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Hydration characteristics of ternary blended cement pastes: A study employing Taguchi analysis

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Research Paper

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Hydration characteristics of ternary blended cement pastes: A study employing Taguchi analysis

Blended cement paste systems are considerably complex owing to the diverse physical morphologies and chemical compositions of the constituent raw materials. Despite this complexity, these systems are increasingly recognised for their enhanced long-term performance and contribution to sustainability. This study examines the hydration characteristics of ternary blended cement pastes employing Taguchi Analysis, a robust statistical tool for investigating multifactorial interactions in material systems. This study systematically evaluates the effects of supplementary cementitious materials, water-to-binder ratio, superplasticiser dosage, and curing conditions to optimise cement paste performance. An orthogonal array design based on the Taguchi method was employed to quantify the influence of these parameters on the chemical shrinkage, hydration kinetics, and pozzolanic activity. Statistical analyses highlight the relative significance of each factor in governing the hydration mechanisms, thereby providing valuable insights for the development of advanced performance-driven cementitious materials.

Key words:

Taguchi analysis, blended cement paste, chemical shrinkage, pozzolanic activity, hydration kinetics

Prethodno priopćenje

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Karakteristike hidratacije cementnih pasta s miješanim cementima: istraživanje pomoću Taguchijeve analize

Sustavi miješanih cementnih pasta pokazuju znatnu složenost zbog raznolikih fizikalnih morfologija i kemijskih struktura njihovih sastavnih sirovina. Unatoč toj složenosti, sve su cjenjeniji zbog poboljšanih dugoročnih svojstava i doprinosa održivosti. Ovo istraživanje ispituje hidratacijska svojstva ternarnih miješanih cementnih pasta primjenom Taguchijeve analize, robusnoga statističkog alata za proučavanje višefaktorskih interakcija u materijalnim sustavima. Sustavnom procjenom utjecaja dodatnih cementnih materijala, omjera vode i veziva, doze superplastifikatora i uvjeta njege studija nastoji optimirati svojstva cementne paste. Primjenom dizajna ortogonalnih nizova Taguchijeve metode analiziran je utjecaj navedenih parametara na kemijsko skupljanje, kinetiku hidratacije i pucolansku aktivnost. Statistički rezultati ističu relativnu važnost svakog faktora u upravljanju mehanizmima hidratacije te pružaju vrijedne spoznaje za razvoj naprednih cementnih materijala usmjerenih na visoka svojstva.

Ključne riječi:

Taguchijeva analiza, miješana cementna pasta, kemijsko skupljanje, pucolanska aktivnost, kinetika hidratacije

1. Introduction

The optimisation of ternary blended cement systems presents a complex challenge [1] in concrete technology because of the multiple interacting factors that influence their hydration behaviour. Comprehensive understanding and control of these interactions remain crucial for developing sustainable and high-performance cementitious materials. The performance of these blended systems, particularly in terms of their hydration behaviour, is significantly influenced by diverse mix design parameters and curing conditions [2]. However, traditional one-factor-at-a-time experimental approaches are both time-consuming and resource-intensive, and frequently fail to capture the complex interrelationships among different variables [3, 4]. The Taguchi method is a powerful statistical tool for optimising multiparameter systems via a systematic and efficient experimental design [5]. This method is particularly valuable when studying complex systems wherein several factors simultaneously influence the overall performance [6-8]. The advantage of the Taguchi analysis [9, 10] lies in its ability to determine the relative importance of each factor and identify optimal combinations while minimising the number of experimental trials. In Taguchi analysis, signal-to-noise (S/N) ratio formulae are applied via a systematic procedure to optimise process robustness [11]. First, an appropriate S/N ratio formula was selected based on the quality characteristics under study.

- **Larger-is-Better** (S/N) $L = 10 \times \log_{10}(1/y^2/n)$, adopted for maximising responses such as strength;
- **Smaller-is-Better** (S/N) $S = -10 \times \log_{10}(y^2/n)$, applied when minimising responses such as defects;
- **Nominal-is-Best** ($10 \log_{10}(\bar{y}^2/s^2)$), employed when targeting specific values.

After completion of the designed experiments, the S/N ratio was calculated for each experimental run using the selected formula. Subsequently, the average S/N ratio for each factor level was computed and the optimal settings were identified by selecting the levels with the highest S/N ratios [12]. By employing orthogonal arrays and S/N ratios, the Taguchi approach can quantify the impact of each variable on the hydration process while incorporating experimental variability. This systematic methodology facilitates evaluation of both the individual and combined effects of various parameters, thereby enabling the development of more sustainable and efficient cement blends by optimising their composition and curing requirements.

This study evaluates the performance of ternary blended cement pastes in terms of chemical shrinkage, Pozzolanic activity Index, and degree of hydration. The controllable factors considered in this study include cement replacement level, water demand, and superplasticiser dosage. Supplementary cementitious materials, namely fly ash and ground granulated blast-furnace slag (GGBS), were incorporated into blended cement systems. Incorporation of GGBS and fly ash offers

multiple synergistic benefits that significantly enhance concrete performance while addressing sustainability concerns. The partial replacement of ordinary Portland cement (OPC) with these supplementary cementitious materials substantially reduces the carbon footprint of concrete production by utilising industrial byproducts that would otherwise be landfilled while simultaneously decreasing the energy-intensive clinker content [13].

From a performance perspective, ternary blended mixes demonstrate measurable improvements compared with ordinary cement. The use of fly ash and GGBS enhances workability because the smooth and round particles of fly ash facilitate the mix flow. These blends also produce less heat during hydration, which reduces the probability of crack formation in large concrete structures. Progressive pozzolanic reactions of fly ash and the cement-like activity of GGBS contribute to the formation of a denser and stronger microstructure, leading to higher long-term strength. In addition, the mixes exhibit enhanced durability, lower permeability, higher resistance to chemical attacks such as sulphate and chloride ingress, and reduced risk of alkali-silica reactions. Overall, these blended systems offer concrete with improved workability, enhanced durability, and increased longevity [14, 15]. Furthermore, the economic advantages provide a compelling case for their adoption, as these industrial by-products typically incur lower costs than OPC while extending the concrete service life via durability enhancements, thereby supporting modern sustainable construction practices wherein lifecycle performance is prioritised in conjunction with initial cost considerations [16].

2. Selection of control factors and levels

2.1. Cement replacement level

Cement replacement level constitutes a critical factor because it directly influences the fundamental chemistry and microstructural development of cementitious systems. Several key mechanisms are altered when cement is partially replaced with supplementary cementitious materials (SCMs) in ternary blends [17]. The cement replacement level influences chemical shrinkage primarily via two mechanisms. First, partial replacement of cement reduces the volume of the primary C-S-H gel formed from cement hydration, as less cement is available for the immediate reaction. Second, SCMs introduce secondary reactions that produce additional C-S-H gel through the pozzolanic reaction, which proceed at a different rate and volume than pure cement hydration. Consequently, a complex relationship emerges: higher replacement levels may initially reduce chemical shrinkage owing to the dilution effect; however, continued pozzolanic activity at later stages may increase the shrinkage [18].

This also determines the potential of the pozzolanic reactions in the system. A higher content of reactive SCMs provides more siliceous and aluminous materials that can react with

calcium hydroxide (CH) produced via cement hydration [19-21]. However, an optimal replacement level exists beyond which the pozzolanic activity is likely limited by insufficient CH availability owing to the reduced cement content. This balance is critical because an excessively high replacement level may result in unreacted SCMs acting merely as fillers, whereas an excessively low replacement level may underutilise pozzolanic capacity. The cement replacement level influences the degree of hydration via multiple mechanisms. This alters the water-to-cement ratio of the effective paste because SCMs typically exhibit different water demands compared with cement. Variations in pore chemistry alter the ionic concentration of the pore solution, which influences the dissolution and precipitation rates. It can also affect the heat evolution pattern, which in turn influences the hydration kinetics. In this study, three cement replacement levels were considered: 30, 50, and 70 %, with fly ash and GGBS as constituents in different proportions.

2.2. Water demand

Water demand represents a critical factor in ternary blended cement systems because it directly influences the available water for cement hydration and pozzolanic reactions [22]. The amount of available water influences the extent of chemical binding, which is directly related to the magnitude of shrinkage. Higher water content can result in increased chemical shrinkage owing to more complete hydration; however, excessive water can create larger capillary pores. By contrast, insufficient water can limit the extent of chemical reactions and reduce overall shrinkage. Water acts as a transport medium for dissolved ions, particularly calcium and silicate ions. This provides the necessary medium for the dissolution of CH and the formation of secondary C-S-H. Available water affects the mobility of reactive species and kinetics of pozzolanic reactions. The optimal water content ensures a continuous pozzolanic activity without excessive dilution of the pore solution [23].

In this study, the optimum water demand of each cement paste mixture was determined using the Puntke test, and excess water contents of 5 %, 10 %, and 15% were selected as the levels of the control factor water demand. The optimum water demand obtained from the Puntke test [24] ensured that the base water requirement for particle packing was satisfied. A 5 % excess represents a lower bound wherein the water content is likely limiting but permits basic hydration, whereas a 15 % excess represents an upper bound that ensures sufficient water for complete hydration while avoiding excessive dilution.

Fresh cement paste samples were prepared by gradually adding distilled water to 300 g of cement powder, followed by continuous mixing to achieve a uniform consistency. Small portions of water were incrementally introduced using a pipette, followed by manual mixing for approximately 2 min after each addition. The paste was gently compacted by tapping the container. This process continued until the cement paste

reached a critical state characterised by a glossy appearance and smooth surface without bleeding, indicating the optimal water content. At this stage, the paste demonstrated cohesive behaviour without segregation upon tilting. Water demand was calculated as the ratio of the total water mass to the binder content and expressed as a percentage. Three replicate tests were performed to ensure reproducibility and the average value was reported as the final water demand of the cement paste. The optimum water demand for pure cement paste (OPC) was 27.5 %. For the ternary mixes the optimum water demands determined via the Puntke test were 28.5 % for 30 % replacement (10 % FA + 20 % GGBS), 28.9 % for 50 % replacement (20 % FA + 30 % GGBS) and 29.3 % for 70 % replacement (30 % FA + 40 % GGBS). These values served as the base W_0 for each corresponding mix to derive the experimental levels in the study, denoted as $W_0 + 5 %$, $W_0 + 10 %$ i $W_0 + 15 %$.

2.3. Superplasticizer dosage

Optimisation of the superplasticiser dosage is crucial because an excessively low dosage may not provide adequate dispersion, leading to particle agglomeration and reduced reaction efficiency, whereas an excessive dosage may induce pronounced hydration retardation and potential segregation. The effectiveness of a superplasticiser strongly depends on the water content and specific surface characteristics of the SCMs used.

This study employed the mini-slump test [25, 26] to determine the optimum superplasticiser dosage for all respective mixes, and a range with upper and lower boundaries was considered for the levels of the control factor. The superplasticiser dosage was optimised using a mini-slump test to evaluate the flow characteristics of the cement paste. Initially, paste samples were prepared with a constant water-to-binder ratio, as determined by the Puntke test, while varying the superplasticiser dosage from 0.1 % to 2.0 % by the weight of cement in 0.1 % increments. The paste was thoroughly mixed for 3 min using a mixer to ensure a uniform dispersion of the superplasticiser.

A truncated cone mould with a base diameter of 60 mm, height of 70 mm, and top diameter of 40 mm was placed on a clean glass plate and filled with fresh cement paste. After filling, the mould was carefully lifted vertically to allow the paste to spread under self-weight. The spread diameter was measured along two perpendicular directions after the paste reached its final position, typically within 2-3 minutes of placement. The spread values were plotted against the corresponding superplasticiser dosages to generate a flow curve. The optimum dosage was defined as the point beyond which no significant increase in the spread diameter was observed (known as the saturation point), indicating the maximum effectiveness of the superplasticiser without segregation or bleeding. The optimum SP dosage for all mixes ranged between 0.6 % and 1 % by mass of the binder. Figure 1 illustrates the mini-slump test used to determine the optimum superplasticiser dosage.

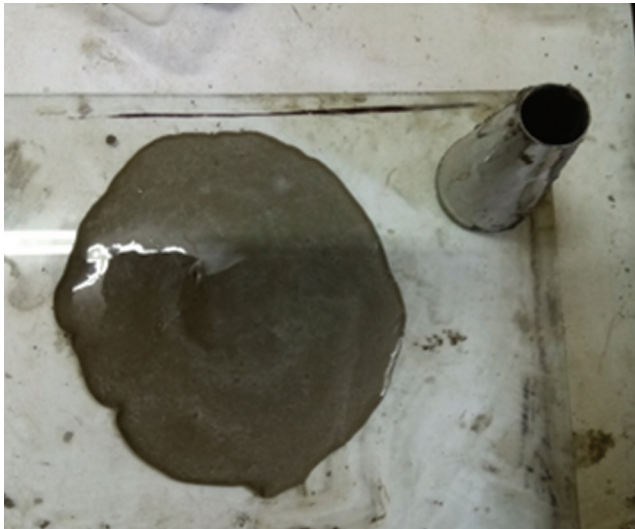


Figure 1. Mini slump test to determine the optimum dosage of superplasticizer

2.4. Curing condition

Curing conditions represent a critical factor because they directly control the availability of moisture and temperature for hydration reactions, particularly influencing long-term performance because highly variable temperatures and humidity can lead to irregular shrinkage patterns and the risk of incomplete pozzolanic reactions owing to moisture loss [27, 28]. However, these factors represent only realistic field conditions. Therefore, this study considered three curing conditions. Simulated controlled condition C1 maintained a room temperature of $30 \pm 2 \text{ }^\circ\text{C}$ and a relative humidity of $50 \pm 5 \%$ via saturated solutions. Ambient laboratory conditions C2 and uncontrolled outdoor conditions C3 remain subject to changes for all the mixes. The ternary blended mortar cubes were cured under all three environmental curing conditions (C1, C2, and C3) to evaluate the influence of the curing environment on the pozzolanic performance. However, the reference OPC mix was cured only in water, and required standard water curing for the reference mortar to ensure a consistent benchmark. The control factors and their levels are listed in Table 1.

Table 1. Control factors and their levels

SI. No.	Name and description of the control factor	Level 1	Level 2	Level 3
1.	Cement replacement level (R)	30 (10F+20G) (R1)	50 (20F+30G) (R2)	70 (30F + 40G) (R3)
2.	Water demand (Optimum (WO +) (W)	WO+5 % (W1)	WO + 10 % (W2)	WO + 15 % (W3)
3.	Superplasticizer dosage (% of binder) (S)	0.6 (S1)	0.8 (S2)	1 (S3)
4.	Curing condition (C)	Simulated controlled conditions (C1)	Ambient laboratory conditions (C2)	Ambient outside conditions (C3)

3. Materials and methods

In this study, several materials were carefully selected and used for experimental investigations. Ordinary Portland cement (OPC) of 53 grade served as the primary binding material, complying with relevant industry standards. Supplementary cementitious materials include Class F Fly ash, which is known for its pozzolanic properties, and GGBS, both of which contribute to enhanced durability and strength development. Figure 2 shows the particle size distributions of the OPC, Fly ash, and GGBS.

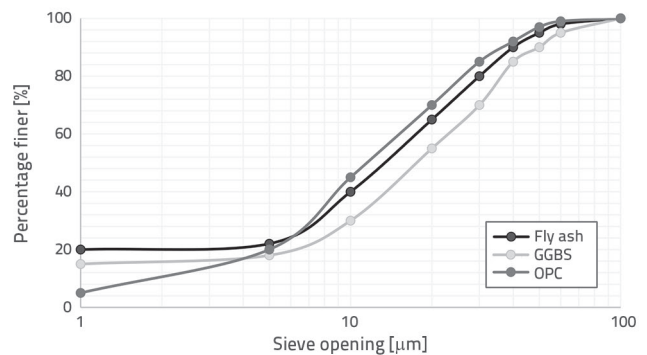


Figure 2. Particle size distribution of OPC, fly ash and GGBS

Figure 3.a and .3b shows the scanning electron microscopy (SEM) images of the Fly ash and GGBS used. The morphology and particle size of Fly ash and GGBS were examined using a Zeiss scanning electron microscope operated at 3.0 kV with an SE2 detector and a magnification of 2.50 kX. Prior to imaging, both samples were oven-dried to remove moisture, mounted on aluminium stubs using carbon tape, and sputter-coated with a thin conductive layer to prevent charging. SEM micrographs were captured under high vacuum and particle dimensions using the instrument’s software. Fly ash exhibited predominantly spherical particles ranging from 3 to 11 µm, whereas GGBS showed irregular, angular particles with sizes between 5 to 17 µm. To achieve the desired workability characteristics, Auramix 400 superplasticizer was incorporated as a chemical admixture. The fine aggregate comprised natural river sand with a nominal maximum size of 4.75 mm, ensuring proper gradation for optimal mix

Table 2. Physical and chemical properties of raw materials used

Constituent oxide [%]	OPC	Fly ash	GGBS
SiO ₂	23.2	59	36
CaO	64.8	2.3	41
Al ₂ O ₃	5		
Fe ₂ O ₃	3.9	3.6	0.4
MgO	3	-	6.8
Na ₂ O	0.2	-	-
K ₂ O	0.8	-	-
Physical properties			
Specific surface area [m ² /kg]	334	420	425
Specific gravity	3.15	2.2	2.24
Loss on ignition [%]	0.4	0.3	0.2
Mineralogical composition of OPC [%] (from Bogue's relations)			
C ₃ S		39.75	
C ₂ S		36.54	
C ₃ A		6.65	
C ₄ AF		11.87	
Other minor constituents		5.19	

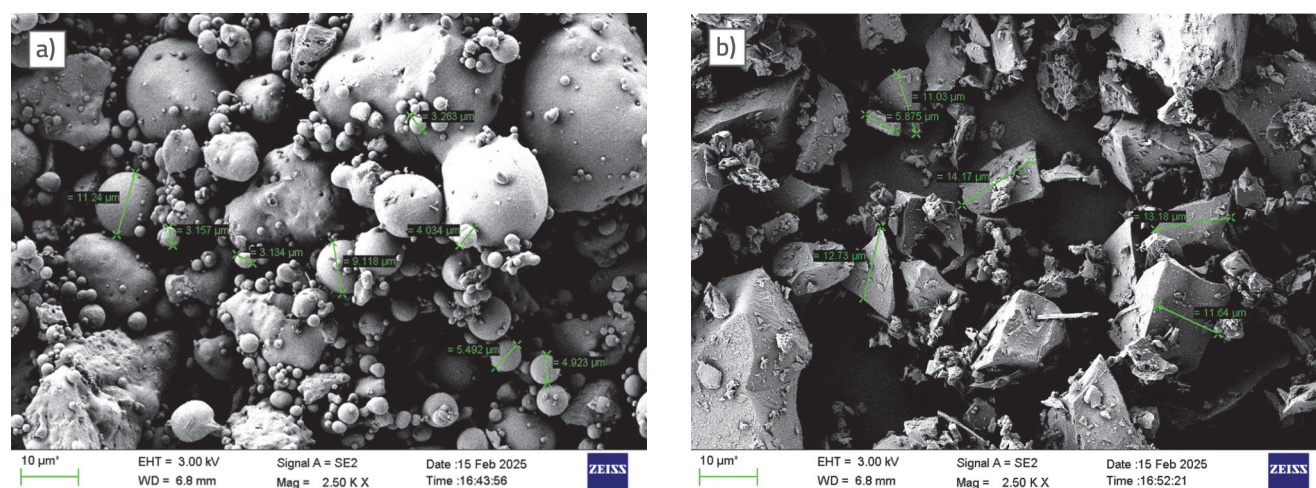


Figure 3. SEM analysis of: a) Fly ash; b) GGBS

performance. The physical properties and oxide composition of OPC, Fly ash, and GGBS determined via X-ray fluorescence are summarised in Table 2.

4. Selection of performance parameters

4.1. Determination of chemical shrinkage

The chemical shrinkage of cement paste was measured employing the gravimetric method following ASTM C1608 [29, 30]. A fresh cement paste was prepared at the optimum water-to-cement ratio and thoroughly mixed for 3 min to ensure homogeneity. Approximately 3 g of the paste was carefully placed into cylindrical glass vials with an internal diameter of

25 mm and a height of 50 mm, ensuring a specimen thickness of approximately 5 to 10 mm. The paste was gently vibrated to remove the entrapped air bubbles and level the surface. The remaining space in each vial was carefully filled with deionised water at 23 °C using a syringe, ensuring not to disturb the surface of the cement paste. A rubber stopper with a graduated pipette inserted through its centre was used to seal the vial, ensuring that the water level was visible in the graduated portion of the pipette.

The assembled specimens were immersed in a water bath maintained at 23 ± 0.1 °C throughout the test duration. The water level in the pipette was recorded at regular intervals: every 30 min for the first 8 h, hourly for the next 16 h, and daily thereafter for 28 days. The chemical shrinkage was calculated as the volume of

absorbed water per gram of cement, which represented the initial mass of cement in the paste. Three replicate specimens were simultaneously tested and the average values were reported to ensure the reliability of the measurements. Figure 4 shows the setup for the chemical shrinkage test.

As per the requirements of ASTM C1608, all chemical shrinkage measurements were conducted exclusively in this controlled water bath environment; therefore, the environmental curing conditions (C1, C2, and C3) used for the other tests in this study were not applied to chemical shrinkage. This standardised approach ensured that the measured volume change reflected only the intrinsic hydration-driven shrinkage of the binder, without interference from external temperature or humidity variations.

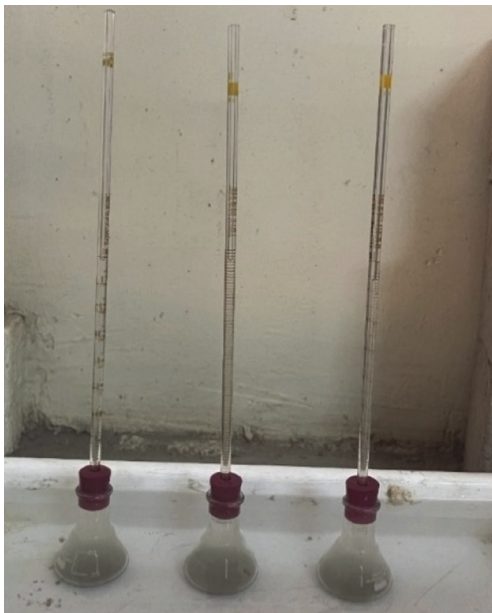


Figure 4. Chemical shrinkage setup

For a comparative interpretation, the chemical shrinkage results of the ternary blended mixes were evaluated against a plain OPC paste prepared at a w/c ratio of 0.40, which exhibited a chemical shrinkage of 0.40 mL/g. Mixes incorporating 30 % replacement showed values of 0.40 to 0.45 mL/g, indicating that partial replacement with fly ash and GGBS did not reduce the hydration-induced volume reduction relative to the OPC reference. This behaviour is attributed to the continued hydration of GGBS and secondary pozzolanic reaction of fly ash, both of which contribute to the formation of additional bound water at an early age. The 50 % replacement mixes exhibited chemical shrinkage in the range of 0.37 to 0.42 mL/g, showing a marginal 5 to 8 % reduction compared with the reference paste. This decrease can be associated with the lower clinker content and slower early hydration of the supplementary cementitious materials, which partially offset the autogenous shrinkage potential at this replacement level. The 70 % replacement mixes recorded values between 0.34 to 0.36 mL/g, corresponding to a 10 to 15 % reduction relative to the OPC paste. Higher proportions of fly ash and GGBS reduced the amount of rapidly hydrating clinker

phases, resulting in a lower rate of chemically bound water formation and consequently reduced chemical shrinkage.

4.2. Determination of pozzolanic activity index

The pozzolanic activity index was determined according to ASTM C311 to assess the reactivity of the pozzolanic material with cement [31]. Two sets of cement paste specimens were prepared: a control mixture using 100 % ordinary Portland cement and a test mixture, wherein the respective percentage of cement was replaced by the pozzolanic material by mass. Both the mixtures were prepared using identical water-to-binder ratios and mixing procedures. The pastes were mixed thoroughly for 5 min to ensure uniform dispersion of all components.

Cubic specimens measuring 50 × 50 × 50 mm were cast from each mixture and compacted into two layers using a tamping rod to eliminate entrapped air. After demoulding, the reference specimens were immersed in water for conventional curing, whereas the ternary blended mixes were cured under the corresponding curing conditions mentioned in the orthogonal array. Compressive strength tests were conducted on both the control and test specimens at 28 days using a compression testing machine at a loading rate of 0.25 MPa/s. The Pozzolanic Activity Index was calculated as the ratio of the compressive strength of the test mixture to that of the control mixture and was expressed as a percentage. Three specimens of each mixture were tested, and the average values were reported to ensure statistical reliability.

4.3. Determination of degree of hydration using non-evaporable water content

The degree of hydration of the cement paste was determined by measuring the nonevaporable water content following a rigorous gravimetric procedure [32]. Cement paste samples were prepared at a predetermined optimum water-to-cement ratio and cured under different conditions. At the specified testing ages (1, 3, 7, 14, and 28 d), approximately 2 g of hardened paste was crushed into small pieces (1-2 mm) and immersed in isopropanol for 24 h to arrest hydration, followed by vacuum drying for 24 h to remove the solvent.

The dried samples were subsequently ground into fine powder and passed through a 75- μm sieve. A portion of this powder (approximately 1 g) was placed in pre-weighed ceramic crucibles and dried at 105 ± 5 °C within an oven for 24 h to remove evaporable water; the corresponding mass was recorded (M_{105}). The samples were subsequently heated to 1000 ± 50 °C within a muffle furnace for 3 h to remove non-evaporable water, and the final mass was recorded (M_{1000}). The non-evaporable water content was calculated as the difference between M_{105} and M_{1000} , and expressed as a percentage of the anhydrous cement mass. The degree of hydration was then computed by dividing the nonevaporable water content by the theoretical nonevaporable water content for complete hydration (23.1 % for ordinary Portland cement). All measurements were performed in triplicate to ensure the reliability of the results.

Table 3. L9 Orthogonal array for experiments and their measurements

Mix	Cement replacement [%] (Fly ash + GGBS) (R)	Water demand (optimum + %) (W)	Superplasticizer dosage (% of binder) (S)	Curing condition (C)	Chemical shrinkage [ml/g]	Pozzolanic activity [%]	Degree of hydration [%]
1	30 (10F + 20G)	W0 + 5 %	0.6	C1	0.4	83.2	77.9
2	30 (10F + 20G)	W0 + 10 %	0.8	C2	0.43	82.6	75.8
3	30 (10F + 20G)	W0 + 15 %	1	C3	0.45	81.3	80.1
4	50 (20F + 30G)	W0 + 5 %	0.8	C3	0.37	85.2	95.2
5	50 (20F + 30G)	W0 + 10 %	1	C1	0.4	84.7	93.1
6	50 (20F + 30G)	W0 + 15 %	0.6	C2	0.42	83.3	86.6
7	70 (30F + 40F)	W0 + 5 %	1	C2	0.34	83.4	82.3
8	70 (30F + 40G)	W0 + 10 %	0.6	C1	0.36	81.3	77.9
9	70 (30F + 40G)	W0 + 15 %	0.8	C3	0.35	82.6	77.9

5. Taguchi analysis

The Taguchi method was implemented to optimise the mixture proportions using an L9 orthogonal array design matrix that accommodated four independent factors at three levels each. The experimental design comprised nine distinct mix combinations determined by the orthogonal array arrangement. The influence of each factor on the response variables was systematically analysed via the S/N ratio calculation, wherein "smaller is better" criterion was adopted for chemical shrinkage and "larger-is-better" criterion was adopted for pozzolanic activity and degree of hydration. The primary effects of the individual factors were evaluated by computing the mean S/N ratios at each level. The optimal combination of factor levels was identified based on the highest S/N ratio, and confirmation tests were conducted to validate the predicted optimal conditions. Delta values and rank analyses were performed to assess the relative influence of each factor on the response variables, enabling the identification of the most significant parameters affecting the concrete properties. The orthogonal array and their direct measurements are listed in Table 3. The observed measurement values revealed that an optimum blend of 50 % cement replacement (20 % fly ash + 30 % GGBS) provided the most balanced performance, combining lower chemical shrinkage, higher pozzolanic reactivity, and an enhanced degree of hydration, reflecting the efficient utilisation of supplementary materials without compromising hydration development.

6. Results and discussions

The S/N ratio and factor effect plot analysis are fundamental components of Taguchi's robust design methodology for optimising the process parameters. The S/N ratio, which combines both the mean response and variation into a single metric, was calculated by transforming a series of experimental observations into a consolidated value that reflects both the desired signal (mean response) and undesired noise (variation). For quality characteristics, three standard S/N ratio formulations were

employed: "larger-is-better", "smaller-is-better", and "nominal-is-best", with the selection depending on the desired outcome of the process optimisation. Following the S/N ratio calculation, factor effect plots were generated by averaging the S/N ratios for each factor level across all the experimental runs. These plots provide a visual representation of the impact of various factor levels on the process performance, wherein the slope of the lines between the factor levels indicates the magnitude of the factor's effect. The optimal parameter combination was identified by selecting the factor levels that maximised the S/N ratio, thereby achieving improved mean performance and reduced variability.

6.1. Chemical shrinkage

The S/N ratio analysis of chemical shrinkage revealed distinct trends across the four experimental control factors studied. For cement replacement, a strong positive correlation was observed with the increasing percentage [32, 33], showing optimal performance at 70 % replacement with the highest S/N ratio of approximately 9 decibels (dB). The water demand factor showed a marginal negative trend [34], with the best performance at an optimal water demand of 5 % and a declining S/N ratio as the water demand increased to 15 %. The superplasticiser dosage demonstrated minimal variation in the S/N ratios across distinct levels (0.6 % to 1 %), with values remaining at approximately 8 dB, suggesting that this factor exerts relatively less impact on the overall performance. Similarly, the curing conditions (C1, C2, and C3) showed negligible variation in S/N ratios, maintaining consistent values of approximately 8 dB, indicating that different curing conditions exert a minimal effect on chemical shrinkage. Based on these results, the optimal parameter combination would include 70 % cement replacement and 5 % water demand, whereas the superplasticiser dosage and curing conditions can be selected based on practical considerations because they do not significantly influence the response variable. Figure 5 shows the factor effect plot for chemical shrinkage and Table 4 lists the delta values and ranks of the mean S/N ratio of each factor for the chemical shrinkage parameter.

Table 4. Signal-to-Noise (S/N) response table for chemical shrinkage

Control factor	Mean signal-to-noise ratio S/N [dB]			Max. to Min. [dB]	Rank
	Level 1	Level 2	Level 3		
Cement replacement level (R)	7.40	8.04	9.12	1.71	1
Water demand (W)	8.65	8.05	7.86	0.79	2
Superplasticizer dosage (S)	8.12	8.36	7.92	0.44	3
Curing condition (C)	8.34	8.07	8.14	0.19	4

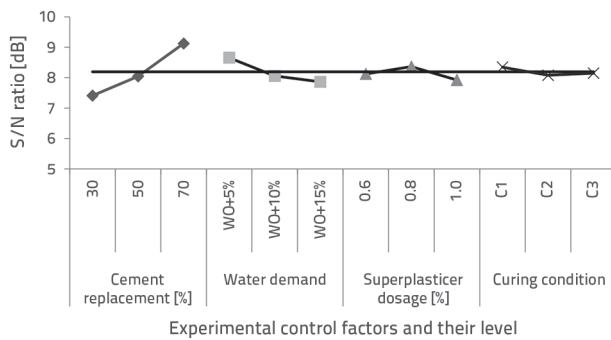


Figure 5. Factor effect plot for chemical shrinkage

6.2. Pozzolanic activity index

Figure 6 shows the factor-effect plot for the pozzolanic activity index, revealing several important trends in the influence of the different control factors on the pozzolanic reaction.

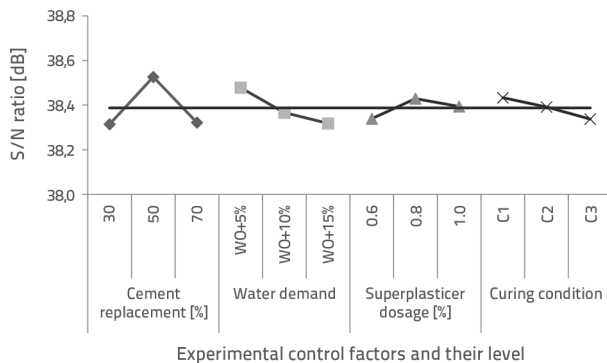


Figure 6. Factor effect plot for pozzolanic activity index

The cement replacement percentage demonstrated a prominent peak at 50 %, indicating that this is the optimal level for maximising pozzolanic activity. The curve shows lower S/N ratios at both 30 % and 70 % replacement levels, suggesting

that both insufficient as well as excessive cement replacement can diminish the pozzolanic performance [35]. Water demand exhibited a declining trend as the water content increased from WO+5 % to WO+15 %. The highest S/N ratio was observed at WO+5 %, indicating that a marginally increased water content above the base level is beneficial for pozzolanic activity; however, excessive water addition may hinder the reaction process [36]. The superplasticiser dosage exhibited a subtle but positive influence of up to 0.8 %, followed by a marginal decline of 1 %. This behaviour suggests that although superplasticisers can enhance pozzolanic activity, an optimal dosage exists beyond which additional amounts provide diminishing returns or potentially negative effects [37]. The curing conditions (C1, C2, and C3) displayed minimal variation in their effect on the pozzolanic activity index, as indicated by the nearly horizontal trend line. This suggests that the pozzolanic reaction is relatively stable across different curing conditions, making it a less critical parameter for optimisation than cement replacement and water demand.

This analysis emphasises the significance of properly balancing cement replacement levels and water demand to achieve optimal pozzolanic activity, whereas the superplasticiser dosage and curing conditions play secondary roles in the process. These findings align with the previously discussed S/N response table analysis, confirming that cement replacement is the most influential factor in controlling the pozzolanic activity. Table 5 presents the S/N ratio response table for pozzolanic activity index.

The S/N response analysis for the pozzolanic activity index reveals that cement replacement level exerted the highest influence among all control factors, with a delta value (Max-Min S/N ratio) of 0.21 dB, earning it the first rank. The S/N ratios for cement replacement showed marginal variations across levels, with Level 2 (38.52 dB) showing a marginally enhanced performance compared with Levels 1 and 3. Water demand emerged as the second most influential factor, with a delta value

Table 5. Signal-to-Noise (S/N) response table for pozzolanic activity index

Control factor	Mean signal-to-noise ratio S/N [dB]			Max. to Min. [dB]	Rank
	Level 1	Level 2	Level 3		
Cement replacement level (R)	38.31	38.52	38.32	0.21	1
Water demand (W)	38.47	38.36	38.31	0.16	2
Superplasticizer dosage (S)	38.33	38.42	38.39	0.09	3
Curing condition (C)	38.43	38.39	38.33	0.095	4

Table 6. Signal-to-Noise (S/N) response table for degree of hydration

Control factor	Mean signal-to-noise ratio S/N [dB]			Max. to Min. [dB]	Rank
	Level 1	Level 2	Level 3		
Cement replacement level (R)	25.10	26.50	25.26	1.40	1
Water demand (W)	25.84	25.69	25.48	0.35	2
Superplasticizer dosage (S)	25.41	25.60	25.85	0.44	3
Curing condition (C)	25.61	25.48	25.76	0.28	4

of 0.16 dB, demonstrating optimal performance at Level 1 (38.47 dB). The curing conditions and superplasticiser dosage showed minimal impacts on the pozzolanic activity index, ranking third and fourth, with significantly close delta values of 0.095 dB and 0.09 dB, respectively. The relatively minor differences in delta values among all factors (ranging from 0.09 to 0.21 dB) suggest that the pozzolanic activity index is fairly stable across different parameter combinations, although the cement replacement level remains the most crucial factor for optimisation.

6.3. Degree of hydration

Figure 7 and Table 6 show the factor-effect plot and S/N response ratio, respectively, for the degree of hydration. S/N ratio analysis of the degree of hydration demonstrated distinct patterns across the four experimental control factors. For cement replacement, a pronounced peak is observed at 50 % with an S/N ratio of approximately 26.5 dB, while both 30 % and 70 % replacement levels show lower values (around 25.2 dB and 25.3 dB respectively), indicating that 50 % replacement is optimal for hydration [38].

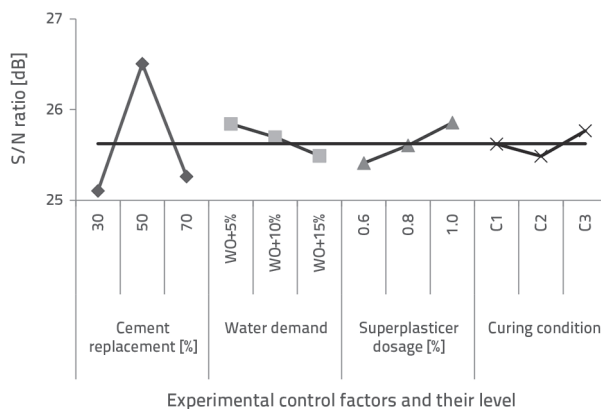


Figure 7. Factor effect plot for degree of hydration

The water demand factor showed a gradual declining trend from WD-5 % to WD-15 %, with the highest S/N ratio at WD-5 %, suggesting that a lower water demand promoted better hydration [37]. For the superplasticiser dosage, an increasing trend is observed from 0.6 % to 1 %, with the optimal S/N ratio achieved at a 1 % dosage, indicating that a higher superplasticiser content benefits the hydration process [38]. The curing conditions (C1, C2, and C3) showed marginal variations, with C3 showing marginally higher S/N ratios than C1 and C2,

although the differences were relatively small. Based on these results, the optimal combination for maximising the Degree of Hydration was 50 % cement replacement, 5 % water demand, and 1 % superplasticiser dosage, while the curing conditions exerted minimal impact on the hydration process.

The analysis shows that the level of cement replacement is the dominant factor influencing the degree of hydration, with a delta value significantly higher than that of the other factors, whereas the other parameters play a secondary role.

7. Conclusion

A comprehensive Taguchi analysis of three key performance parameters, namely chemical shrinkage, Pozzolanic activity index, and degree of hydration, enabled identification of optimal experimental conditions for ternary blended cement pastes incorporating fly ash and GGBS. The key conclusions are as follows.

- Cement replacement emerged as a critical factor across all parameters. Chemical shrinkage was minimised at 70 % replacement, whereas both pozzolanic activity and degree of hydration were maximised at 50 % replacement. This suggests that a moderate-to-high cement replacement level (50 to 70 %) is beneficial for the overall performance.
- Water demand consistently showed improved results at lower levels (WD-5 %) across all three parameters, indicating that minimal water content is favourable for optimal material properties.
- The superplasticiser dosage demonstrated varying effects. It exerted minimal impact on chemical shrinkage and pozzolanic activity; however, it showed a positive correlation with the degree of hydration, suggesting that higher dosages (1 %) is likely beneficial for hydration processes.
- The curing conditions and relative humidity exhibited minimal influence across the parameters, suggesting that these factors are less critical in determining the final properties. These findings provide valuable insights for optimising concrete mixtures with high cement replacement levels, indicating that careful control of water demand and superplasticiser dosage is crucial for achieving the desired performance characteristics, whereas curing conditions offer more flexibility in the manufacturing process.
- Based on the analysis of the signal-to-noise (S/N) response tables for chemical shrinkage, pozzolanic activity index and degree of hydration, several consistent patterns emerged that yield comprehensive conclusions regarding concrete mixture design optimisation.

- The cement replacement level consistently emerged as the most influential control factor for all three properties investigated. It ranked first in each analysis with delta values of 1.71 dB for chemical shrinkage, 0.21 dB for Pozzolanic activity index, and 1.40 dB for degree of hydration. This demonstrates that the careful selection of the cement replacement level is critical for the simultaneous optimisation of multiple concrete performance parameters. The optimal cement replacement level was approximately level 2 (50 %), as indicated by the S/N ratios for pozzolanic activity and degree of hydration, whereas higher levels (level 3) seemed more effective for controlling chemical shrinkage.
- Water demand consistently ranked second in importance for both chemical shrinkage and pozzolanic activity index; however, it dropped to third in terms of the degree of hydration. This suggests that the water content plays a vital but secondary role in determining the concrete performance, with its effect varying depending on the specific properties being optimised. Generally, a lower water demand (level 1) indicated improved performance.
- Super plasticiser dosage showed a variable influence, ranking third for chemical shrinkage and fourth for pozzolanic activity, but rising to second for the degree of hydration. This variability indicates that the effectiveness of a superplasticiser significantly depends on the properties being targeted for improvement, making it an important parameter for selective optimisation.
- The curing conditions consistently demonstrated the least influence on both the chemical shrinkage and degree of hydration, ranking fourth. However, these were marginally higher (third) for the pozzolanic activity index. The minimal

variation in the S/N ratios across the curing conditions suggests that this parameter exerts a limited impact on the studied properties compared with other factors.

- Furthermore, the volumetric behaviour of cement paste differs fundamentally from that of concrete because of the restraining influence of aggregates, presence of an interfacial transition zone, and composite nature of the material. Although the chemical shrinkage and hydration characteristics obtained in this study were derived from paste-level investigations, these results are crucial for understanding the intrinsic reactivity of the binder system and predicting early age volumetric changes in concrete. Paste-scale measurements provide the foundational input for modelling autogenous shrinkage, internal relative humidity evolution, and the degree of hydration in concrete. Therefore, although the findings obtained at the paste scale cannot be directly extrapolated to concrete behaviour, the trends established in this study offer valuable insights for the design and optimisation of ternary-blended concretes incorporating fly ash and GGBS.
- Overall, these findings provide clear guidance for concrete mixture design: priority should be given to optimising the cement replacement level, followed by adjustments to water demand and superplasticiser dosage. Although curing conditions remain important, their influence on the investigated properties appears comparatively less significant.

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