*IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*
*e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 23, Issue 5 Ser. I (Sep. – Oct. 2026), PP 33-37*
*www.iosrjournals.org*

# Optimization of Quinary Blend Ultra-High Performance Concrete Matrix Using Taguchi Method

Aditya Punia[1], Dr. Hari Krishan Sharma [2], Dr. Sanjay Kumar Sharma[1]
[1]*(National Institute of Technical Teachers Training & Research, Chandigarh, India)*
[2]*(National Institute of Technology, Kurukshetra, India,)*
*Corresponding author: aditya.civil18@nitttrchd.ac.in*

***Abstract:***
*This study presents the parametric optimization of a sustainable quinary blend Ultra-High Performance Concrete incorporating Cement, Alccofine-1203, Fly Ash, Micro-Silica, and Ultrafine Fly Ash utilizing the Taguchi $L_{\{25\}}$ design method. Optimization based on the 'Larger- the-Better' S/N ratio was used to identify the ideal mix proportions. Based on the "Larger-the-Better" signal-to-noise ratio criteria, the optimal combination was found to be at Cement (Level 4), Alccofine-1203 (Level 4), Fly Ash (Level 3), Micro-Silica (Level 3), and Ultrafine Fly Ash (Level 3), corresponding to the respective level percentages of these factors. Analysis of Variance established that Micro-Silica acts as the primary mechanical driver, yielding a highly dominant percentage contribution of 66.23%. Cement displayed a strong secondary engineering trend with a 15.24% contribution, followed by Ultrafine Fly Ash with 13.12% contribution in variation of compressive strength of UHPC. These findings demonstrate that micro-structural particle packing and high-efficiency pozzolanic reactions along with optimum dosage of supplementary cementitious materials play a vital role in achieving the high compressive strength of UHPC.*
***Key Word**: Ultra High Performance Concrete, Taguchi Method, Compressive Strength, UHPC, ANOVA, S/N Ratio*

---

Date of Submission: 03-09-2026 Date of Acceptance: 13-09-2026

---

## I. Introduction and Rationale for Quinary Blended Systems

In recent years, the construction industry has seen a massive shift toward Ultra-High Performance Concrete (UHPC) to fulfil the requirements of modern high-rise buildings, long-span bridges, and impact and blast resistant infrastructure. Achieving a compressive strength benchmark exceeding 100 MPa demands an exceptionally dense microstructural matrix, an ultra-low water-to-binder (w/b) ratio, and the elimination of micro-voids within the Interfacial Transition Zone (ITZ). Traditional concrete relies heavily on Ordinary Portland cement (OPC). However, conventional high-cement mix designs face severe engineering limits, including high heat of hydration, excessive autogenous shrinkage, micro-cracking, and a massive carbon footprint.

To overcome these performance bottlenecks, concrete technology has evolved from simple binary, ternary and quaternary mix design combinations. While these approaches enhance early and long-term properties, they often leave performance gaps. This research bridges that gap by investigating an advanced quinary (5-blend) ultra high performance matrix utilizing Cement, Alccofine, Fly Ash, Micro-Silica, and Ultrafine Fly Ash. The scientific merit of a quinary system lies in its ability to unlock synergistic, multi-scale particle packing and staggered, multi-stage chemical reactions. Firstly, it improves primary hydration & early nucleation, as OPC initiates primary hydration, and highly reactive Alccofine-1203 acts as an early-stage micro-pore filler and acceleration catalyst, boosting early-age mechanical integrity. Secondly, it improves micro-to-nano pozzolanic synergy, as highly reactive micro-silica rapidly consumes calcium hydroxide ($Ca(OH)_2$) crystals, turning them into secondary calcium silicate hydrate (C-S-H) gels to densify the ITZ at the micro-scale. Concurrently, Ultrafine Fly Ash fills sub-micron interstitial voids, providing a secondary packing layer that standard SCMs cannot reach. Finally, it enhances the long term matrix stability as fly ash utilizes its spherical morphology to reduce water demand during mixing while also ensuring steady, long-term strength development through delayed pozzolanic activity.

Optimizing a complex 5-component system using traditional trial-and-error methods requires hundreds of resource-intensive lab trials. To resolve this, this study implements a rigorous Taguchi $L_{\{25\}}$ Orthogonal Array optimization method. This approach isolates the precise mechanical contribution of each material, establishing a highly robust, statistically validated method for the next generation of sustainable UHPC.

## II. Methodology

The mix design approach for UHPC in this investigation was established on the fundamental principles of multi-scale particle packing density optimization, microstructural homogenization, and capillary porosity minimization[1,2] and modified Anderson and Anderson model[3]. To achieve a dense, low porosity matrix, a fixed binder-to-fine-aggregate ratio of 1:1 was selected. The exclusion of coarse aggregates, combined with an equal proportion of binder and fine aggregate, ensures optimal filling of inter-particle voids, eliminates local stress concentrations at the aggregate-paste interface, and promotes better rheological behaviour[2,4]. To restrict free capillary water and develop a densely packed C-S-H microstructure, the water-to-binder ($w/b$) ratio was fixed at a low value of 0.20, which is typical for UHPC mix designs relying on PCE superplasticizers to maintain workability without segregation[2,5].

To ensure sufficient paste volume for complete aggregate coating and fluid workability, an initial baseline binder content of 1000 kg/m$^3$ was adopted, following established standards for dense cementitious matrices[6,7]. To optimize the binder blend both physically and chemically, a quinary binder system was developed consisting of cement (OPC-53) combined with four SCMs, i.e., alccofine-1203, fly ash, micro-silica, and ultrafine fly ash. The synergistic combination of these five materials leverages micro-filling effects across continuous particle size distributions while enhancing secondary pozzolanic reactions that convert calcium hydroxide ($Ca(OH)_2$) into high density C-S-H gel[8,9].

Given that optimizing five binder ingredients across five variation levels in a full factorial design would require $5^5 = 3{,}125$ individual experimental trials, a statistical design of experiments (DoE) using a Taguchi $L_{25}$ $(5^5)$ orthogonal array was implemented. The Taguchi method allows systematic investigation of main factor effects and interactions across all 5 factors at 5 levels using only 25 representative mix runs[10,11]. This reduces experimental overhead, material consumption, and testing duration while providing robust, statistically reliable identification of the optimal binder blend for high mechanical and durability performance[11,12].

To systematically establish the binder matrix composition, the substitution ranges for the primary binder i.e., cement and the four SCMs were defined based on literature recommended thresholds for multi scale particle packing and pozzolanic efficiency. The primary binder, OPC- 53, was varied across five levels from 60% to 92%, with 8% increments, ensuring that a sufficiently high volume of primary hydraulic reactant remained while allowing significant SCM replacement to evaluate clinker reduction[1,7]. Both fly ash and alccofine-1203 were varied from 2% to 10% at 2% increments. Fly ash provides spherical micro-ball-bearing action that enhances rheology while supporting long term strength via secondary pozzolanic activity[8]. However, higher substitution rates can delay early age strength development[6]. Alccofine-1203, an ultrafine slag with high reactivity and micro filling capability, accelerates early hydration and densifies the ITZ when used in controlled dosages up to 10%[9].

Micro-silica replacement was varied from 3% to 15% at 3% increments, as silica fume is essential for filling the sub-micron voids between cement grains and reacting with free calcium hydroxide to form additional C-S-H gel[2,13]. Keeping silica fume levels within 15% prevents agglomeration, excessive superplasticizer demand, and autogenous shrinkage cracking triggered by higher dosages[5]. Ultrafine fly ash was investigated between 1% and 5% at 1% increments. Due to its extremely fine particle distribution and high specific surface area, ultrafine fly ash acts as an effective nano to micro scale filler that refines capillary pore networks. Keeping its variation lower prevents adverse impacts on water demand and workability loss[9,14].

The experimental mix designs according to the Taguchi $L_{25}$ $(5^5)$ orthogonal array, along with the corresponding experimental compressive strength results obtained for all 25 trial mixes, is presented in Table 1. To identify the optimal binder combination, signal-to-noise ($S/N$) ratio analysis based on the "larger-the-better" criterion was performed, along with Analysis of Variance (ANOVA) to determine the statistical contribution of each binder ingredient toward compressive strength development.

**Signal-to-Noise (S/N) Ratio Calculation**

To optimize the compressive strength of UHSC, the "Larger-the-Better" quality characteristic was selected. The S/N ratio $(\eta)$ is mathematically defined as per Equation 1.

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \qquad \text{Equation 1}$$

Where:
- $\eta = \text{Signal} - \text{to} - \text{Noise ratio (dB)}$
- $n =$ Number of replications/tests per experimental run
- $Y_i =$ Compressive Strength in MPa for the $i$-th test

**Analysis of Variance (ANOVA) and Sum of Squares ($SS$)**

The total variation in the experimental data is measured by the Total Sum of Squares ($SS_T$), as per Equation 2.

$$SS_T = \sum_{i=1}^{N} (\eta_i - \bar{T})^2 \qquad \text{Equation 2}$$

The variation assigned to each specific parameter (Factor Sum of Squares, ($SS_F$)) is calculated as per Equation 3.

$$SS_F = \frac{5}{N} \sum_{j=1}^{k} \left(A_j - \bar{T}\right)^2 \qquad \text{Equation 3}$$

The Mean Square ($MS$) for each factor is derived by dividing its Sum of Squares by its corresponding Degrees of Freedom ($DF$), as per Equation 4.

$$MS_F = \frac{SS_F}{DF_F} \qquad \text{Equation 4}$$

Where:

- N = Total number of experimental trials
- $\eta_i$ = S/N ratio for $\text{trial}_i$
- $\bar{T}$ = Overall mean of all S/N ratios
- $A_j$ = Mean S/N ratio for factor A at level j
- $k$ = Number of factor levels

## III. Results and Discussions

The results of compressive strength at 28 days for all 25 mix designs established as per Taguchi method are presented in Table 1.

**Table 1:** Mix Design Proportions and Results of Compressive Strength

| Trial No. | Cement (kg/m$^3$) | Alccofine (kg/m$^3$) | Fly Ash (kg/m$^3$) | Micro-Silica (kg/m$^3$) | Ultrafine Fly Ash (kg/m$^3$) | Compressive Strength (MPa) |
|---|---|---|---|---|---|---|
| 1. | 882 | 29 | 29 | 44 | 15 | 74 |
| 2. | 789 | 53 | 53 | 79 | 26 | 112 |
| 3. | 714 | 71 | 71 | 107 | 36 | 120 |
| 4. | 652 | 87 | 87 | 130 | 43 | 52 |
| 5. | 600 | 100 | 100 | 150 | 50 | 50 |
| 6. | 782 | 23 | 46 | 103 | 46 | 68 |
| 7. | 716 | 42 | 63 | 126 | 53 | 61 |
| 8. | 694 | 61 | 82 | 153 | 10 | 55 |
| 9. | 747 | 88 | 110 | 33 | 22 | 80 |
| 10. | 764 | 112 | 22 | 67 | 34 | 78 |
| 11. | 752 | 20 | 59 | 149 | 20 | 64 |
| 12. | 809 | 43 | 85 | 32 | 32 | 82 |
| 13. | 745 | 59 | 98 | 59 | 39 | 93 |
| 14. | 760 | 80 | 20 | 90 | 50 | 117 |
| 15. | 738 | 97 | 39 | 117 | 10 | 66 |
| 16. | 800 | 19 | 76 | 57 | 48 | 89 |
| 17. | 778 | 37 | 93 | 83 | 9 | 103 |
| 18. | 792 | 57 | 19 | 113 | 19 | 75 |
| 19. | 737 | 70 | 35 | 132 | 26 | 76 |
| 20. | 785 | 93 | 56 | 28 | 37 | 73 |
| 21. | 773 | 17 | 84 | 101 | 25 | 75 |
| 22. | 786 | 34 | 17 | 128 | 34 | 55 |
| 23. | 836 | 55 | 36 | 27 | 45 | 73 |
| 24. | 814 | 71 | 53 | 53 | 9 | 100 |
| 25. | 760 | 83 | 66 | 74 | 17 | 115 |

Based on the response of compressive strength, and selection of "Larger-the-Better" approach for maximizing the compressive strength of UHPC matrix, S/N ratios were obtained from the DoE Taguchi method, as presented in Table 2. S/N ratios are also illustrated in Figure 1.

**Table 2:** S/N Ratios for Factor at Various Levels

| Level | Cement | Alccofine | Fly Ash | Micro-Silica | Ultrafine Fly Ash |
|---|---|---|---|---|---|
| 1 | 36.73605 | 36.65908 | 37.37989 | 37.21578 | 36.70204 |
| 2 | 35.02064 | 37.50033 | 37.084 | 39.40774 | 38.35236 |

| | | | | | |
|---|---|---|---|---|---|
| 3 | 37.45143 | 37.57059 | 37.58717 | 40.08388 | 38.50169 |
| 4 | 38.32933 | 37.61275 | 36.58471 | 34.92044 | 35.58008 |
| 5 | 38.20729 | 36.40199 | 37.10896 | 34.1169 | 36.60856 |
| Delta | 3.30869 | 1.21076 | 1.00247 | 5.96698 | 2.9216 |
| Rank | 2 | 4 | 5 | 1 | 3 |

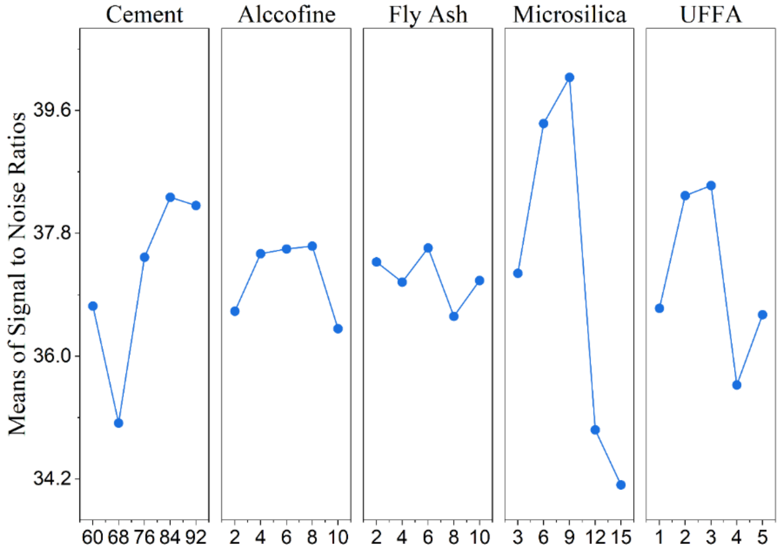


**Figure 1:** S/N Ratios Obtained from the response of Compressive Strength

**Factor Significance and Ranking**

The Delta value measures the maximum change in the S/N ratio across the 5 levels. A higher Delta value signifies that the factor has a more profound impact on compressive strength variation. The rank and delta values for factors are presented in Table 3.

**Table 3:** Ranking and Significance of Factors

| Rank | Factor | Delta Value | Impact Level |
|---|---|---|---|
| 1 | Micro-Silica | 5.96698 | Most Critical |
| 2 | Cement | 3.30869 | Highly Significant |
| 3 | Ultrafine Fly Ash | 2.9216 | Significant |
| 4 | Alccofine-1203 | 1.21076 | Moderately Significant |
| 5 | Fly Ash | 1.00247 | Less Significant at 28 days |

**Level by Level Analysis**

The delta (Δ) values and ranking indicate the relative sensitivity of the compressive strength to variations in binder composition:

- **Micro-Silica (Rank 1, $\Delta_{S/N}$ = 5.97):** Serves as the primary governing factor. Peak performance is attained at **Level 3** (S/N = 40.08 dB), beyond which higher replacement levels (Levels 4 and 5) induce significant degradation (34.92044 and 34.1169 dB respectively), consistent with microstructural agglomeration and unreacted silica saturation.
- **Cement (Rank 2, $\Delta_{S/N}$ = 3.31):** Demonstrates an upward trajectory with maximum response observed at **Level 4** (S/N = 38.33 dB), maintaining matrix alkalinity and primary hydration products (C-S-H).
- **Ultrafine Fly Ash (Rank 3, $\Delta_{S/N}$ = 2.92):** Exhibits optimal enhancement at **Level 3** (S/N= 38.50 dB), contributing micro-filler packing before declining sharply at Level 4.
- **Alccofine-1203 (Rank 4, $\Delta_{S/N}$ = 1.21):** Demonstrates a steady positive response up to **Level 4** (S/N = 37.61 dB) before tapering at Level 5.
- **Fly Ash (Rank 5, $\Delta_{S/N}$ = 1.01):** Displays minimal variability across levels, reaching a slight optimum at **Level 3** (S/N = 37.59 dB), suggesting that fly-ash variation has minimal effect on early age compressive strength of concrete at 28 days.

**Analysis of Variance (ANOVA) and Percentage Contribution**

The percentage contribution of the factors in variation of compressive strength, is calculated using ANOVA, and is presented in Table 4. The quantitative contribution analysis confirms that binder behaviour is dominated by the pozzolanic and particle-packing effects of Micro-Silica, which accounts for 66.23% of the total variance in the model. Cement content and Ultra-Fine Fly Ash (UFFA) serve as secondary controlling variables, contributing 15.24% and 13.12%, respectively. In contrast, Alccofine (4.36%) and conventional Fly Ash (1.05%) exert modest to negligible statistical influence within the investigated parametric domain. Consequently, precise proportioning of Micro-Silica and UFFA near their intermediate dosage levels (Level 3) is important to avoid dilution effects and post-peak strength declines.

**Table 4:** Percentage Contribution of Factors (ANOVA)

| Factor | Degrees of Freedom | Sum of Squares | Mean Square | Percentage Contribution |
|---|---|---|---|---|
| Micro-Silica | 4 | 10286.29 | 2571.57 | 66.23% |
| Cement | 4 | 2366.26 | 591.57 | 15.24% |
| Ultrafine Fly Ash | 4 | 2037.12 | 509.28 | 13.12% |
| Alccofine-1203 | 4 | 677.27 | 169.32 | 4.36% |
| Fly Ash | 4 | 163.53 | 40.88 | 1.05% |
| Total (Model) | 20 | 15530.47 | -- | 100.00% |

**Optimal Parametric Mix Design**

Based on the "larger-the-better" signal-to-noise ratio criteria, the optimal parametric combination to achieve the highest UHPC compressive strength is Cement (Level 4), Alccofine-1203 (Level 4), Fly Ash (Level 3), Micro-Silica (Level 3), and Ultrafine Fly Ash (Level 3).

## IV. Conclusions

The following definitive conclusions are drawn from the Taguchi $L_{25}$ parametric optimization and ANOVA of the quinary blend UHPC:

- **Optimal Mix Design Formulation:** The optimized parametric combination for maximizing the compressive strength performance of the quinary mix design was successfully identified as: Cement (Level 4), Alccofine-1203 (Level 4), Fly Ash (Level 3), Micro-Silica (Level 3), and Ultrafine Fly Ash (Level 3).
- **Dominance of Nano/Micro-SCMs:** The delta ranking and percentage contribution data indicate that sub-micron SCMs govern the mechanical properties of UHPC. Micro-Silica (Rank 1) controls 66.23% of the total strength variation, followed closely by Cement (Rank 2) at 15.24% and Ultrafine Fly Ash (Rank 3) at 13.12%.

## References

[1]. Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. *Cement and Concrete Research*, *25*(7), 1501–1511. https://doi.org/10.1016/0008-8846(95)00144-1

[2]. Wille, K., El-Tawil, S., & Naaman, A. E. (2014). Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading. *Cement and Concrete Composites, 48*, 53–66. https://doi.org/10.1016/j.cemconcomp.2013.12.015

[3]. Lachance, F., Charron, J.-P., & Massicotte, B. (2016). Development of precast bridge slabs in high-performance fiber-reinforced concrete and ultra-high-performance fiber-reinforced concrete. *ACI Structural Journal*, 113(5), 929–939. https://doi.org/10.14359/51689020

[4]. Wu, Z., Shi, C., He, W., & Wang, D. (2017). Static and dynamic compressive properties of ultra-high performance concrete (UHPC) with hybrid steel fiber reinforcements. *Cement and Concrete Composites*, *79*, 148–157. https://doi.org/10.1016/j.cemconcomp.2017.02.010

[5]. Graybeal, B. A. (2006). *Material property characterization of ultra-high performance concrete* (Publication No. FHWA-HRT-06-103). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/06103/

[6]. Hunger, M. (2010). *An integral design concept for ecological self-compacting concrete* (Doctoral dissertation, Eindhoven University of Technology).

[7]. Krahl, P. A., Gidrão, G. M. S., & Carrazedo, R. (2019). Cyclic behavior of UHPFRC under compression. *Cement and Concrete Composites*, *104*, Article 103363. https://doi.org/10.1016/j.cemconcomp.2019.103363

[8]. Yu, R., Spiesz, P., & Brouwers, H. J. H. (2014). Static properties and impact resistance of a green ultra-high performance hybrid fibre reinforced concrete (UHPHFRC): Experiments and modeling. *Construction and Building Materials, 68*, 158–171. https://doi.org/10.1016/j.conbuildmat.2014.06.033

[9]. Sahoo, S., Selvaraj, R., & Patel, S. (2021). Synergistic effect of alccofine and secondary SCMs on mechanical and durability performance of ultra-high-performance concrete. *Journal of Building Engineering*, 43, 103132.

[10]. Taguchi, G. (1986). *Introduction to quality engineering: Designing quality into products and processes*. Asian Productivity Organization / Krauss Organization.

[11]. Roy, R. K. (2010). *A primer on the Taguchi method* (2nd ed.). Society of Manufacturing Engineers.

[12]. Karthik, S., & Mohan, K. S. R. (2021). A Taguchi approach for optimizing design mixture of geopolymer concrete incorporating fly ash, ground granulated blast furnace slag and silica fume. *Crystals*, 11(11), 1279. https://doi.org/10.3390/cryst11111279

[13]. Shi, C., Wu, Z., Xiao, J., Wang, D., Wu, Q., & Wu, Z. (2012). A review on ultra high performance concrete: Design, raw materials, particle packing and mechanical properties. *Construction and Building Materials*, 37, 241–249. https://doi.org/10.1016/j.conbuildmat.2012.07.025

[14]. Zhou, Z., & Qiao, P. (2020). Direct tension test for characterization of tensile behavior of ultra-high performance concrete. *Journal of Testing and Evaluation*, *48*, 470–471. https://doi.org/10.1520/JTE20170644