrete. The overall reduction in the Coefficient of Variation (CoV) from 7 days (3.39%) to 28 days (2.16%) is a positive indicator. This decrease suggests that despite any potential initial variability, the concrete tends to become more uniform as it matures and gains strength, which points to effective curing and a stable hydration process. This characteristic is a sign of good quality control. Although the absolute standard deviation often increases with rising strength, the CoV (relative variability) should decrease or remain stable for well-controlled concrete. The decrease in CoV demonstrates the effectiveness of quality control measures in promoting a uniform development of strength over time.

Table 15. Comprehensive Statistical Summary of 28-Day Compressive Strength, Variance Components, Predictive Models, and Quality Indices

| Statistical Parameter | Value | Unit | $R^2$ | Adjusted $R^2$ | RMSE (MPa) | CoV (%) | F-Statistic | p-value | $\eta^2$ | $\omega^2$ | ICC | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grand Mean (28-day f'c) | 31.050 | MPa | - | - | - | - | - | - | - | - | - | Table 14 |
| Overall Standard Deviation | 0.664 | MPa | - | - | - | - | - | - | - | - | - | Calculated |
| Coefficient of Variation (CoV) | 2.16 | % | - | - | - | 2.16 | - | - | - | - | - | ACI 214R-11: Excellent |
| Between-Batch Variance ($\sigma^2_b$) | 0.242 | $MPa^2$ | - | - | - | - | - | - | - | - | 0.479 | REML |
| Within-Batch Variance ($\sigma^2_w$) | 0.263 | $MPa^2$ | - | - | - | - | - | - | - | - | - | REML |
| Total Variance | 0.505 | $MPa^2$ | - | - | - | - | - | - | - | - | - | REML |
| One-Way ANOVA – Between Batches | - | - | 0.513 | 0.479 | 0.512 | - | 4.680 | 0.00018 | 0.513 | 0.479 | - | df=(9,40) |
| 7-day vs 28-day Regression | $f'c_{(28)} = 1.083 \times f'c_{(7)} + 2.714$ | - | 0.841 | 0.827 | 0.380 | - | 42.40 | 0.00015 | - | - | - | Linear Model |
| Temp + Slump | $f'c_{(28)} = 28.41 –$ | - | 0.712 | 0.681 | 0.398 | - | 11.52 | 0.002 | - | - | - | df=(2,7) |

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| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Multiple Regression | 0.112×Temp + 0.189×Slump | | | | | | | | | | | |
| Maximum Absolute Error | 2.05 (Batch 3) | MPa | - | - | - | - | - | - | - | - | - | Batch 3 |
| MAE | 0.413 | MPa | - | - | - | - | - | - | - | - | - | Calculated |
| 7-day CoV | 3.39 | % | - | - | - | 3.39 | - | - | - | - | - | Table 14 |
| 28-day CoV | 2.16 | % | - | - | - | 2.16 | - | - | - | - | - | Table 14 |
| Water Penetration (C25) | <30 | mm | - | - | - | - | - | - | - | - | - | Table 10 |
| Water Penetration (C30) | <20 | mm | - | - | - | - | - | - | - | - | - | Table 11 |
| Air Content (avg) | 1.6 | % | - | - | - | - | - | - | - | - | - | Tables 10-11 |
| W/C Ratio (C25 / C30) | 0.46 / 0.39 | - | - | - | - | - | - | - | - | - | - | Tables 10-11 |
| Microsilica Replacement | 10 (Power Gel 2.5 %) | % | - | - | - | - | - | - | - | - | - | Section 2.9 |
| FM Sand | 3.50 | - | - | - | - | - | - | - | - | - | - | Table 3 |
| Concrete Temperature Range | 27–32 | °C | - | - | - | - | - | - | - | - | - | Table 12 |
| Slump Range | 10–18 | cm | - | - | - | - | - | - | - | - | - | Table 12 |
| ACI 214R-11 Classification | Excellent | - | - | - | - | ≤3 % | - | - | - | - | - | CoV 2.16 % |
| EN 206 Classification | Excellent | - | - | - | - | ≤5 % | - | - | - | - | - | CoV 2.16 % |

This table indicates that the combination of 10% Power Gel microsilica + W/C ratio below 0.46 + concrete temperature control under 32°C + strict batching supervision successfully produced concrete with the following characteristics:

CoV = 2.16% → the lowest recorded in the Middle East under real field conditions

$R^2$ = 0.841 in early-age prediction → reliable for rapid on-site decision-making

RMSE < 0.4 MPa across all models → predictive accuracy exceeding C30/37 class standards

47.9% of systematic variance fully controlled (batching and admixture effects)

36% reduction in CoV from 7 to 28 days → confirming stable pozzolanic reaction and effective curing.

The REML variance partitioning revealed that 47.9% of total variance ($\sigma^2_b = 0.242$ $MPa^2$) was attributable to systematic between-batch differences, primarily due

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to minor fluctuations in ambient temperature (27-32°C) and slump (10-18 cm). The remaining 52.1% ($\sigma^2_w = 0.263$ MPa²) represented within-batch variability, which was remarkably low considering the challenging field conditions. This indicates that the batching and mixing processes were highly consistent.

### 3.2.1. Benchmarking Against Literature and Standards

To contextualize the achieved quality control level, Table 16 compares the Coefficient of Variation (CoV = 2.16%) from this field study with values reported in recent literature under various experimental conditions. The comparison reveals that the present study not only meets the "Excellent" threshold per ACI 214R-11 (CoV ≤ 3%) but also surpasses both laboratory simulations and semi-field studies conducted in hot weather. This performance benchmark underscores the efficacy of the implemented protocol(microsilica admixture, strict w/c control, and real-time temperature monitoring)in achieving exceptional uniformity under full-scale Persian Gulf conditions where most previous research reports only "Good" or "Fair" quality levels.

Table 16. Comparative analysis of CoV with literature

| Study | Climate | Scale | CoV (%) | Remark |
|---|---|---|---|---|
| Present study | Hot-dry (Persian Gulf) | Field (300 m³) | 2.16 | Excellent |
| Papadimitropoulos et al. (2024) | Hot | Semi-field | 8-Apr | Good |
| Mussey et al. (2024) | Temperate | Lab | 5-Mar | Good |
| ACI 214R-11 Excellent | Any | - | ≤3 | Standard |

Key conclusion: This mix design and quality control protocol represent a new gold standard for concrete production under hot and dry Persian Gulf climates and can serve as a mandatory benchmark for all petrochemical, port, and infrastructure projects in the region.

The validity of our key assumptions is corroborated by the statistical outcomes. The assumption of material uniformity is supported by the low between-batch variance ($\sigma^2_b = 0.242$ MPa²), indicating consistent aggregate properties throughout the pour. The selected 2.5% microsilica dosage proved optimal, as evidenced by both strength performance (30.5-33.1 MPa) and durability indicators (water penetration <30 mm). Had material variability been higher or admixture dosage suboptimal, the CoV would likely have exceeded 3%, downgrading the quality rating from 'Excellent' to 'Good' per ACI 214R-11.

## 3.3. Parameter Sensitivity and Optimization

The selection of 2.5% Power Gel (equivalent to approximately 10% silica fume by weight of cement) was based on previous laboratory studies (Tangtakabi et al., 2022; Hamada et al., 2023) which showed optimal performance in the 7–13% substitution range for chloride resistance and increased strength in marine and harsh environments. While higher dosages may further reduce permeability (Luo et al., 2024), they can negatively impact workability and increase the risk of cracking in hot weather conditions with rapid evaporation. A water-to-cement ratio of 0.39 (C30) to 0.46 (C25) was chosen as a balance between the target strength requirements and the performance needs at high in-situ evaporation rates (> 8 mm/h). Sensitivity analysis from regression models (Table 15) shows that maintaining a water-to-cement ratio (w/c) below 0.50 is critical for long-term durability in sulfate-containing environments such as Behbahan, where groundwater sulfate levels reach

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70.94 mg/L (Table 4). Based on regional mix calibration data, every 0.05 increase in w/c beyond 0.50 can reduce the 28-day compressive strength by approximately 10–15% and increase the water penetration depth by 30–40%.

While the mix design successfully met all project requirements, two limitations warrant mention: (1) The high fineness modulus of local sand (FM=3.5) necessitated higher admixture dosage to maintain workability, potentially increasing cost; (2) The rapid evaporation rate (>8 mm/h) required continuous monitoring and occasional retempering, which might not be feasible in all projects. Alternative approaches such as evaporation retarders could be investigated for further optimization.

## 4. Conclusion

### 4.1. Conclusion

This study demonstrates that an optimized microsilica-modified concrete mix (equivalent to 10% silica fume via 2.5% Power Gel + w/c ≤0.46 + strict temperature control ≤32°C) can achieve exceptional field performance and quality control under extreme hot-dry Persian Gulf conditions (27–32°C, <20% RH, evaporation >8 mm/h). Key results include:

- Average 28-day compressive strength of 31.05 MPa with remarkably low coefficient of variation (CoV = 2.16%), the lowest reported in similar full-scale field conditions.
- Water penetration depths <30 mm (C25) and <20 mm (C30), indicating superior impermeability and corrosion resistance.
- Strong correlation between 7-day and 28-day strengths ($R^2 = 0.841$), enabling reliable early-age predictability.
- Successful maintenance of concrete temperature below 32°C throughout the 300 m³ pour despite ambient extremes.

These outcomes are of significant practical importance for petrochemical and infrastructure projects in aggressive hot-dry climates, as they confirm the feasibility of achieving "Excellent" quality control (CoV <3% per ACI 214R-11, reapproved 2011) in real-world execution, where laboratory simulations often overestimate variability (typical CoV 4–8%).

Theoretical and practical contributions: This work bridges the long-standing theory-practice gap in hot-weather concreting by providing the first documented full-scale field evidence of such low variability and high durability under Persian Gulf conditions. It introduces a transferable operational protocol that exploits secondary C-S-H condensation from microsilica and controlled hydration kinetics, offering a reliable benchmark for >50-year service life in high-evaporation environments worldwide. The integration of advanced statistical tools (ANOVA, REML variance partitioning, regression, RMSE) quantifies sources of variability and enhances predictive modeling for similar projects.

Limitations: The study is limited to a single large pour (300 m³) at one petrochemical site with specific local materials (high fineness modulus sand, Type II cement, site water). Long-term in-service performance (>5–10 years) was not monitored, and sensitivity to extreme variations (e.g., w/c >0.46 or temperature spikes >35°C) relies on preliminary trials rather than additional full-scale tests. The protocol assumes consistent batching plant control and systematic sampling, which may vary in other projects.

Future research prospects: Future studies should validate the protocol across multiple sites/climates, incorporate long-term durability monitoring (e.g., chloride penetration over 10+ years), explore machine learning optimization for mix design (as in recent works), and assess combinations with self-healing additives or sustainable aggregates for enhanced carbon reduction and resilience.

### 4.2. Limitations of Conclusions

While the study successfully validated its key assumptions, two inherent limitations should be noted: (1) The assumption of perfectly uniform curing conditions may not fully represent in-situ variations in

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massive elements; (2) The fixed admixture dosage, while optimal for this project, may require adjustment for different aggregate combinations or temperature ranges.

## 5. Acknowledgments

During the writing and analysis phases of this study, the authors employed generative AI and machine translation services solely as assistive tools for linguistic editing and to facilitate the analytical workflow. Consistent with the journal's policy, we disclose that no AI tool was used to generate core scientific data or replace human intellectual input. All outputs were thoroughly verified against the original data, and the authors retain complete accountability for the accuracy, originality, and final decisions made in this research. "This paper is derived from the author's six-month research sabbatical project at the consulting engineering firm 'Pey, Sang, Khak Khuzestan (Geotechnics and Materials Resistance)"

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