

Investigating the Impact of Fly Ash Replacement with Portland Cement on Porosity, Water Absorption, and Compressive Strength of Geopolymer Mortars in a Tidal Acid Environment

Ratni Nurwidayati

Civil Engineering Program, Engineering Faculty, Lambung Mangkurat University, Indonesia
ratninurwidayat@ulm.ac.id (corresponding author)

Ninis Hadi Haryanti

Physics Program, Mathematics, and Natural Sciences Faculty, Lambung Mangkurat University, Indonesia
ninishadiharyanti@ulm.ac.id

Nursiah Chairunnisa

Civil Engineering Program, Engineering Faculty, Universitas Lambung Mangkurat, Indonesia
nursiah.chairunnisa@ulm.ac.id

Ade Yuniati Pratiwi

Civil Engineering Program, Engineering Faculty, Universitas Lambung Mangkurat, Indonesia
ade.pratiwi@ulm.ac.id

Wiku Adhiwicaksana Krasna

Civil Engineering Program, Engineering Faculty, Universitas Lambung Mangkurat, Indonesia
wakrasna@ulm.ac.id

Nadia Rahmadania

Civil Engineering Program, Engineering Faculty, Universitas Lambung Mangkurat, Indonesia
nadiarahmadania5@gmail.com

Received: 27 July 2025 | Revised: 1 September 2025 | Accepted: 15 September 2025

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.13667>

ABSTRACT

This study examines how Portland cement affects the physical and mechanical properties of geopolymer mortar when exposed to tidal water after 28 days of curing, when used instead of fly ash. Geopolymer, an alternative to concrete, utilizes waste materials to replace Portland cement. However, it has a relatively slow setting time. This study evaluated the influence of varying levels of Portland cement replacement on the setting time, water absorption, porosity, sorptivity, and compressive strength by replacing fly ash with Portland cement at levels of 0%, 5%, 7%, and 10%. The specimens were cured for 24 h at 100 °C after molding. After 28 days, the specimens were exposed to an artificial acidic environment with a pH of 3 for one month. The results showed that replacing fly ash with Portland cement reduced the initial and final setting times. The water absorption, porosity, and sorptivity increased as the percentage of Portland cement replacement rose, while the compressive strength of the geopolymer mortar improved with 7% and 10% Portland cement replacements.

Keywords-acid; geopolymer; porosity; sorptivity; tidal

I. INTRODUCTION

The process of manufacturing cement requires large amounts of energy and emits carbon dioxide (CO₂) into the atmosphere. So it is important that some alternatives be considered in order to reduce the former's effects on the environment. Blended cement, which includes materials like fly ash, ground granulated blast furnace slag, silica fume, and geopolymer concrete, known as "green concrete" because it does not contain cement, are some of them. Alsaman *et al.* [1] evaluated the energy and CO₂ emissions of geopolymer and normal concrete, showing that Portland cement plays a significant role in the energy consumption and emissions associated with traditional concrete, accounting for 80% of the energy usage and 91% of the emissions. Geopolymer concrete with a compressive strength of 40 MPa achieves a 46% reduction in the energy use and a 73% decrease in the CO₂ emissions compared to normal concrete. Geopolymers are produced without a mixed design formula due to their strong dependence on raw materials, which makes controlling their characteristics challenging [2]. The setting time of geopolymer paste is an important parameter because it affects the mixing and casting processes [3]. Understanding the factors that influence the setting time of geopolymers is essential for controlling the setting duration and achieving the desired timeframe [4]. Some experts assert that geopolymer paste sets quickly [5], whereas others contend that it sets slowly and may not set within a day [6]. To improve this condition, numerous experiments have been conducted, including the addition of Portland cement, citric acid, superplasticizers, sucrose, borax, and calcium chloride [7-11]. Assi *et al.* [12] evaluated the effect of sucrose on improving the initial and final setting times and concluded that sucrose delays setting by raising the viscosity, which postpones the beginning of geopolymerization. Sucrose prevented fly ash particles from entering the alkaline solution, which slowed the process and together with calcium, slowed the setting process, by thickening the fluid. The absorption of precipitated minerals onto fly ash particles slowed geopolymerization, reducing the geopolymer's mechanical properties [10]. Zhang *et al.* [13] used a composite of fly ash and Ground Granulated Blast-furnace Slag (GGBS). The impact of adding the admixture depends on the type of solid activator and the proportion used [9]. Shaaban *et al.* [14] examined the setting time of rice husk ash blended with calcined dolomite powder, suggesting that an increased proportion of rice husk ash prolongs the setting time due to the slower pozzolanic reaction associated with rice husk ash. Nath and Sarker [11] found that using 5% Portland cement reduced the setting time of geopolymer in an ambient environment. They concluded that the optimal mixture was achieved by replacing 5% of the total binder with Portland cement and maintaining a liquid-to-binder ratio of 0.4. Calcium sources were found to significantly shorten the setting time and enhance the mechanical properties [15]. Kaja *et al.* [16] explored the effect of Portland cement on the alterations in the geopolymerization process. They proposed replacing 5%-7% of the fly ash with cement to achieve early-age compressive strength. Mehta and Siddique [17] replaced up to 30% of the fly ash with Portland cement and the compressive strength increased as the percentage of fly ash replaced by Portland

cement increased, reaching an optimum replacement at 20%. The durability of concrete in harsh environments is a serious concern, because calcium hydroxide (Ca(OH)₂) and calcium silicate hydrates (C-S-H) react in acidic conditions, resulting in damage to the concrete. Deterioration may arise from the numerous chemical reactions between the aggressive environment and the concrete's calcium-containing constituents. Using geopolymers in structural applications, particularly in acidic environments, requires an evaluation of their durability. Authors in [18-21] demonstrated that geopolymer is more resistant to acidic environments than traditional concrete. The periodic change in the river water levels or tides, resulting in the concrete's intermittent submersion, diminishes its strength [22-24]. However, little is known about the impact of tidal cycles in a corrosive, acidic environment on geopolymers that incorporate fly ash as a substitute for Portland cement. While previous studies have examined the effects of Portland cement on setting time, strength development, and general acid resistance of geopolymers, they have not thoroughly investigated how replacing fly ash with Portland cement affects the fresh and durability properties under tidal acidic conditions. In particular, the combined influence of incremental cement replacement on porosity, absorption, and strength when subjected to wet-dry cycles in acidic environments has not been sufficiently addressed. The present study examined the durability of a low-calcium, fly ash-based geopolymer mortar in an acidic environment under temperature-controlled conditions. The artificial acidic environment consisted of hydrochloric acid with a pH of 3. Portland cement was substituted partially for fly ash at percentages of 0%, 5%, 7%, 10%, and 15%, and activated using solutions of sodium silicate and hydroxide. The setting time, compressive strength, and permeation parameters—including water absorption, porosity, and sorptivity—were studied, while the compressive strength was evaluated before and after one month of immersion in an acid solution.

II. EXPERIMENTAL PROGRAM

A. Materials

The fine aggregate was obtained from the nearest local quarry, exhibiting a fineness modulus of 2.13. Its water content, absorption, weight, and volume were measured at 2.4%, 2.46%, 1.47 g/cm³, and 2.68, respectively. The fly ash was sieved through a 200-mesh sieve with a 45- μ m aperture to comply with ASTM C618 regarding the pozzolanic grain fineness percentage. The specification states that no more than 34% should be retained on sieve no. 325, which has a 75- μ m aperture. The fly ash used in this study came from the Asam-Asam coal-fired power plant in South Kalimantan, Indonesia, where 9.4% was retained on sieve no. 325, thereby fulfilling the ASTM C618 criteria. The specific gravity of the fly ash was measured at 3.05, and its volume weight was recorded at 1.18 g/cm³, as presented in Table I. According to the XRF results, the fly ash is class F, as the amounts of SiO₂, Al₂O₃, and Fe₂O₃ equaled 86.29. The alkaline solution used was a blended mixture of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) at a ratio of 2.5:1. Sulfuric acid (H₂SO₄) and

hydrochloric acid (HCl) solutions were used to create two artificial acidic environments.

TABLE I. FLY ASH CHEMICAL CONTENT

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO ₂	TiO ₂	P ₂ O ₅	SO ₃
%	48.86	11.29	26.14	6.74	4.46	0.11	0.43	0.36	0.78	0.05	0.34

B. Mix Proportion and Procedure

The proportional relationship among the constituent materials determined the formulation of geopolymer mortar. The present study used an alkaline solution, maintaining a ratio of Na₂SiO₃ to 8M NaOH at 2.5. The geopolymer paste was synthesized using a weight ratio of fly ash to an alkaline solution of 60:40. Geopolymer mortar was composed of fine aggregate and geopolymer paste, with a formulation of 65% and 35%, respectively, as shown in Table II. The following Geopolymer Pastes (GP) were used in the study: GP-0, GP-5, GP-7, GP-10, and GP-15, where the percentage of fly ash replacement with Portland cement was 0%, 5%, 7%, 10%, and 15%, respectively.

TABLE II. MIXTURE PROPORTIONS OF THE GEOPOLYMER MORTAR

Mixture	Fine aggregate (kg)	Portland cement (kg)	Fly ash (kg)	Na ₂ SiO ₃ (kg)	8M NaOH solution (kg)
GP-0	6.4	0	2.06	0.39	0.984
GP-5	6.4	0.10	1.96	0.39	0.984
GP-7	6.4	0.14	1.92	0.39	0.984
GP-10	6.4	0.21	1.86	0.39	0.984
GP-15	6.4	0.31	1.75	0.39	0.984

8M NaOH was prepared by dissolving 320 grams of NaOH flakes in 1 L of solution. This solution generates heat; consequently, it must be prepared one day before manufacturing the specimens. An 8M NaOH solution was combined with Na₂SiO₃ following the prescribed dosage and the fly ash and alkali solution were poured into the mixer. Subsequent to thorough stirring, the addition of fine aggregate continued until the mixture attained homogeneity and then it was molded. After the molding process, the test object was placed in an oven set at a temperature of 100 °C for a period of 12 h and then, the material was left at room temperature until the compressive strength test limit at 28 days was attained. The curing regime at 100 °C for 12 h was determined through preliminary experiments conducted in the laboratory prior to this study, which showed that this condition facilitated expeditious geopolymerization, thereby inducing robust early strength development while impeding microcracking, a phenomenon that has been observed to occur under protracted or more rigorous curing regimens. An artificial acid solution was prepared by combining H₂SO₄ and HCl until the resulting acidic water achieved a pH of 3. This pH level was selected to represent a common acid concentration observed in natural acidic environments. The usage of H₂SO₄ and HCl as probes enabled the modeling of two distinct acidic conditions: H₂SO₄ is classified as a stronger, more aggressive acid, while HCl is considered a lighter, less aggressive acid. To ensure the stability of the artificial acidic water within a designated pH range, daily pH monitoring was conducted over a 24-h period.

In instances where an increase in pH was observed, the introduction of either H₂SO₄ or HCl solution was imperative to restore the pH of the sulfuric acid water to a range of 3. The compressive strength test was conducted using cylinders with a diameter of 26 mm and a height of 52 mm. The decision to employ a diminutive cylinder size was based on the material efficiency and ease of handling. It is important to note that the adopted dimensions maintain the standard height-to-diameter ratio of 2:1, which is essential for the validity of the compressive strength testing. Testing was performed at 28 days to determine the controlled compressive strength prior to the exposure to an acid environment. Subsequent to a 28-day period, the test specimen was placed in an acidic environment with a pH of 3. The compressive strength test was conducted after one month of the test specimen being immersed in an acid solution. Two acid solutions were used in this research. The test specimen was submerged for seven days, then retrieved and maintained at ambient temperature for an additional seven days before being re-immersed, thereby simulating wet-dry tidal conditions. This cycle was repeated for a total of four weeks, resulting in two complete wet-dry cycles. The test specimen remained submerged in the acid solution until the designated test duration was complete. Currently, there is no ASTM standard that covers geopolymer paste, mortar, or concrete. Consequently, certain tests employ ASTM standards that are designated for cement paste, cement mortar, and conventional concrete. The evaluation of geopolymer mortar's absorption and porosity was conducted through the use of ASTM C 642-06 [25], a standard test method for assessing the properties of geopolymer mortars. The ASTM C1585-13 [26] protocol was applied to facilitate the sorptivity testing. The experiment used a cylinder with a diameter of 10 cm and a height of 5 cm. The evaluation was conducted at the 28-day mark.

III. RESULTS AND DISCUSSION

A. Setting Time

The ASTM C191-08 [27] was used to execute the setting time evaluation. The initial setting was achieved when the Vicat needle penetrates to a depth of 25 mm, whereas the final setting occurs if the needle does not leave an imprint on the test specimen or if the penetration measurement is 0 mm. Figure 1 presents the initial and final settings in comparison, with the total setting time exhibiting a range of variation, with a minimum of 207 min and a maximum of 1,260 min recorded. The initial and final settings of the geopolymer paste were 360 min and 900 min, respectively. For Portland cement replacements of 0%, 5%, 7%, 10%, and 15%, the initial settings were 360 min, 105 min, 74 min, 60 min, and 42 min, respectively, and the final settings were 900 min, 255 min, 210 min, 150 min, and 165 min, respectively. Subsequent to the initial setting, 0%, 5%, 7%, 10%, and 15% PCC replacements required 540 min, 150 min, 136 min, 90 min, and 123 min to achieve the final setting time, respectively.

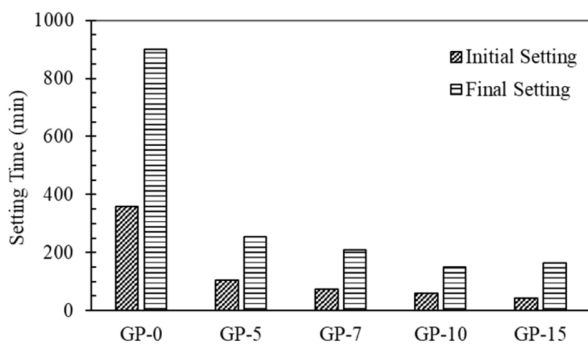


Fig. 1. Setting time of the geopolymer paste of blended fly ash and Portland cement.

The higher the percentage of PCC is, the shorter is the period between the initial and final settings. With the exception of 15%, it required 123 min to arrive at the final setting from the initial, longer than 10% PCC and shorter than 7% PCC. This result shows that substituting fly ash with PCC accelerates the setting time of geopolymer paste. It appears that the higher the proportion of replacement is, the shorter is the period necessary to set both the initial and final settings. This advantage can be attributed to the reduced chemical reaction rate of the geopolymer paste synthesized with fly ash precursors. The dissolution of raw materials was accelerated, and the compound solidified more rapidly due to the incorporation of calcium [28]. The increased formation of amorphous C-S-H gel leads to a shorter setting time [29]. This result aligns with the findings of [30-32]. The role of the calcium content within the system, which enhances the setting of the geopolymer paste, can be derived not solely from Portland cement, but also from GGBS, calcium hydroxide ($\text{Ca}(\text{OH})_2$), calcium oxide (CaO), or high-calcium fly ash [33, 34]. The compaction process demonstrated a substantial enhancement when the geopolymer paste was integrated with Portland cement in comparison with the geopolymer paste used in isolation. This enhancement was attributed to the rapid chemical reaction between calcium in Portland cement and an alkaline solution, accelerating the setting and hardening process [31]. Furthermore, the elevated temperature curing and heightened NaOH molarity expedite the setting time of geopolymer paste, in addition to increasing the calcium content in its base material [29, 35]. The initial setting for the GP-15 was 42 min, with a final setting time of 165 min. The adoption of ASTM C191 [27] on the cement paste setting time indicates that the initial setting time must be a minimum of 45 min, while the final setting time must not exceed 375 min. Consequently, the GP-15 mixture was not subjected to further evaluation. It has been demonstrated that approximately 5-10% of Portland cement replacement in geopolymers can yield a setting time that is analogous to that of Portland cement [31].

B. Absorption and Porosity

The absorption and porosity of the specimens were measured at 28 days of curing, prior to their exposure to the acid environment. Figure 2 presents the absorption and porosity of the three geopolymer mixtures (GP-5, GP-7, and GP-10) at 28 days of curing. The specimens with 5% Portland cement (GP-5) demonstrate the lowest absorption and porosity

compared to those with a higher Portland cement content, such as GP-7 and GP-10. The absorption and porosity values for GP-5 were recorded at approximately 6.07% and 16.43%, respectively. As the percentage of Portland cement increased, both the absorption and porosity in the geopolymer mortar also increased. The GP-10 specimen demonstrated the highest values for both properties, with the absorption recorded at 6.54% and porosity at 20.06%. These results indicate that the addition of Portland cement contributes to the formation of a more porous structure in geopolymer mortar. The observed increase in porosity with higher Portland cement content suggests that more pore cavities develop as the cement content rises, leading to increased absorption and porosity. Saif *et al.* [32] documented analogous trends in geopolymer systems comprising varying cement contents. The enhanced absorption and porosity can be ascribed to the elevated presence of calcium-rich phases in Portland cement, which may exert an influence on the microstructure and pore formation within the geopolymer matrix.

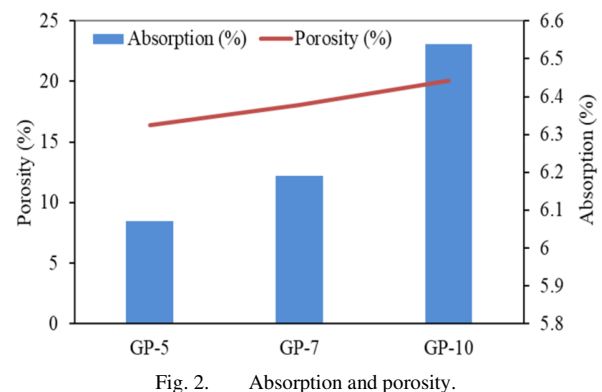


Fig. 2. Absorption and porosity.

C. Sorptivity

Figure 3 presents the initial and final absorption rates of the geopolymer mortar, with fly ash partially replaced by Portland cement. The sorptivity on the initial absorption is indeterminate due to a correlation coefficient of less than 0.98, as determined by ASTM C 1585 [26]. In comparison, the sorptivity on the secondary absorption was $1.0 \text{ mm/sec}^{1/2}$, $1.4 \text{ mm/sec}^{1/2}$, and $1.5 \text{ mm/sec}^{1/2}$, respectively, for Portland cement 5%, 7%, and 10%. The specimens with 5% cement content demonstrated the lowest absorption levels in comparison to those with 7% and 10% cement content. The findings of this study indicated that the absorption performance of geopolymer mortar using fly ash is contingent upon the cement content. Mehta and Siddique [17] partially replaced fly ash with 20% Portland cement, and Chotetanorm *et al.* [36] used bottom ash as a raw material for geopolymer mortar. Increasing the replacement of fly ash with Portland cement results in greater absorption due to elevated porosity, as indicated by a higher sorptivity [36].

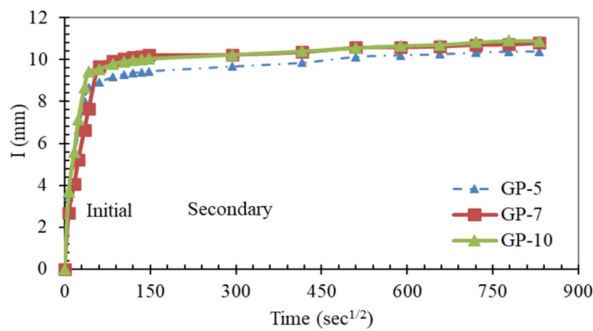


Fig. 3. Effect of fly ash replacement with Portland cement on sorptivity.

D. Compressive Strength

Figure 4 shows the alterations in the compressive strength prior to and following one month of exposure to tidal acidic environments. The control compressive strength is defined as the strength at 28 days of age, with no exposure to an acidic environment of HCl and H₂SO₄. The wet condition in the graph indicates that the test object was continuously immersed in acidic water, whereas WD refers to wet and dry cycles, where the test object was soaked for seven days, followed by seven days at room temperature. At the 28-day mark, the compressive strength exhibited a range of 10.09 MPa-10.79 MPa, with GP-10 demonstrating the lowest value and GP-5 showing the highest. Despite the modest magnitude of the observed variations, a discernible trend emerged, indicating a decline in the compressive strength as the proportion of Portland cement increased. This finding aligns with the observed trends in absorption, porosity, and sorptivity, which exhibited an upward trajectory with increasing the Portland cement content. A comparative analysis of the microstructures of GP-5, GP-7, and GP-10 revealed that GP-5 exhibited a denser microstructure compared to GP-7 and GP-10. An increased quantity of pores in geopolymer mortar is associated with a decline in the compressive strength. This inverse relationship between the porosity and compressive strength is in agreement with the findings of [16], where it was stated that an elevated cement content in alkali-activated fly ash binder enhances the transport properties while concurrently diminishing the gel formation. Conversely, Yip *et al.* [37] advanced the hypothesis that the decline in the compressive strength is attributable to the alterations in the Si/Al ratio.

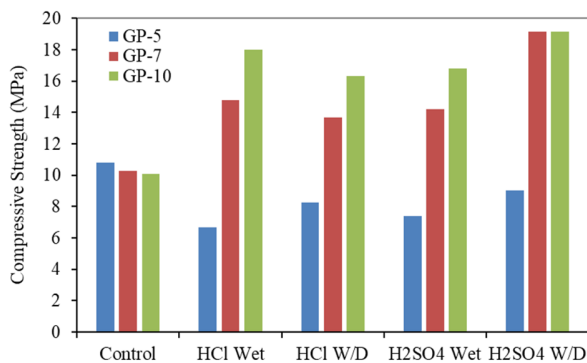


Fig. 4. The compressive strength of mortar post-exposure to an acidic environment.

As a result of the exposure to an acidic environment, a decline in the compressive strength of geopolymer mortar was observed in GP-5. The reduction in compressive strength of the test specimens subjected to wet-dry cycles was less significant than that of the specimens continuously immersed in acidic environments. The reduction in compressive strength during the wet-dry cycle was 16% in HCl solution and 23% in H₂SO₄ solution, respectively. Conversely, the values recorded in the continuously submerged condition were 38% and 31%, respectively. It appeared that the continuous exposure to an acidic environment was more detrimental than alternating between wet and dry cycles. In contrast, GP-7 and GP-10 exhibited an intriguing contrasting trend, marked by an enhancement in the compressive strength when exposed to an acidic environment. The GP-7 specimen demonstrated compressive strengths of 14.80 MPa and 13.69 MPa when subjected to HCl solution under continuous immersion and wet-dry cycles, respectively. The compressive strengths in H₂SO₄ solution were measured at 14.2 MPa and 19.15 MPa, respectively. The data indicate an increase in the compressive strength ranging from 33% to 86% in comparison with the strength evaluated at 28 days. In a similar manner, GP-10 specimens exhibited compressive strengths of 18.02 MPa and 16.34 MPa when subjected to continuous immersion in HCl solution and wet-dry cycles, respectively, as well as 16.80 MPa and 19.15 MPa in H₂SO₄ solution. A comparison of the compressive strength values measured after 28 days revealed an increase ranging from 33% to 86%. Following the exposure to the acidic environment, GP-5 exhibited a reduction in the compressive strength. Conversely, GP-7 and GP-10 demonstrated a significant increase in the latter. This discrepancy can be attributed to the elevated calcium content observed in the 7% and 10% Portland cement replacement samples. The presence of these replacement materials has been shown to influence the formation of ettringite and calcium-silicate-hydrate phases, resulting in the observed variation in the mechanical properties of the samples. The penetration of acidic solutions into the pore system resulted in increased ettringite precipitation, due to the presence of additional calcium. In the short term, these products occupied micro voids, resulting in a denser and less porous matrix with an enhanced load-bearing capacity. Xie *et al.* [38] observed that ettringite initially refined the microstructure and enhanced the compressive strength, although the excessive formation eventually caused deterioration. This mechanism explains the unusual strength gain of GP-7 and GP-10 compared with GP-5, where the lower calcium content limited the development of such secondary products.

IV. CONCLUSIONS

The present study shows that partially replacing fly ash with Portland cement has a substantial impact on the fresh and durability properties of geopolymer mortar. The proportion of Portland cement was increased, resulting in a reduction of both the initial and final setting times. This finding serves to confirm the accelerating role of calcium in the geopolymerization process. The addition of higher Portland cement contents to the specimens resulted in increased absorption, porosity, and sorptivity. However, the specimens with 5% replacement exhibited a denser microstructure and higher compressive

strength after 28 days of hydration. Conversely, under conditions of acidic tidal exposure, a contrasting trend was noted. The compressive strength of GP-5 decreased, while GP-7 and GP-10 exhibited significant strength gains. This enhancement is attributed to the formation of secondary products, including ettringite and calcium-silicate-hydrate phases, which have been observed to fill the pore spaces and temporarily densify the matrix. These findings underscore the efficacy of moderate Portland cement replacement (7%–10%) in enhancing the setting behavior of geopolymer mortar and its resistance to acidic environments. This makes geopolymer mortar a viable option for structures exposed to harsh tidal conditions.

ACKNOWLEDGMENT

The authors would like to thank the Institute of Research and Community Service, Lambung Mangkurat University, for the Grand Research with contract number 1374.92/UN8.2/PG/2024. The authors also extend their gratitude to the Structures and Materials Laboratory of Civil Engineering Faculty, Lambung Mangkurat University, as well as to the instructors and students who contributed to the completion of this research.

REFERENCES

- [1] A. Alsalmán, L. N. Assi, R. S. Kareem, K. Carter, and P. Ziehl, "Energy and CO₂ emission assessments of alkali-activated concrete and Ordinary Portland Cement concrete: A comparative analysis of different grades of concrete," *Cleaner Environmental Systems*, vol. 3, Dec. 2021, Art. no. 100047, <https://doi.org/10.1016/j.cesys.2021.100047>.
- [2] R. Nurwidayati, M. B. Ulum, J. J. Ekaputri, T. Triwulan, and P. Suprobo, "Characterization of Fly Ash on Geopolymer Paste," *Materials Science Forum*, vol. 841, pp. 118–125, 2016, <https://doi.org/10.4028/www.scientific.net/MSF.841.118>.
- [3] X. Dai, S. Aydin, M. Y. Yardimci, and G. De Schutter, "Early structural build-up, setting behavior, reaction kinetics and microstructure of sodium silicate-activated slag mixtures with different retarder chemicals," *Cement and Concrete Research*, vol. 159, Sept. 2022, Art. no. 106872, <https://doi.org/10.1016/j.cemconres.2022.106872>.
- [4] Y. Alrefaei, Y.-S. Wang, and J.-G. Dai, "The effectiveness of different superplasticizers in ambient cured one-part alkali activated pastes," *Cement and Concrete Composites*, vol. 97, pp. 166–174, Mar. 2019, <https://doi.org/10.1016/j.cemconcomp.2018.12.027>.
- [5] P. Kamhangritirong, P. Suwanvitaya, and P. Chindaprasirt, "Synthesis and Properties of High Calcium Fly Ash Based Geopolymer for Concrete Applications," in *36th Conference on Our World in Concrete & Structures*, Singapore, 2011.
- [6] P. Nath, P. K. Sarker, and V. B. Rangan, "Early Age Properties of Low-calcium Fly Ash Geopolymer Concrete Suitable for Ambient Curing," *Procedia Engineering*, vol. 125, pp. 601–607, Jan. 2015, <https://doi.org/10.1016/j.proeng.2015.11.077>.
- [7] Y. Zhang, J. Yang, and X. Cao, "Effects of several retarders on setting time and strength of building gypsum," *Construction and Building Materials*, vol. 240, Apr. 2020, Art. no. 117927, <https://doi.org/10.1016/j.conbuildmat.2019.117927>.
- [8] A. Kusbiantoro, M. S. Ibrahim, K. Muthusamy, and A. Alias, "Development of Sucrose and Citric Acid as the Natural based Admixture for Fly Ash based Geopolymer," *Procedia Environmental Sciences*, vol. 17, pp. 596–602, Jan. 2013, <https://doi.org/10.1016/j.proenv.2013.02.075>.
- [9] S. H. Bong, B. Nematollahi, A. Nazari, M. Xia, and J. Sanjayan, "Efficiency of Different Superplasticizers and Retarders on Properties of 'One-Part' Fly Ash-Slag Blended Geopolymers with Different Activators," *Materials*, vol. 12, no. 20, Jan. 2019, Art. no. 3410, <https://doi.org/10.3390/ma12203410>.
- [10] U. Rattanasak, K. Pankhet, and P. Chindaprasirt, "Effect of chemical admixtures on properties of high-calcium fly ash geopolymer," *International Journal of Minerals, Metallurgy, and Materials*, vol. 18, no. 3, pp. 364–369, June 2011, <https://doi.org/10.1007/s12613-011-0448-3>.
- [11] P. Nath and P. K. Sarker, "Use of OPC to improve setting and early strength properties of low calcium fly ash geopolymer concrete cured at room temperature," *Cement and Concrete Composites*, vol. 55, pp. 205–214, Jan. 2015, <https://doi.org/10.1016/j.cemconcomp.2014.08.008>.
- [12] L. N. Assi, E. Deaver, and P. Ziehl, "Using sucrose for improvement of initial and final setting times of silica fume-based activating solution of fly ash geopolymer concrete," *Construction and Building Materials*, vol. 191, pp. 47–55, Dec. 2018, <https://doi.org/10.1016/j.conbuildmat.2018.09.199>.
- [13] Y. Zhang, W. Liu, and M. Liu, "Setting time and mechanical properties of chemical admixtures modified FA/GGBS-based engineered geopolymer composites," *Construction and Building Materials*, vol. 431, p. 136473, June 2024, <https://doi.org/10.1016/j.conbuildmat.2024.136473>.
- [14] M. Shaaban, O. F. Hussien, and S. Khalifa, "Characteristics and Microstructure of Geopolymer Mortars incorporating Ground Granulated Blast Furnace Slag and Calcined Dolomite Powder: A Sustainable Solution for Construction Materials," *Engineering, Technology & Applied Science Research*, vol. 15, no. 2, pp. 21791–21799, Apr. 2025, <https://doi.org/10.48084/etasr.10095>.
- [15] M. Askarian, Z. Tao, G. Adam, and B. Samali, "Mechanical properties of ambient cured one-part hybrid OPC-geopolymer concrete," *Construction and Building Materials*, vol. 186, pp. 330–337, Oct. 2018, <https://doi.org/10.1016/j.conbuildmat.2018.07.160>.
- [16] A. M. Kaja, A. Lazaro, and Q. L. Yu, "Effects of Portland cement on activation mechanism of class F fly ash geopolymer cured under ambient conditions," *Construction and Building Materials*, vol. 189, pp. 1113–1123, Nov. 2018, <https://doi.org/10.1016/j.conbuildmat.2018.09.065>.
- [17] A. Mehta and R. Siddique, "Properties of low-calcium fly ash based geopolymer concrete incorporating OPC as partial replacement of fly ash," *Construction and Building Materials*, vol. 150, pp. 792–807, Sept. 2017, <https://doi.org/10.1016/j.conbuildmat.2017.06.067>.
- [18] F. N. Okoye, S. Prakash, and N. B. Singh, "Durability of fly ash based geopolymer concrete in the presence of silica fume," *Journal of Cleaner Production*, vol. 149, pp. 1062–1067, Apr. 2017, <https://doi.org/10.1016/j.jclepro.2017.02.176>.
- [19] M. A. M. Ariffin, M. A. R. Bhutta, M. W. Hussin, M. Mohd Tahir, and N. Aziah, "Sulfuric acid resistance of blended ash geopolymer concrete," *Construction and Building Materials*, vol. 43, pp. 80–86, June 2013, <https://doi.org/10.1016/j.conbuildmat.2013.01.018>.
- [20] V. Sata, A. Sathonsaowaphak, and P. Chindaprasirt, "Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack," *Cement and Concrete Composites*, vol. 34, no. 5, pp. 700–708, May 2012, <https://doi.org/10.1016/j.cemconcomp.2012.01.010>.
- [21] S. Thokchom, P. Ghosh, and S. Ghosh, "Resistance of Fly Ash Based Geopolymer Mortars in Sulfuric Acid," *ARPN Journal of Engineering and Applied Sciences*, vol. 4, no. 1, pp. 65–70, Feb. 2009.
- [22] I. T. Wicaksono and R. Nurwidayati, "The Effect of pH Water on the Concrete Mixtures and Curing Condition on the Compressive Strength of Concrete," *IOP Conference Series: Earth and Environmental Science*, vol. 999, no. 1, Nov. 2022, Art. no. 012006, <https://doi.org/10.1088/1755-1315/999/1/012006>.
- [23] L. Jiang and D. Niu, "Study of deterioration of concrete exposed to different types of sulfate solutions under drying-wetting cycles," *Construction and Building Materials*, vol. 117, pp. 88–98, Aug. 2016, <https://doi.org/10.1016/j.conbuildmat.2016.04.094>.
- [24] *C618-02 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete*. West Conshohocken, PA, USA: ASTM International, 2010.
- [25] *C642-21 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*. West Conshohocken, PA, USA: ASTM International, 2006.

- [26] *C1585-20 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes*. West Conshohocken, PA, USA: ASTM International, 2013.
- [27] *C191-21 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*. West Conshohocken, PA, USA: ASTM International, 2008.
- [28] W. Huo, Z. Zhu, J. Zhang, Z. Kang, S. Pu, and Y. Wan, "Utilization of OPC and FA to enhance reclaimed lime-fly ash macadam based geopolymers cured at ambient temperature," *Construction and Building Materials*, vol. 303, Oct. 2021, Art. no. 124378, <https://doi.org/10.1016/j.conbuildmat.2021.124378>.
- [29] H. E. Elyamany, A. E. M. Abd Elmoaty, and A. M. Elshaboury, "Setting time and 7-day strength of geopolymer mortar with various binders," *Construction and Building Materials*, vol. 187, pp. 974–983, Oct. 2018, <https://doi.org/10.1016/j.conbuildmat.2018.08.025>.
- [30] T. Phoo-ngernkham, P. Chindaprasirt, V. Sata, S. Pangdaeng, and T. Sinsiri, "Properties of high calcium fly ash geopolymer pastes with Portland cement as an additive," *International Journal of Minerals, Metallurgy, and Materials*, vol. 20, no. 2, pp. 214–220, Feb. 2013, <https://doi.org/10.1007/s12613-013-0715-6>.
- [31] T. Suwan and M. Fan, "Influence of OPC replacement and manufacturing procedures on the properties of self-cured geopolymer," *Construction and Building Materials*, vol. 73, pp. 551–561, Dec. 2014, <https://doi.org/10.1016/j.conbuildmat.2014.09.065>.
- [32] M. S. Saif, M. O. R. El-Hariri, A. I. Sarie-Eldin, B. A. Tayeh, and M. F. Farag, "Impact of Ca+ content and curing condition on durability performance of metakaolin-based geopolymer mortars," *Case Studies in Construction Materials*, vol. 16, June 2022, Art. no. e00922, <https://doi.org/10.1016/j.cscm.2022.e00922>.
- [33] P. Nath and P. K. Sarker, "Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," *Construction and Building Materials*, vol. 66, pp. 163–171, Sept. 2014, <https://doi.org/10.1016/j.conbuildmat.2014.05.080>.
- [34] S. Yaseri, V. Masoomi Verki, and M. Mahdikhani, "Utilization of high volume cement kiln dust and rice husk ash in the production of sustainable geopolymer," *Journal of Cleaner Production*, vol. 230, pp. 592–602, Sept. 2019, <https://doi.org/10.1016/j.jclepro.2019.05.056>.
- [35] D. Hardjito, C. Cheak, and C. L. Ing, "Strength and Setting Times of Low Calcium Fly Ash-based Geopolymer Mortar," *Modern Applied Science*, vol. 2, no. 4, July 2008, Art. no. p3, <https://doi.org/10.5539/mas.v2n4p3>.
- [36] C. Chotetanorm, P. Chindaprasirt, V. Sata, S. Rukzon, and A. Sathonsaowaphak, "High-Calcium Bottom Ash Geopolymer: Sorptivity, Pore Size, and Resistance to Sodium Sulfate Attack," *Journal of Materials in Civil Engineering*, vol. 25, no. 1, pp. 105–111, Jan. 2013, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000560](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000560).
- [37] C. K. Yip, G. C. Lukey, J. L. Provis, and J. S. J. van Deventer, "Effect of calcium silicate sources on geopolymerisation," *Cement and Concrete Research*, vol. 38, no. 4, pp. 554–564, Apr. 2008, <https://doi.org/10.1016/j.cemconres.2007.11.001>.
- [38] F. Xie, J. Li, G. Zhao, C. Wang, Y. Wang, and P. Zhou, "Experimental investigations on the durability and degradation mechanism of cast-in-situ recycled aggregate concrete under chemical sulfate attack," *Construction and Building Materials*, vol. 297, Aug. 2021, Art. no. 123771, <https://doi.org/10.1016/j.conbuildmat.2021.123771>.