

Effect of Multi-Variable Mix Composition on the Setting Time and Flow Properties of Fly Ash-GGBFS Geopolymer Mortar

Bayu Rahmat Ramadhan^{*1}, Andi Arham Adam², Sri Nur Akifa³, Suci Amalia Namira Wahidin⁴, Novacharisma Vindiantri Verucha⁵ and Misel Borro Allo⁶

^{1,2,3,4,5,6}Civil Engineering Department, Engineering Faculty, Tadulako University, Palu
e-mail: [*bayurramadhan@untad.ac.id](mailto:bayurramadhan@untad.ac.id), andi.arham@untad.ac.id, srinurakifa@gmail.com,
scnamira@gmail.com, novacharismavindiantri.v06@gmail.com, misel.borroallo@gmail.com.

Abstract

The development of eco-friendly construction materials increasingly emphasizes the utilization of industrial by-products, with fly ash being a prominent alternative binder to Portland cement. However, Type F fly ash exhibits inherently low calcium (CaO) content, leading to slow geopolymerization and a dependency on high-temperature curing for strength gain. This study investigates the potential of utilizing 100% fly ash as a binder in geopolymer mortar by incorporating Ground Granulated Blast Furnace Slag (GGBFS) as a calcium-rich additive. The experimental program examined the influence of GGBFS content (10%, 20%, 30% by fly ash weight), activator-to-binder ratio (0.30, 0.35, 0.40), and aggregate-to-binder ratio (2.25, 2.50, 2.75) on fresh properties under ambient curing conditions. The results demonstrate that GGBFS incorporation significantly improved early reactivity and workability. Increasing GGBFS content shortened both initial and final setting times by up to 35% compared to fly ash-only mixes, indicating the formation of C-A-S-H gel alongside N-A-S-H gel. Optimum flowability was achieved at an activator/binder ratio of 0.35, whereas higher ratios (0.40) led to reduced viscosity and faster setting. Furthermore, an aggregate/binder ratio of 2.50 provided the best balance between workability and cohesiveness. Overall, the addition of 20–30% GGBFS enabled ambient-cured geopolymer mortars to achieve satisfactory fresh properties without the need for thermal curing, highlighting their potential as sustainable construction materials.

Keywords: Fly Ash, GGBFS, Geopolymer, Mortar, Setting Time, Workability

Abstrak

Pengembangan material konstruksi ramah lingkungan semakin menekankan pemanfaatan produk samping industri, dengan fly ash menjadi salah satu bahan pengikat alternatif yang menonjol untuk menggantikan semen Portland. Namun, fly ash tipe F memiliki kandungan kalsium (CaO) yang rendah, sehingga menyebabkan proses geopolimerisasi berlangsung lambat serta bergantung pada curing suhu tinggi untuk memperoleh kekuatan. Penelitian ini mengkaji potensi pemanfaatan fly ash 100% sebagai bahan pengikat dalam mortar geopolimer dengan menambahkan Ground Granulated Blast Furnace Slag (GGBFS) sebagai aditif kaya kalsium. Program eksperimental dilakukan untuk mengevaluasi pengaruh variasi kadar GGBFS (10%, 20%, 30% terhadap berat fly ash), rasio aktivator terhadap binder (0,30; 0,35; 0,40), serta rasio agregat terhadap binder (2,25; 2,50; 2,75) terhadap sifat segar mortar geopolimer pada kondisi curing suhu ruang. Hasil penelitian menunjukkan bahwa penambahan GGBFS secara signifikan meningkatkan reaktivitas awal dan workability. Peningkatan kadar GGBFS memperpendek waktu ikat awal maupun akhir hingga 35% dibandingkan campuran dengan fly ash murni, yang mengindikasikan terbentuknya gel C-A-S-H bersamaan dengan gel N-A-S-H. Flowability optimum diperoleh pada

rasio aktivator/binder sebesar 0,35, sedangkan rasio yang lebih tinggi (0,40) cenderung menurunkan viskositas sekaligus mempercepat waktu ikat. Selain itu, rasio agregat/binder sebesar 2,50 memberikan keseimbangan terbaik antara workability dan kohesivitas. Secara keseluruhan, penambahan GGBFS sebesar 20–30% memungkinkan mortar geopolimer yang dikondisikan pada suhu ruang untuk mencapai sifat segar yang memadai tanpa memerlukan curing termal, sehingga menunjukkan potensinya sebagai material konstruksi berkelanjutan.

Keywords: Abu Terbang, GGBFS, Geopolimer, Mortar, Setting Time, Workability

1. Introduction

The escalating global demand for sustainable infrastructure necessitates a paradigm shift in construction material development, particularly focusing on the utilization of industrial waste materials as alternative binders (Palomo et al., 2016). In this regard, geopolimer technology presents a promising avenue for valorizing industrial by-products into sustainable construction materials, significantly reducing the carbon footprint associated with traditional cement production (Amer et al., 2021). Central Sulawesi, Indonesia, offers a unique opportunity for such development, given its rich abundance of steel waste from nickel factories and power plant (PLTU) waste, which includes significant quantities of fly ash. Fly ash as a promising raw material for producing geopolimer concrete, offering a viable substitute for conventional Portland cement due to its pozzolanic and latent hydraulic properties (Duxson et al., 2007). The adoption of geopolimer technology fundamentally contributes to environmental sustainability by reducing CO₂ emissions associated with cement production and mitigating landfill burden from industrial waste (Kehinde et al., 2024)(Kumar et al., 2017).

However, Type F fly ash, which is commonly available, inherently possesses a low calcium (CaO) content (Rukzon & Chindaprasirt, 2009). This characteristic often leads to slower geopolimerization kinetics, necessitating high-temperature curing to achieve adequate early strength and accelerate the formation of strength-contributing hydration products (Ramachandran et al., 2002). This requirement for heat curing can pose practical limitations in certain construction scenarios, particularly in regions where heating facilities are not readily available or economically feasible, thus hindering the widespread adoption of fly ash-based geopolimers (Singh, 2018). To overcome the challenges associated with Type F fly ash reactivity under ambient conditions, this research aims to optimize the utilization of 100% fly ash as the primary binder in geopolimer mortar through the strategic addition of Ground Granulated Blast Furnace Slag (GGBFS). GGBFS is incorporated as a supplementary cementitious material due to its high content of reactive calcium, which is expected to significantly accelerate the geopolimerization process and promote the formation of calcium-aluminate-silicate-hydrate (C-A-S-H) gel, a key component for early strength development in geopolimer systems [7]. The alkaline activation for the geopolimerization process is achieved by combining sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solutions, with their respective ratios being a critical parameter for controlling the reaction kinetics and fresh properties (Temuujin et al., 2010)(Loekito & Wardhono, 2018). The raw materials, including fine aggregate, GGBFS, fly ash, and alkaline activators, were meticulously characterized to ensure their suitability and properties for the experimental program.

This study systematically investigates the influence of multi-variable mix composition on the fresh properties of fly ash-GGBFS geopolimer mortar at ambient temperature (without heat curing). The levels for activator/binder ratio (D), GGBFS content (G), and aggregate/binder ratio (A) were chosen based on both practical considerations and values commonly reported in previous geopolimer mortar studies (A. Adam, 2009). For D, the range of 30%, 40%, and 50% was used because values below 30 may not provide enough alkaline solution for proper geopolimerization, while values above 40 can make the mix too viscous and hard to place (Nath & Sarker, 2014). For G, 10%, 20%, 30% GGBFS replacement was selected to study the effect of calcium content. Past research shows that 10–20% can improve early strength at room temperature, while higher levels

(>40%) often reduce workability too quickly (Olivia & Nikraz, 2012). For A, values of 2.25 and 2.5, 2.75 were chosen because lower ratios can lead to paste-rich mixes that shrink, and higher ratios can cause segregation (Neville, 2011). These ranges keep the mixes practical for field use while allowing comparison with earlier studies. The specific fresh properties evaluated are flowability and setting time. The findings from this research are anticipated to demonstrate that the judicious inclusion of GGBFS can substantially enhance the early reactivity of fly ash-GGBFS geopolymer mortar, making it viable for applications under ambient curing conditions (Amran et al., 2022). This study is expected to contribute valuable insights towards the development of sustainable construction materials by optimizing industrial waste utilization, particularly for applications not requiring high-temperature curing (Biondi et al., 2019) (A. A. Adam, 2019) (Farooq et al., 2021).

2. Research Method

2.1 Material Used

The fly ash employed as the primary aluminosilicate source in this study was sourced from PLTU in the Morowali industrial area or PT. IMIP. Chemical composition analysis, conducted at the Integrated Science Laboratory of Universitas Hasanuddin, revealed its classification as Type F fly ash according to ASTM C618-03 as presented on table 1. Ground Granulated Blast Furnace Slag (GGBFS) was incorporated into the mix as a source of reactive calcium to enhance early reactivity. The GGBFS was obtained from PT. Krakatau Steel in Cilegon, Indonesia. Its specific gravity was determined to be 3.005 kg/liter. Chemical analysis confirmed a composition suitable for use in geopolymer systems, featuring key oxides such as Silicon Oxide (SiO₂) at 29.6%, Calcium Oxide (CaO) at 24.3%, and Aluminium Trioxide (Al₂O₃) at 13.4% as presented also in Table 1.

Table 1. Fly Ash and GGBS Composition

Parameter	Fly Ash (%)	Parameter	GGBS (%)
SiO ₂	55,54	MgO	1,9
Fe ₂ O ₃	23,76	S ₂	0,58
Al ₂ O ₃	14,02	SO ₃	1,45
CaO	2,02	Cl	0,02
K ₂ O	1,58	CaO	24,3
SO ₃	1,3	SiO ₂	29,6
TiO ₂	0,92	Al ₂ O ₃	13,4
MnO	0,291	Na ₂ O	0,37
Others	0,5559	K ₂ O	0,91

Natural sand was utilized as the fine aggregate in the mortar mixtures. Comprehensive testing of the fine aggregate's physical properties was conducted. The results indicated that its specific gravity (bulk oven-dry: 2.559, bulk SSD: 2.583, apparent: 2.622), water absorption (0.949%), bulk density (loose: 1.306 gr/cm³, compacted: 1.434 gr/cm³), moisture content (1.460%), silt content (1.758%), and organic impurities (color matching standard No. 2) all met the specified requirements. Based on these characteristics, the fine aggregate was classified as normal aggregate, suitable for mortar production as presented in Figure 1.

The alkaline activator solution utilized in this study comprised sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). The NaOH solution, sourced from a chemical supplier, was found to have a specific gravity of 1.2783 kg/liter. Conversely, the sodium silicate solution's properties conformed to its standards; its moisture content was 42.725% (within the maximum limit of 62.5% per MSDS 2006), and its specific gravity was 1.58845 kg/liter, complying with the maximum specification of

z1.59% for grade 159. Stoichiometric analysis of the sodium silicate further revealed Na₂O and SiO₂ contents of 14.192% and 29.498%, respectively (Thunuguntla & Gunneswara Rao, 2018).

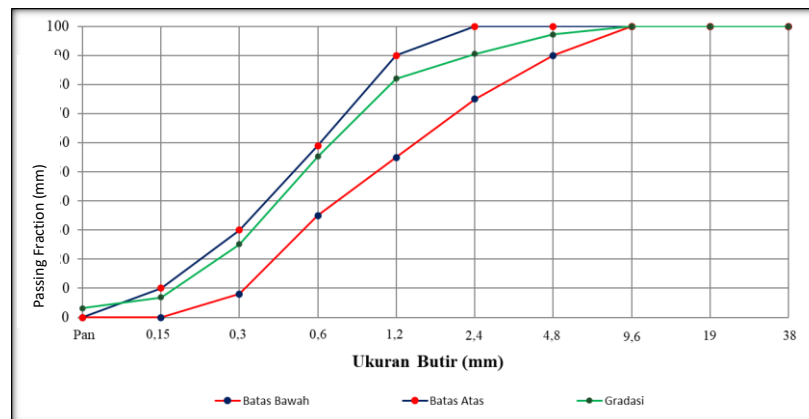


Figure 1. Grading of Fine Agregate

2.2 Taguchi Method Mix Desain

The experimental design for the geopolymers mortar mixes was established using the Taguchi method with three factors at three levels each, resulting in nine distinct geopolymer mix proportions (GF-1 to GF-9). These variations encompassed the activator/binder ratio (D: 30%, 35%, 40%), the percentage of GGBFS within the fly ash (G: 10%, 20%, 30%), and the aggregate/binder ratio (A: 2.25, 2.50, 2.75). Additionally, a pure fly ash mix (F-1) and a Portland Composite Cement (PCC) mix (P-1) were included as comparative control designs. The calculation of the mix design based on previous research (A. Adam, 2009). (Van De Walle, 2019)

Table 2. Mix Design

Code Mix	Akt/FA(%)	W/S	GGBS Percentage(%)	Agg/binder	Cement Percentage(%)
GF-1	30	0.45	10	2.25	-
GF-2	30	0.45	20	2.5	-
GF-3	30	0.45	30	2.75	-
GF-4	35	0.45	10	2.5	-
GF-5	35	0.45	20	2.75	-
GF-6	35	0.45	30	2.25	-
GF-7	40	0.45	10	2.75	-
GF-8	40	0.45	20	2.25	-
GF-9	40	0.45	30	2.5	-
F-1	40	0.45	0	2.25	-
P-1	-	0.45	0	2.25	100

2. 2 Mixing Method and Testing

In this experimental program, a total of 11 mix designs were prepared to investigate the influence of GGBFS content, activator-to-binder ratio, and aggregate-to-binder ratio on the performance of fly ash-based geopolymer mortar. For each mix design, three specimens were cast and tested at three different curing ages: 7, 14, and 28 days. This approach ensured statistical reliability of the results by providing triplicate data for each testing age. Accordingly, the total number of specimens were 99 Samples. The preparation of geopolymer mortar followed a standardized mixing procedure. All raw materials were first precisely weighed according to their respective mix design compositions. Solid sodium hydroxide (NaOH) was initially dissolved in water and stirred for approximately 45

seconds until complete dissolution, then allowed to rest for 24 hours prior to use for 10M Sodium Hydroxide. Subsequently, the weighed GGBFS and fly ash were dry-mixed for 2 minutes to achieve homogeneity, after which sand was incorporated and mixed for an additional 1 minute. This dry blend was then combined with the pre-rested sodium hydroxide solution and sodium silicate solution for additional 2 minute(Pilehvar et al., 2017). Any additional water required was then introduced, and the mixture was continuously stirred for 1 minute. A 15-second pause was implemented to scrape any paste adhering to the bowl walls (A. Adam, 2009)(Zuo et al., 2019).



Figure 2. Ambient cured Geopolymer Speciment

Following the mixing procedure, the fresh properties of the mortar were immediately evaluated. The primary tests conducted included assessing the flowability using the flow table test and determining the setting time (both initial and final) and Vcat Penetration for setting time(ASTM C191-19, 2019). To statistically evaluate the influence of the varied factors (D, G, A) on these fresh properties, the Analysis of Variance (ANOVA) method was employed. This approach allowed for the systematic assessment of each factor's contribution to the observed workability and setting time characteristics of the geopolymer mortar.

3. Result and Discussion

3.1 Workability Test Results of Mortar (Flow Table Test)

Workability testing is a crucial parameter for determining the ease of handling and consistency of mortar mixtures. This test is performed using a flow table apparatus, with results presented as a flow percentage. A higher flow table value indicates a more fluid or easily workable mixture. The tests were conducted on various types of mixtures, including geopolymer mixtures (GF-1 to GF-9), pure fly ash mixtures (F-1), and Portland Composite Cement (P-1) mixtures as a comparative reference. The geopolymer mixtures were systematically varied based on the activator/binder ratio (D), the percentage of GGBFS within the fly ash (G), and the aggregate/binder ratio (A).

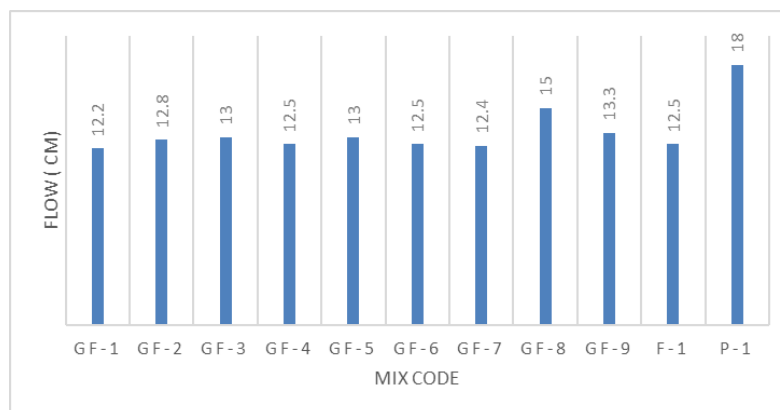


Figure 3. Flow Table Results for the Investigated Mix Designs

Based on Figure 3, the flow table values for geopolymer mixtures (GF-1 to GF-9) generally ranged between 12.2 and 15.0. The pure fly ash mixture (F-1) exhibited a value of 12.5, which falls within the workability range of geopolymer mixtures containing GGBFS. Conversely, the Portland Composite Cement (PCC) mixture (P-1) had the highest flow table value of 18.0, indicating a higher degree of workability compared to all tested geopolymer mixtures.

The lower workability of geopolymer mixes compared to PCC can be explained through geopolymerization reaction theory. Geopolymers undergo a dissolution–polycondensation process in which aluminosilicate species (SiO_4 and AlO_4 tetrahedra) released from fly ash or GGBFS rapidly react with alkaline activators. High early reactivity, especially from GGBFS (rich in reactive calcium), tends to accelerate the formation of calcium–aluminosilicate–hydrate (C-A-S-H) or hybrid N-A-S-H/C-A-S-H gels, leading to rapid stiffening and reduced fluidity (Joseph, 2008) (Provis & Deventer, 2014). This explains why GGBFS-containing mixes did not significantly exceed the workability of the pure fly ash mix (F-1), despite the potential for higher early strength (Amer et al., 2021).

3.1.1. Statistical Analysis and Research Implications

To analyze the influence of individual factors (Activator/Binder Ratio (D), GGBFS Percentage (G), and Aggregate/Binder Ratio (A)) on the flow table values of the geopolymer mixtures, Analysis of Variance (ANOVA) was conducted. The analysis results showed the following p-values for each factor: activator/binder ratio (D) was 0.461197, GGBFS percentage (G) was 0.377495, and aggregate/binder ratio (A) was 0.809339.

Table 3. Statistical Analysis (ANOVA) of Flow Table Results

Variation Source	(SS)	(df)	F-Value	(p-value)
Faktor D (C(D))	1.620	2	1.168	0.461
Faktor G (C(G))	2.287	2	1.649	0.378
Faktor A (C(A))	0.327	2	0.236	0.809
Galat (Residual)	1.387	2	-	-

Based on the ANOVA results, no single factor—namely, the Activator/Binder Ratio (D), GGBFS Percentage (G), or Aggregate/Binder Ratio (A)—demonstrated statistically significant influence on the flow table values at the common significance level of 0.05 within the tested range of combinations [14]. This indicates that the variations in parameters D, G, and A, at the levels investigated, did not produce differences in workability substantial enough to be considered statistically significant (Calfee & Piontkowski, 2016).

In statistical analysis, a higher p-value implies that a factor has the least or most negligible statistical influence on the observed outcome. As a reminder, all p-values for the three factors (D, G, and A) were above the 0.05 significance threshold. This signifies that none of these factors, individually, showed a statistically significant effect on the workability within the examined data range.

However, while none of the factors were statistically significant, a comparative glance at their p-values can offer a qualitative indication of their relative influence. Among the three factors, the GGBFS Percentage (G) exhibited the lowest p-value (0.377495), suggesting it had a relatively stronger, albeit still not statistically significant, effect on the flow table values compared to the other factors. This might imply that other underlying factors, or more complex interactions among these parameters, may be more dominant and warrant further exploration (Jensen, 2017). The limited number of unique mix combinations (9 samples for ANOVA) could also affect the statistical power of the analysis, potentially obscuring more subtle effects (Columb & Atkinson, 2015).

3.2 Setting Time Result

Setting time is a critical parameter in the development of geopolymer mortar, as it governs the workable life and construction efficiency (Rashidian-Dezfouli & Rangaraju, 2017). Key factors influencing the setting time in geopolymer systems include the activator-to-binder ratio (D), the

GGBFS content within the fly ash (G), and the aggregate-to-binder ratio (A). Variations in these three factors can significantly modify the polymerization reactions that occur from the initial to the final stages of the hardening process .

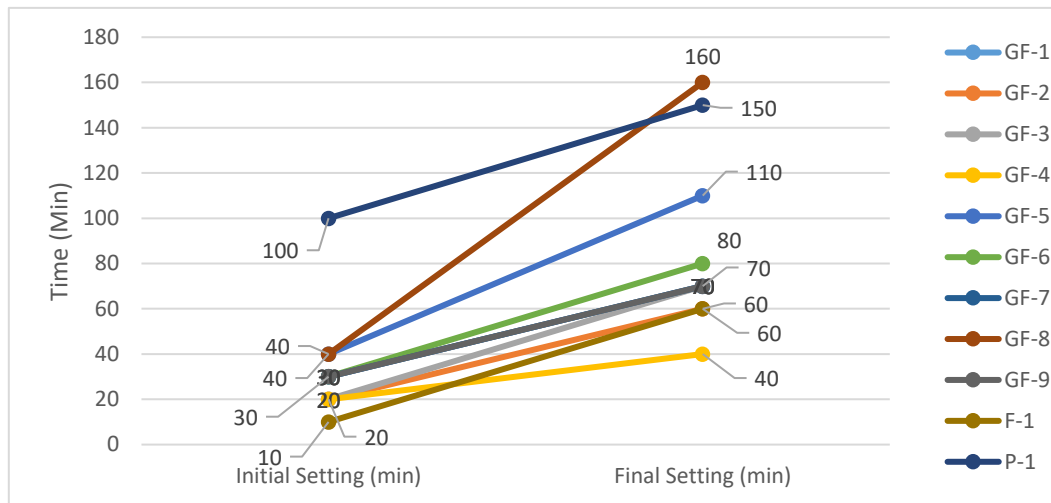


Figure 4. Initial and Final Setting Time Graph

Figure 4 and 5 illustrates significant variations in both the initial and final setting times among the nine geopolymer mix combinations (GF-1 to GF-9). The Portland Composite Cement (PCC) mixture (P-1) exhibited overall slower setting times compared to most geopolymer mixtures, whereas the pure fly ash mixture (F-1) showed a very rapid initial setting and a relatively quick final setting.

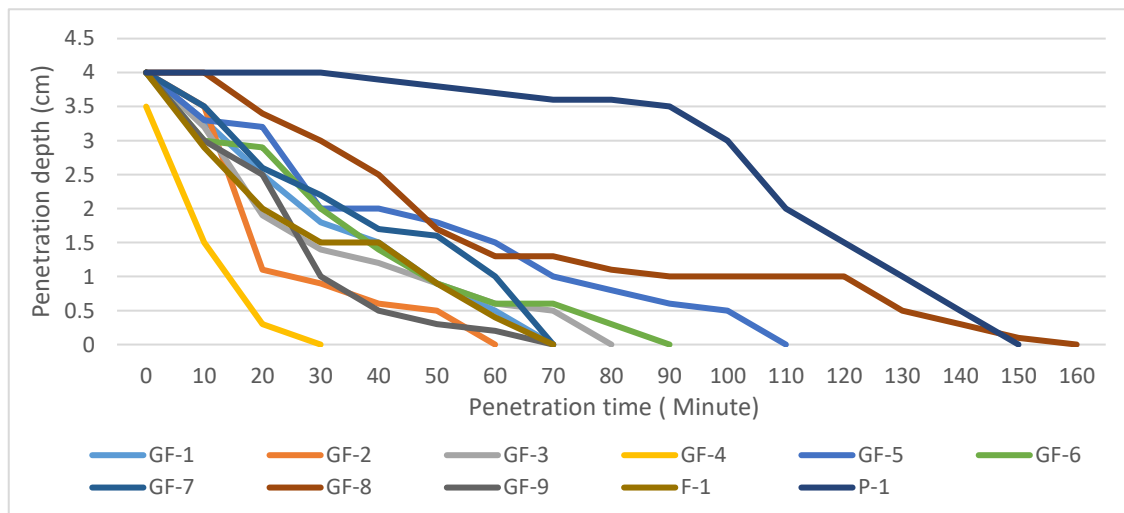


Figure 5. Vcat Penetration Graph every 10 Minute

3.2.1 Effect of Activator/Binder Ratio, GGBFS Content, and Aggregate/Binder Ratio on the Setting Time of Geopolymer Mortar

Based on Figure 4 and 5 the Activator/Binder Ratio (D) was investigated at three levels: 30, 35, and 40. Generally, an increase in D from 30 to 40 caused a tendency towards an increase in the final setting time. This trend is observable across the GF-1 to GF-9 mixtures, where D40 (specifically GF-8) exhibited the longest final setting time (160 minutes), while D35 (GF-4) showed a relatively short final setting time (40 minutes). An increase in the D ratio leads to a higher concentration of OH^- and Na^+ ions, which can accelerate the initial dissolution of fly ash/GGBFS. However, excessive alkali

content can potentially delay the subsequent geopolymer gel formation reactions (Vijayan et al., 2020).

The GGBFS content (Variable G) was investigated at three levels: 10%, 20%, and 30%. Based on the data, the final setting time for G10 mixes ranged from 40–70 minutes, while G30 mixes showed more stability, generally around 70–80 minutes. Notably, G20 mixes exhibited the highest variability in final setting time, reaching up to 160 minutes. GGBFS typically accelerates early reactions due to its calcium content; however, at the 20% level (specifically for mixes GF-8 and GF-5), the observed setting times were highly inconsistent. This suggests a strong interaction between the GGBFS content (G) and potentially other factors like the activator/binder ratio (D), which influences the reaction products and overall setting behavior (Divanedari & Eskandari-Naddaf, 2020).

The Aggregate/Binder Ratio (A) was investigated at three levels: 2.25, 2.5, and 2.75. Mixtures with an A ratio of 2.5 (GF-2, GF-4, GF-9) exhibited the shortest and most stable final setting times. Conversely, A ratios of 2.25 and 2.75 tended to yield longer final setting times. An excessively low aggregate ratio ($A = 2.25$) can result in a mixture that is too fluid, thereby retarding the formation of a rigid structure. Conversely, an overly high aggregate ratio ($A = 2.75$) may reduce the free moisture necessary for initial geopolymerization reactions, consequently extending the setting time [20].

3.2.2 Statical Analysis (ANOVA) of Geopolymer Mortar Setting Time

To determine the relative influence of each variable on the final setting time, a 3-factor, 3-level ANOVA was performed, utilizing a Taguchi L9 approach. The results of this analysis are presented in the following table:

Table 4. Statistical Analysis (ANOVA) of Setting Time Result

Faktor	Sum of Squares	df	F-Value	p-value
D (Aktivator)	1755.556	2	2.821	0.262
G (GGBFS)	4022.222	2	6.464	0.134
A (Agregat)	3288.889	2	5.286	0.159
Residual	622.222	2	-	-

Based on the ANOVA results, although no individual factor showed statistical significance at a 95% confidence level ($p > 0.05$) [14], factor G (GGBFS content) exhibited the highest F-value (6.464), followed by A and D. This qualitatively suggests that G tends to be the most dominant factor in influencing the final setting time, especially when combined with a specific D ratio.

Furthermore, interactions among the mixed composition variables appear to exert a considerable influence on the setting time of geopolymer mortar, particularly at extreme value combinations. This is distinctly evident in mixture GF-8 (D40, G20, and A2.25), where its final setting time reached 160 minutes—significantly longer than other mixtures. Such a case indicates synergistic or antagonistic effects between variables that cannot be explained solely by the individual factors' separate influences (Jensen, 2017). This condition highlights that the use of advanced statistical methods, such as two-way ANOVA for interaction analysis, is highly recommended for future experiments. The aim would be to more accurately evaluate the influence of interactions between factor pairs (e.g., $D \times G$, $D \times A$, or $G \times A$) on the setting time.

Based on experimental trends, a combination of activator ratio (D) between 30–35, GGBFS content (G) between 10–30%, and aggregate ratio (A) of 2.5 yielded final setting times within the optimal range of 60–80 minutes. This range is considered most suitable for rapid construction applications, as it allows sufficient workability time while simultaneously achieving early structural stability of the material. These findings align with recent research indicating that a moderate increase in GGBFS can accelerate early reactivity and improve the initial performance of geopolymer mortar. However, if not accompanied by appropriate activator and aggregate ratio adjustments, it may lead to retardation or instability in the setting process (Fang et al., 2024).

3.2.3. Effect Size Analysis

The previous ANOVA analysis indicated that no single factor was statistically significant at $\alpha = 0.05$: activator-to-binder ratio (D) $p = 0.461$; percentage of GGBFS (G) $p = 0.378$; aggregate-to-binder ratio (A) $p = 0.809$; with residual (error) $SS = 1.387$ and $df = 2$. To capture the magnitude of practical effects, we calculated the partial eta squared (η^2p):

Table 4. Statistical Analysis (ANOVA) of Setting Time Result

Faktor	SS (effect)	p-value	η^2p	Cohen's f	Size Effect (Cohen)
D (C(D))	1.620	0.461	0.539	1.081	Big
G (C(G))	2.287	0.378	0.622	1.284	Big
A (C(A))	0.327	0.809	0.191	0.486	Medium–Big

Although the p -values were not statistically significant, the η^2p values indicate large practical effects for D and G, and medium-to-large effects for A within the tested range. These findings are consistent with the geopolymer reaction mechanism: (i) an increase in D initially reduces viscosity through ionic dispersion, but at higher levels accelerates polycondensation, thereby decreasing flow; and (ii) an increase in G (rich in CaO) accelerates the formation of hybrid C-A-S-H/N-A-S-H gels (Davidovits, 1991), which promotes stiffening and suppresses workability. Thus, while practical effects are present, they were not detected as statistically significant due to limited statistical power.

Although the ANOVA did not reveal statistically significant effects at $\alpha = 0.05$, the estimated effect sizes indicate a substantial practical contribution of activator composition ($\eta^2p \approx 0.54$; $f \approx 1.08$) and GGBFS content ($\eta^2p \approx 0.62$; $f \approx 1.28$) to workability. These large effects are consistent with geopolymerization theory, in which the accelerated gelation of C-A-S-H/N-A-S-H in mixes with higher GGBFS and/or activator dosage reduces flow.

For setting time, the non-parallel trends among mixes (e.g., the notably longer final setting of GF-8) suggest the presence of compositional interaction, although this was not statistically confirmed due to limited statistical power. Given the very low error degrees of freedom ($df = 2$) and the absence of replication for each combination, the risk of a Type II error is high. Therefore, we report effect sizes and recommend follow-up experiments with adequate replication and a full factorial design to confirm potential D×G interaction effects.

3.3. Limitations and Recommendations for Future Research

While this study provides valuable insights into the effects of activator/binder ratio, GGBFS content, and aggregate/binder ratio on the fresh properties of geopolymer mortar, several limitations should be acknowledged when interpreting the findings. First, the number of tested samples was relatively limited, meaning the range of parameter variations did not fully represent the potential spectrum of mix combinations. Second, all tests were conducted under ambient curing conditions without the application of hot-curing methods, which may influence the rate of geopolymerization and setting time behavior—particularly in fly ash-based mixes. Third, environmental factors such as relative humidity and daily temperature fluctuations were not monitored, which could impact performance outcomes, especially under tropical field conditions.

Based on these limitations, future research is recommended to:

Expand the sample size and parameter variations to enable more robust statistical analysis, including a more comprehensive study of factor interactions. Compare mix performance under different curing conditions—both ambient and elevated temperature—to identify optimal thermal responses. Conduct field trials in various climatic conditions to validate the applicability of the identified optimal setting time range. Lastly, incorporate mechanical and long-term durability assessments to ensure the results are relevant for real-world structural applications.

4. Conclusion

This study investigated the fresh properties of geopolymer mortar with varied activator/binder ratio (D), GGBFS content (G), and aggregate/binder ratio (A). For workability, geopolymer mixes consistently showed flow table values between 12.2 and 15.0, comparable to pure fly ash mortar (12.5), but lower than Portland Composite Cement (18.0). Statistical analysis (ANOVA) indicated no single factor (D, G, or A) had a statistically significant influence on workability within the tested ranges.

Regarding setting time, geopolymer mortars generally set faster than PCC, though pure fly ash showed a notably rapid initial set. While individual factors were not statistically significant from ANOVA, qualitative trends emerged: higher D ratios tended to prolong setting. GGBFS content (G) appeared qualitatively as the most influential factor, yet its effect was inconsistent, particularly at 20% GGBFS, suggesting strong interactions with other variables. An optimal aggregate ratio of $A = 2.5$ yielded faster and more consistent setting. The research highlighted the critical role of factor interactions, as seen in mixture GF-8 (D40–G20–A2.25), which exhibited an exceptionally long final setting time of 160 minutes. This emphasizes complex synergistic or antagonistic effects among parameters, which cannot be fully explained by individual factor analyses alone.

For practical applications requiring moderate setting times (60–80 minutes), optimal mix ranges were identified: $D = 30\text{--}35$, $G = 10\text{--}30\%$, and $A = 2.5$. This setting time window offers significant advantages for real-world use in tropical climates or situations without hot-curing facilities. In hot and humid environments, overly rapid setting can hinder workability, limit placement time, and increase the risk of cold joints, while excessively delayed setting can expose fresh mortar to early-stage moisture loss, surface cracking, or contamination. A controlled 60–80 minute window provides sufficient handling and placement time for field crews, facilitates better compaction and finishing, and ensures that initial strength development is not compromised. This balance is particularly valuable for on-site casting, repair works, and prefabrication in remote locations where controlled curing environments are unavailable.

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