# The Mechanical Properties of Kaolin-Based Geopolymer Concrete with Portland Cement Addition

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**ABSTRACT**

**In this study, Portland cement was added to a mixture to address low early strength challenges in kaolin-based geopolymers. The effects of various curing conditions were examined, including room temperature and elevated temperatures (60°C and 90°C), as well as the influence of Superplasticizer (SP) dosages (0–3%) on compressive and tensile strengths. The results showed that curing at 60°C for 24 hours provided the optimal balance between early and long-term strength development, achieving compressive strengths of 26.7 MPa at 28 days. Although curing at 90°C offered rapid early strength, it resulted in diminished long-term performance due to potential microstructural damage. SP addition improved workability and mechanical properties, with the optimal dosages being identified as 1% for room-temperature curing and 2% for elevated-temperature curing. The findings stress the importance of curing conditions and material composition in achieving high-performance geopolymer concrete. This type of concrete, when cured under controlled elevated temperatures, is suitable for precast applications where thermal curing is feasible, making it a promising eco-friendly alternative for structural elements in sustainable construction.**

***Keywords-elevated temperature curing; geopolymer concrete; kaolin; Portland cement addition; superplasticiser***

# I. INTRODUCTION

Portland cement has been the primary concrete production binder, that is, the most widely employed construction material. However, its increasing use raises environmental concerns, as its production emits large amounts of $CO_2$ into the atmosphere. The cement industry contributes approximately 5–8% of global $CO_2$ emissions [1-2]. About two-thirds of the latter originate from the calcination of limestone, where calcium carbonate is decomposed into calcium oxide and carbon dioxide. The remaining one-third is attributed to fossil fuel combustion during the calcination process [3].

Portland cement extensive utilization also results in greenhouse gas emissions and global warming. Therefore, finding new or alternative materials is important. Many studies have attempted to develop materials as an alternative binder to concrete, expected to either replace or reduce Portland cement employment.

Geopolymer binder [4], for instance, could substitute Portland cement. Various materials rich in silicon and aluminum have been also investigated for geopolymer synthesis. These include both natural and industrial by-product materials, such as kaolin, metakaolin, kaolinite [5], fly ash [6-7], slag [8], silica fume [9], rice husk ash [10], red mud [11], mining wastes [12], Palm Oil Fuel Ash (POFA) [13], natural pozzolan [14], combination of metakaolin and fly ash [15], slag and fly ash [16], fly ash and silica fume [17], rice husk ash and metakaolin [18], rice husk ash and fly ash [19-20], metakaolin and slag [21], slag and silica fume [22], fly ash and POFA [23], red mud and fly ash [24], metakaolin and red mud [25], fly ash, slag, and silica fume [26], rice husk ash, silica fume, and metakaolin [27], POFA, eggshell ash, and silica fume [28], red mud, slag, and silica fume [29], fly ash and ground granulated blast slag [30].

Kaolin, a natural material, can be easily accessed and has various industrial applications. However, due to its crystalline nature and low reactivity, the former is unsuitable for use in cementitious binders, which can be overcome by increasing its reactivity.

A common method to increase the reactivity of non-reactive materials, including kaolin, is through thermal treatment or calcination process to form metakaolin [31]. Thermal treatment can transform the crystalline kaolin to amorphous metakaolin. The former requires high temperature ranges, namely 700 – 850°C, to get the amorphous material [32]. Lower temperature could result in not very active material or metakaolin, while a calcination temperature higher than 850°C or 900°C could lead to material recrystallization, and thus make it less reactive [33]. Regarding the optimal calcination temperature for converting kaolin to metakaolin, no definite value has been identified [5, 34]. This is due to others factors, besides temperature, influencing this thermal or heat treatment to transform kaolin to metakaolin. These factors include the duration of treatment, rate of heating and cooling, temperature, mineral composition, and kaolin particle size [5, 31]. For example, for poor Greek kaolin, the optimal heat treatment temperatures to convert it into highly reactive metakaolin are reported to be 650°C for kaolin with low alunite content and 850°C for kaolin with high alunite content, with a treatment duration of 3 hours [35]. Calcination of high-quality kaolin clay from Serbia [31] shows that the desired result was obtained at a temperature of 650°C for 1.5 hours. Authors in [33], investigated low-grade kaolinitic clay calcined at 500-1000°C for 1 hour, and concluded that calcination at 800°C results in the highest pozzolanic reactivity. Generally, it has been revealed that the optimal calcination temperatures are in the range of 600 – 900°C, with the duration varying from 1 hour to 24 hours, depending on the temperatures [34]. For geopolymers incorporating kaolin or metakaolin, such a range of calcination temperatures was also utilized [36-41].

Another method to improve the reactivity of the source material in paste, mortar, or concrete mixtures is by curing them at elevated temperatures. Like kaolin, fly ash is a low reactivity material, but it is widely employed as a source material for geopolymer. To improve its reactivity including the resulted properties, elevated temperature curing is applied for curing fly ash-based geopolymer, such as that reported in [6, 42, 43].

Ordinary Portland Cement (OPC) has been also deployed in the geopolymer mixture with low reactivity source materials, like fly ash. Authors in [44] studied the properties of high-calcium fly ash geopolymer mortar under different curing conditions. A portion of the fly ash was replaced by OPC at up to 15% by weight of the binder. The results demonstrated that the compressive strength of the geopolymer mortar with membrane cured increased with the increase of OPC replacement. Besides better compressive strength, the OPC replacement also reduced the porosities and water absorption. Authors in [45] examined the properties of geopolymer paste, incorporating fly ash and OPC (GeoPC). It was exhibited that the increase in OPC replacement could enhance the setting time, early strength, and microstructures of GeoPC. Authors in [46] concluded that the use of a small amount of OPC in fly ash based geopolymer concrete cured at ambient conditions could result in acceptable normal strength concrete. Concrete with compressive strength of 40 MPa could be achieved by utilizing 5% OPC in the total binder. OPC presence could also make the geopolymerization faster. Authors in [47] studied replacing low-calcium fly ash with OPC in geopolymer concrete. OPC levels of 0–30% were tested for strength and durability over 365 days. A 20% OPC replacement yielded optimal results, with a compressive strength of 66.81 MPa and improved durability, including reduced porosity and chloride permeability. Higher OPC levels reduced performance due to moisture loss and decreased geopolymer gel. Authors in [48] examined how small additions of OPC (5–10%) affect Class F fly ash geopolymers, cured at ambient temperature. Minimal OPC significantly boosts early strength and accelerates setting by promoting C-S-H and (N,C)-A-S-H gel formation, especially with lower silica modulus (Ms) activators. The optimal OPC content is 5 % for Ms = 1.2 and 7.5 % for Ms =

1.5. However, excess OPC impairs long-term geopolymerization due to silica depletion and gel incompatibility. Thus, limited OPC improves early performance but may reduce long-term strength. Authors in [49] explored how varying OPC content affects metakaolin-based geopolymers. A 5% OPC addition produced optimal results, with 71.1 MPa compressive and 6.75 MPa flexural strength, due to enhanced geopolymerization and C-S-H/N-A-S-H gel formation. However, higher OPC levels (10–30%) reduced strength by limiting water for hydration and disrupting gel networks. Microstructural analysis confirmed structural deterioration at higher OPC. Overall, small OPC additions improve strength and density, but excessive use weakens performance. Authors in [50] evaluated recycled OPC (ROPC) as a supplementary binder in low-calcium fly ash geopolymer mortars under ambient curing. Adding 7.5–10% ROPC, reduced initial setting time from 1095 to 165 min and raised 28-day strength to 66 MPa. While ROPC increased porosity and water absorption, it enhanced CaO content and promoted C–S–H/geopolymer gel formation. Thus, it offers a sustainable alternative to enhance early performance without heat curing; though, long-term durability may remain a concern.

In preliminary studies, kaolin-based geopolymer concrete has exhibited very low compressive strength, with some mixes failing to set properly. Therefore, the present study aims to develop kaolin-based geopolymer concrete incorporating Portland cement and to evaluate its mechanical properties, particularly compressive and tensile strengths. The study also investigates the effects of curing conditions and SP dosages on these properties.

## II. MATERIALS AND METHOD

### *A. Materials*

Kaolin used as the source material for producing geopolymer concrete was obtained from a local deposit in North Sulawesi Province, Indonesia. It was sieved through a No. 50 ASTM sieve before being used in the mix. Its chemical composition is presented in Table I, where it is demonstrated that silicon oxide ($SiO_2$) and aluminum oxide ($Al_2O_3$) together account for approximately 80% of the total content.

General-purpose OPC, compliant with the Indonesian National Standard, was utilized as an additive in the mixture. The alkaline activator solution was prepared by combining sodium hydroxide (NaOH) solution with sodium silicate solution. Specifically, a 14 M sodium hydroxide solution was mixed with sodium silicate to form the activator. Fine and coarse aggregates commonly used in the construction industry and locally sourced were employed in the concrete production. Additionally, a polycarboxylate-based SP—widely used in the regional construction industry—was incorporated into selected mixtures.

### *B. Mixture Proportion*

Two types of mixture proportion were used in this study. Regarding the first mixture, the percentage by weight of the binder (kaolin, sodium hydroxide, sodium silicate, and Portland cement) is 29% and for the aggregates (fine and coarse), it is 71% (26% of fine aggregate and 45% of coarse aggregate). The sodium silicate to sodium hydroxide ratio is 2.7. For the second mixture, the binder: the aggregate ratio is 30:70 (21% of fine aggregate and 49% of coarse aggregate), while the sodium silicate to sodium hydroxide ratio is 3.3. For both mixtures, the addition of Portland cement is 15% of/by the weight of total binder. Polycarboxylate-based SP was added in the second mixture based on a designed dosage, as explained in the experimental program. The SP dosage is in percentage of the total weight of the binder. The fine aggregate has a fineness modulus of 3.44, an apparent specific gravity of 2.75, and a maximum water absorption of 10.82%. The coarse aggregate, with a maximum size of 19 mm, has an apparent specific gravity of 2.76, a maximum water absorption of 1.67%, and a Los Angeles abrasion loss of 18.14%. Mixture I was used to study the effect of curing types to the resulted compressive strength and tensile strength (split tensile strength and flexural tensile strength), whereas Mixture II was deployed to study the effect of SP addition.

TABLE I. CHEMICAL COMPOSITION OF KAOLIN

| Oxides | Content (%) |
|---|---|
| $Al_2O_3$ | 33.0 |
| $SiO_2$ | 48.3 |
| $P_2O_5$ | 0.95 |
| $K_2O$ | 0.79 |
| CaO | 0.50 |
| $TiO_2$ | 4.63 |
| $V_20_5$ | 0.11 |
| $Fe_2O_3$ | 4.34 |
| CuO | 0.06 |
| $Ga_2O_3$ | 0.04 |
| SrO | 0.24 |
| $ZrO_2$ | 0.55 |
| $MoO_3$ | 6.49% |

### *C. Manufacturing of Specimens*

Before mixing all materials, according to the designed mixture composition, the sodium hydroxide solution was prepared by dissolving sodium hydroxide pellets in tap water to achieve the desired concentration (14 M). This solution was then combined with the sodium silicate solution to form the alkaline activator. Coarse and fine aggregates were first dry-mixed in a concrete mixer. Subsequently, kaolin and OPC were added, and mixing continued until a uniform blend was achieved. The previously prepared alkaline activator solution was then gradually added to the dry mixture, while mixing continued until a homogeneous fresh concrete was obtained. The fresh concrete was cast into prepared molds and compacted using a combination of rodding and vibration table methods. Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were used for compressive and split tensile strength tests (Figure 1). For flexural tensile strength tests, prismatic specimens measuring 100 mm × 100 mm × 400 mm were utilized (Figure 2).

### *D. Curing of Specimens*

Two types of curing were applied for the specimens i.e. room temperature curing and elevated temperature curing (oven curing). The latter aims to enhance the reactivity of kaolin as a source material in geopolymer mixtures. It has been demonstrated that elevated temperature curing improves the mechanical properties of geopolymers formulated with low-reactivity source materials, such as fly ash or kaolin [6, 42, 43, 51]. This curing method accelerates the geopolymerization process by promoting the dissolution of aluminosilicate precursors and facilitating the formation of a hardened structure, particularly during the early stages of the reaction [52]. Four types of elevated temperature curing were utilized, based on the temperature and curing period duration as described in the next section.

### *E. Experimental Program*

The experimental program involved:

- Mixture I: Curing types: Room temperature, oven 60°C for 6 hours (60°C-6h), oven 60°C for 24 hours (60°C-24h), oven 90°C for 6 hours (90°C-6h), oven 90°C for 24 hours (90°C-24h). Testing age for each curing type: 7 days, 14 days, and 28 days for compressive strength, and 7 days and 28 days for tensile strength (split tensile and flexural tensile strength.
- Mixture II: SP dosage: 0%, 1%, 1.5%, 2%, and 3% by weight of total binder. Curing types for each SP dosage: Room temperature and oven 60°C for 24 hours (60°C-24h). Compressive strength test at 7 days and 28 days for all SP dosages. Tensile strength (split tensile and flexural tensile strength) tests were only for 0% and 2% SP dosages. Four specimens were prepared for the compressive strength and split tensile strength tests, while three specimens were prepared for the flexural tensile strength test.

All test results were compiled, tabulated, and cross-validated across specimens to ensure accuracy. For each test group, the average values were calculated from multiple specimens, and consistency was checked. These data were then used as the foundation for trend comparison and interpretation in the subsequent analysis.

## III. RESULTS AND DISCUSSION

The data obtained from the experimental program, including compressive and tensile strength results under various curing conditions and SP dosages, were systematically analyzed to evaluate performance trends. These verified test results form the basis for the analytical discussion presented in this section.

### *A. Effect of Curing Types*

The test results of Mix-1 kaolin-based geopolymer concrete with Portland cement addition are illustrated in Figures 3-5, Tables II and III for compressive strength and tensile strength at various curing types.

#### *1) Compressive Strength*

Figure 3 and Table II present the development of compressive strength at various curing conditions. It can be seen from the graph that the compressive strength of the specimens cured at room temperature increased steadily over time, rising from 7.7 MPa at 7 days to 15.3 MPa at 28 days. This indicates that the geopolymerization process progresses more slowly under ambient conditions due to the limited reaction speed of the binders.

Elevated temperature curing significantly enhances the early-age strength of geopolymer concrete, with particularly pronounced strength gains observed in specimens cured at 60°C for 24 hours and 90°C for 6 hours, demonstrating that heat effectively accelerates the geopolymerization process.

Fig. 1. Specimens for compressive strength and split tensile strength tests.

Fig. 2. Specimens for flexural tensile strength tests.

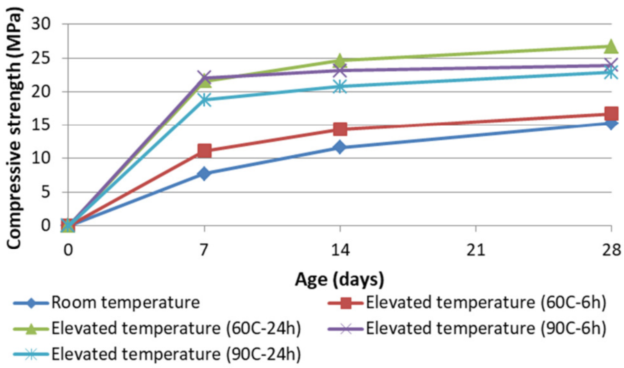


Fig. 3. Compressive strength development for various curing types.

TABLE II. COMPRESSIVE STRENGTH FOR VARIOUS CURING TYPES

| Curing types | Compressive strength (MPa) | | |
|---|---|---|---|
| | Age (days) | | |
| | 7.0 | 14 | 28 |
| Room temperature | 7.7 | 11.6 | 15.3 |
| Elevated temperature (60°C-6h) | 11.2 | 14.3 | 16.8 |
| Elevated temperature (60°C-24h) | 21.5 | 24.6 | 26.7 |
| Elevated temperature (90°C-6h) | 22.1 | 23.1 | 23.9 |
| Elevated temperature (90°C-24h) | 18.8 | 20.8 | 22.9 |

Curing at 60°C for 6 hours slightly improves early-age strength compared to room temperature curing, but the long-term strength gain is relatively modest. The short duration of heating is likely insufficient to fully activate the binders. While curing at the same temperature but for longer time (24 hours) results in the highest overall compressive strength at all ages (21.5 MPa at 7 days, 24.6 MPa at 14 days and 26.7 at 28 days), indicating that extended curing at a moderate temperature provides optimal activation of the geopolymer matrix, leading to greater strength development.

Curing at 90°C for 6 hours results in high early strength (similar to that achieved at 60°C for 24 hours), but the strength plateaus after 14 days. This suggests that short-term curing at a high temperature achieves rapid strength development. However, it might result in higher porosity, limiting further reactions over time, due to potential micro-cracking or over-activation and extended curing at 90°C. This may lead to diminished long-term strength gain [53, 54].

Curing at 60°C provides a more balanced strength gain across all ages, with 60°C for 24 hours identified as the optimal curing condition, whereas curing at 90°C accelerates early-age strength development but fails to sustain the same level of improvement over time, potentially due to the adverse effects of high-temperature exposure.

Strength development from 7 to 28 days is significant for curing at room temperature and at 60°C for 6 hours, highlighting the importance of allowing sufficient curing periods to realize the full potential of kaolin-based geopolymer concrete.

Authors in [44] concluded that incorporating OPC as an additive in high-calcium fly ash-based geopolymers enhances mechanical properties, including compressive strength. It was also stated that curing methods significantly influence the performance of OPC-containing geopolymers, with elevated temperature curing leading to higher early-age compressive strength. Additionally, research on low-calcium fly ash-based geopolymers has demonstrated that OPC inclusion accelerates the geopolymerization process and enables setting times comparable to those of conventional cement concrete. The incorporation of as little as 5% OPC in the total binder has been shown to achieve compressive strengths exceeding 50 MPa for mortar samples and approximately 40 MPa for concrete samples at 28 days [46].

### 2) *Tensile Strength*

Figures 4 and 5 and Table III display the split tensile strength and flexural tensile strength, respectively, at 7 and 28 days under various curing conditions. The highest split tensile strength (Figure 4) for both 7 days and 28 days is achieved by specimens cured at 60°C for 24 hours (2.28 MPa and 2.38 MPa, respectively). The lowest values were observed in specimens cured at room temperature (1.09 MPa at 7 days and 1.45 MPa at 28 days). Elevated temperature curing consistently outperformed room temperature curing at both 7 and 28 days.

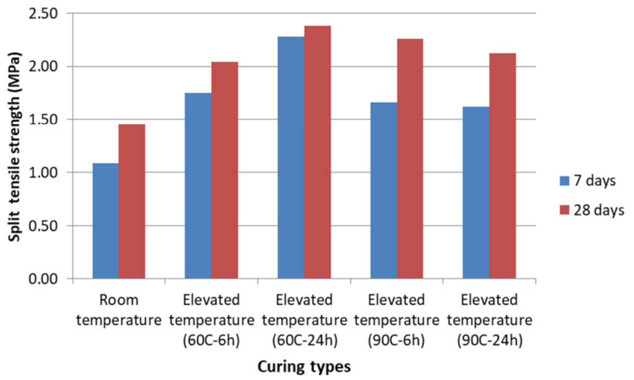


Fig. 4. Split tensile strength at 7 and 28 days for various curing conditions.

The split tensile strength for all curing conditions ranges around 9%-12% of its companion compressive strength. As can be seen from Figure 5, similar to the split tensile strength, curing at 60°C for 24 hours results in the highest flexural tensile strength at both 7 days (3.2 MPa) and 28 days (3.91 MPa). Generally elevated temperature curing results in higher flexural tensile strength compared to room temperature curing for 7 days and 28 days except for the 28-day strength of curing at 90°C for 24 hours, where the flexural tensile strength (3.22 MPa) is a bit lower than that of room temperature curing (3.38 MPa). The flexural tensile strength for all curing conditions ranges around 14%-25% of its companion compressive strength.

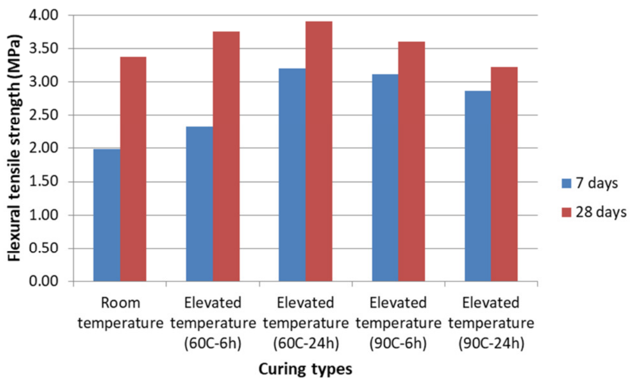


Fig. 5. Flexural tensile strength at 7 and 28 days for various curing conditions.

TABLE III. TENSILE STRENGTH FOR VARIOUS CURING TYPES

| **Curing types** | **Split tensile strength (MPa)** | |
|---|---|---|
| | 7 days | 28 days |
| Room temperature | 1.09 | 1.45 |
| Elevated temperature (60°C-6h) | 1.75 | 2.04 |
| Elevated temperature (60°C-24h) | 2.28 | 2.38 |
| Elevated temperature (90°C-6h) | 1.66 | 2.26 |
| Elevated temperature (90°C-24h) | 1.62 | 2.12 |
| **Curing types** | **Flexural tensile strength (MPa)** | |
| | 7 days | 7 days |
| Room temperature | 1.99 | 3.38 |
| Elevated temperature (60oC-6h) | 2.32 | 3.76 |
| Elevated temperature (60oC-24h) | 3.20 | 3.91 |
| Elevated temperature (90oC-6h) | 3.12 | 3.60 |
| Elevated temperature (90oC-24h) | 2.87 | 3.22 |

Authors in [49] demonstrated that the addition of 5% ordinary Portland cement to metakaolin-based geopolymers, oven-cured at 60 °C for 48 hours, enhanced geopolymerization due to the heat generated from cement hydration. As a result, the compressive strength reached 71.1 MPa, and the flexural strength 6.75 MPa.

All test results for compressive strength, split tensile strength and flexural tensile strength indicate that 60°C for 24 hours is the optimal curing condition, providing the best early-age and long-term strength combination. Room temperature curing can be a sustainable option, though it requires more time to achieve comparable strengths and 90°C curing. Especially for extended durations, it could result in long-term strength reductions.

### *B. Effect of Superplasticizer Addition*

#### *1) Compressive Strength*

The effect of SP addition in the mix on the compressive strength of kaolin-based geopolymer is evaluated by varying the SP content in the mix from 0% (no addition), to 1%, 1.5%, 2%, and 3% by weight of the total binder, including Portland cement. Two types of curing were applied, room temperature and elevated temperature curing. For elevated temperature, only curing at 60°C for 24 hours (considered as the optimal curing condition as discussed in previous section) was applied. The compressive strength was tested at 7 and 28 days.

Figure 6 and Table IV demonstrate that, for room temperature curing, all mixes with SP give higher compressive strength compared to the mix with no SP. The addition of 1% SP significantly increases compressive strength at both 7 and 28 days, suggesting that this level enhances the geopolymerization process and improves mechanical properties. However, beyond 1%, the compressive strength progressively decreases at both ages, with reductions recorded at 1.5%, 2%, and 3%, likely due to excessive SP interfering with the geopolymer matrix's bonding structure or reducing water availability for geopolymerization. The highest compressive strength is achieved at 1% SP addition, identifying it as the optimal content for this formulation.

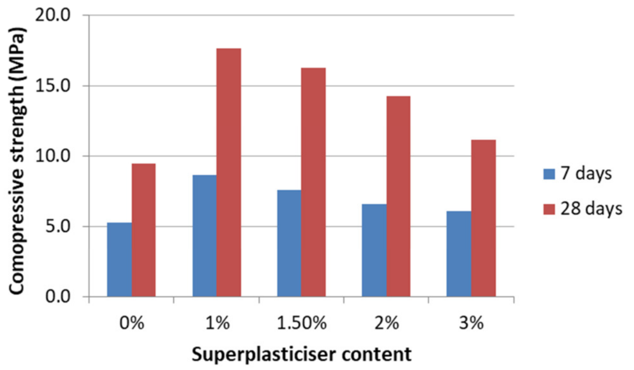


Fig. 6. Compressive strength of specimens cured at room temperature.

As shown in Figure 7 and Table IV, under elevated temperature curing, SP addition of up to 2% results in a significant increase in compressive strength at both 7 and 28 days. The highest strength is achieved at 2%, indicating enhanced geopolymerization and the formation of a stronger matrix. Beyond 2%, compressive strength begins to decline, as observed at 3%, possibly due to particle over-dispersion, resulting in a less cohesive matrix; though, strength remains higher than at 0%. All mixes with SP result in higher compressive strength than the mix without SP. The optimal SP content for elevated temperature curing is 2%, achieving compressive strengths of 19.6 MPa at 7 days and 22.2 MPa at 28 days.

Compressive strength consistently increases from 7 to 28 days across all SP levels, indicating ongoing geopolymerization and densification of the concrete matrix over time, a process further accelerated by elevated temperature curing.

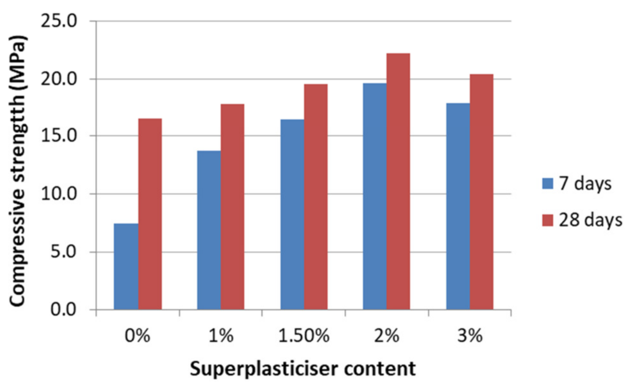


Fig. 7. Compressive strength of specimens cured at elevated temperature (60°C-24h).

#### *2) Tensile Strength*

SP influence on tensile strength (split tensile and flexural tensile strength) is evaluated only for two mixes with 0% and 2% SP content. Figure 8 and Table V indicate that under room temperature curing, the addition of 2% SP results in a noticeable increase in split tensile strength from 1.36 MPa to 1.6 MPa at 7 days, and from 2.14 MPa to 2.19 MPa at 28 days, showing a slightly higher increase at 7 days compared to elevated temperature curing. For the latter, the split tensile strength improves more modestly at 7 days, increasing from 1.88 MPa to 1.93 MPa, but exhibits a more pronounced improvement at 28 days, rising from 2.18 MPa to 2.59 MPa, indicating that heat accelerates the long-term SP benefits by enhancing geopolymerization and matrix integrity.

TABLE IV. COMPRESSIVE STRENGTH FOR VARIOUS SP CONTENT AND CURING TYPES

| **Curing types** | **SP content** | **Compressive strength (MPa)** | |
|---|---|---|---|
| | | 7 days | 28 days |
| Room temperature | 0% | 5.3 | 9.5 |
| | 1% | 8.7 | 17.7 |
| | 1.50% | 7.6 | 16.3 |
| | 2% | 6.6 | 14.3 |
| | 3% | 6.1 | 11.1 |
| Elevated temperature ($60^oC$-24h) | 0% | 7.4 | 16.5 |
| | 1% | 13.7 | 17.8 |
| | 1.50% | 16.5 | 19.5 |
| | 2% | 19.6 | 22.2 |
| | 3% | 17.9 | 20.4 |

Under room temperature curing (Figure 9 and Table V), adding 2% SP slightly increases flexural tensile strength from 2.46 MPa to 2.72 MPa at 7 days, and from 3.19 MPa to 3.30 MPa at 28 days, indicating a limited impact on flexural properties in these conditions. In contrast, elevated temperature curing results in more significant improvements, with flexural tensile strength increasing from 2.67 MPa to 3.23 MPa at 7 days and from 3.23 MPa to 3.91 MPa at 28 days, highlighting the combined effect of accelerated geopolymerization and improved matrix integrity facilitated by the SP.

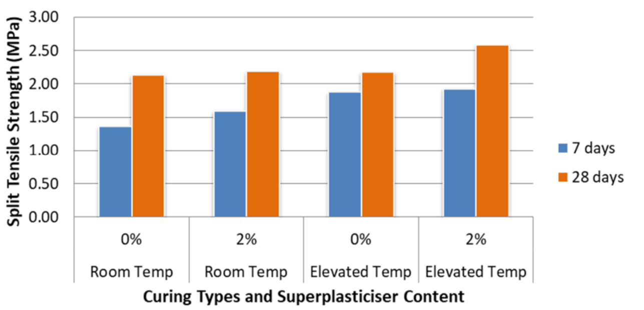


Fig. 8. Split tensile strength at 7 and 28 days for varied curing type and SP content.

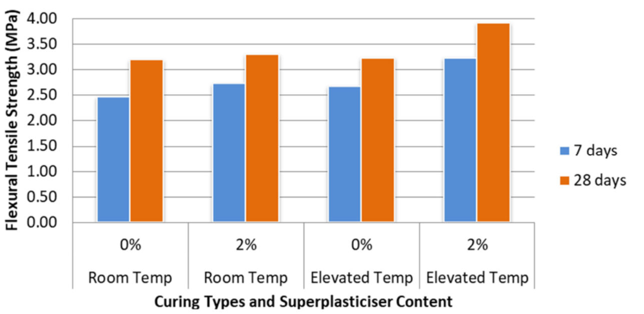


Fig. 9. Flexural tensile strength at 7 and 28 days for varied curing type and SP content.

TABLE V. TENSILE STRENGTH FOR VARIOUS SP CONTENT AND CURING TYPES

| **Curing types** | **SP content** | **Split tensile strength (MPa)** | | **Flexural tensile strength (MPa)** | |
|---|---|---|---|---|---|
| | | 7 days | 28 days | 7 days | 28 days |
| Room temperature | 0% | 1.36 | 2.14 | 2.46 | 3.19 |
| | 2% | 1.6 | 2.19 | 2.72 | 3.30 |
| Elevated temperature | 0% | 1.88 | 2.18 | 2.67 | 3.23 |
| | 2% | 1.93 | 2.59 | 3.23 | 3.91 |

The increase in strength of kaolin-based geopolymer concrete with polycarboxylate-based SP can be attributed to its dual-action dispersion mechanism, combining electrostatic repulsion and steric hindrance. Polycarboxylate SPs are composed of a main backbone, typically polyacrylic acid chains, bearing negatively charged carboxylate groups that adsorb onto the surfaces of binder particles, including kaolin and Portland cement. These surface-bound charges induce electrostatic repulsion, preventing the particles from aggregating. Additionally, the molecular structure of Polycarboxylate SPs includes long lateral ether chains, which extend into the surrounding matrix. These side chains create steric hindrance, a physical barrier that further separates particles and maintains dispersion even in high-alkaline environments, such as those found in this geopolymer system. This steric effect is particularly valuable when the electrostatic repulsion is partially suppressed due to ionic strength or elevated pH conditions. As a result, polycarboxylate SPs enhance the homogeneity of the fresh mix, improve workability, and contribute to a denser matrix, ultimately leading to increased mechanical strength [55-59]. Although workability was not directly measured in this study, its positive effect on both compressive and tensile strength can be inferred when compared to mixes without SP use.

### *C. Potential Applications and Benefits*

At this stage of research, kaolin-based geopolymer concrete with the addition of Portland cement has achieved compressive strength values that meet the minimum requirement for structural concrete. This requirement, as specified by the Indonesian National Standard [60], is a minimum compressive strength of 20 MPa. Although the maximum compressive strength obtained at 26.7 MPa is relatively modest, it demonstrates the material's potential. Given that this strength is achieved under elevated temperature curing, the concrete is currently more applicable to precast concrete production, where controlled curing conditions are feasible. However, at this stage, it is more appropriately suited for non-structural precast components.

Kaolin-based geopolymer concrete is useful for sustainable construction. It partly replaces Portland cement and helps reduce carbon dioxide emissions. This is especially helpful in areas with plenty of kaolin, as it provides a local and eco-friendly option for making concrete.

## IV. CONCLUSIONS AND RECOMMENDATIONS

### *A. Conclusions*

This research investigates the enhancement of kaolin-based geopolymer concrete through the addition of Portland cement to improve its reactivity. It evaluates the effects of various curing temperatures and Superplasticizer (SP) dosages on the mechanical properties of concrete. The study identifies the optimal curing conditions and SP dosages that balance early-age strength with long-term performance, providing valuable insights for sustainable construction applications. However, it has certain limitations. That is, the scope of mechanical performance evaluation was limited to compressive and tensile strengths, without incorporating microstructural analysis. The following conclusions summarize the key findings of this study:

- Kaolin-based geopolymer concrete incorporating Portland cement demonstrates satisfactory mechanical performance. The addition of 15% Portland cement to the mixture results in compressive strength that meets the minimum requirement for structural concrete as specified by the Indonesian National Standard, which is 20 MPa.
- Curing conditions play an important role in the resulting mechanical properties. Elevated temperatures significantly enhance the compressive and tensile strength (split tensile strength and flexural tensile strength) of kaolin-based geopolymer concrete with Portland cement addition especially at early ages.
- The most effective curing condition among the curing types applied is 60°C for 24 hours, providing a balance between strength development and curing efficiency.
- Curing at 90°C for shorter durations, provides rapid early strength but may compromise long-term performance, while extended curing at this temperature can result in reduced strength.
- SP addition generally improves kaolin-based geopolymer compressive strength with Portland cement addition at early ages and at longer term. The optimal dosage is 1% for room temperature curing and 2% for elevated temperature curing.
- Compared to the findings from previous studies on geopolymers using other source materials, such as fly ash and metakaolin with Portland cement addition, the strength of kaolin-based geopolymer concrete—while satisfactory—remains relatively lower. This presents a challenge and an opportunity for future research to further investigate and optimize its formulation, and so enhance the mechanical properties of kaolin-based geopolymer concrete.

### *B. Recommendations For Future Research*

Kaolin-based geopolymer concrete presents considerable potential as a sustainable construction material. The incorporation of a small amount of Portland cement has been shown to enhance the system's reactivity and improve its mechanical properties. However, several aspects require further investigation to fully realize its potential. Future research should focus on optimizing the mix design, including determining the ideal proportion of Portland cement and refining the ratios between source materials and alkaline activators to enhance both workability and strength. Achieving higher mechanical performance would expand the material's suitability for structural precast concrete applications. Additionally, the development of mix designs and curing methods that enable effective performance under ambient conditions remains a key challenge for future works.

Microstructural studies are essential to gaining a deeper understanding of the geopolymerization mechanisms in kaolin-based systems. Such insights can help maximize the material's potential and address its current limitations. Achieving satisfactory mechanical properties under ambient curing conditions presents a major challenge but is crucial for reducing the production cost of kaolin-based geopolymer concrete.

Moreover, blending kaolin with other industrial by-products or waste materials, such as fly ash, is a promising approach—particularly in regions where such materials are abundantly available. This strategy not only improves material performance, but also supports the development of environmentally friendly concrete technologies.

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## REFERENCES

[1] A. M. Rashad, "Alkali-activated metakaolin: A short guide for civil Engineer – An overview," *Construction and Building Materials*, vol. 41, pp. 751–765, Apr. 2013, https://doi.org/10.1016/j.conbuildmat.2012.12.030.

[2] O. Ayeni, A. P. Onwualu, and E. Boakye, "Characterization and mechanical performance of metakaolin-based geopolymer for sustainable building applications," *Construction and Building Materials*, vol. 272, Feb. 2021, Art. no. 121938, https://doi.org/10.1016/j.conbuildmat.2020.121938.

[3] L.-M. Bjerge and P. Brevik, "CO2 Capture in the Cement Industry, Norcem CO2 Capture Project (Norway)," *Energy Procedia*, vol. 63, pp. 6455–6463, 2014, https://doi.org/10.1016/j.egypro.2014.11.680.

[4] J. Davidovits, "Geopolymers and geopolymeric materials," *Journal of Thermal Analysis*, vol. 35, no. 2, pp. 429–441, Mar. 1989, https://doi.org/10.1007/bf01904446.

[5] Z. H. Zhang, H. J. Zhu, C. H. Zhou, and H. Wang, "Geopolymer from kaolin in China: An overview," *Applied Clay Science*, vol. 119, pp. 31–41, Jan. 2016, https://doi.org/10.1016/j.clay.2015.04.023.

[6] "On the Development of Fly Ash-Based Geopolymer Concrete," *ACI Materials Journal*, vol. 101, no. 6, 2004, https://doi.org/10.14359/13485.

[7] X. Ge, Y. Liu, Y. Mao, X. Hu, and C. Shi, "Characteristics of fly ash-based geopolymer concrete in the field for 4 years," *Construction and Building Materials*, vol. 382, Jun. 2023, Art. no. 131222, https://doi.org/10.1016/j.conbuildmat.2023.131222.

[8] Z. Ou, R. Feng, T. Mao, and N. Li, "Influence of mixture design parameters on the static and dynamic compressive properties of slag-based geopolymer concrete," *Journal of Building Engineering*, vol. 53, Aug. 2022, Art. no. 104564, https://doi.org/10.1016/j.jobe.2022.104564.

[9] Y. Wang and J. Zhao, "Comparative study on flame retardancy of silica fume-based geopolymer activated by different activators," *Journal of Alloys and Compounds*, vol. 743, pp. 108–114, Apr. 2018, https://doi.org/10.1016/j.jallcom.2018.01.302.

[10] S. S. Hossain, P. K. Roy, and C.-J. Bae, "Utilization of waste rice husk ash for sustainable geopolymer: A review," *Construction and Building Materials*, vol. 310, Dec. 2021, Art. no. 125218, https://doi.org/10.1016/j.conbuildmat.2021.125218.

[11] Z. Du, S. Sheng, and J. Guo, "Effect of composite activators on mechanical properties, hydration activity and microstructure of red mud-

based geopolymer," *Journal of Materials Research and Technology*, vol. 24, pp. 8077–8085, May 2023, https://doi.org/10.1016/j.jmrt.2023.05.049.

[12] F. Pacheco-Torgal, S. Jalali, J.P. Castro Gomes, "Utilization of mining wastes to produce geopolymer binders," in *Geopolymers, Structures, Processing, Properties and Industrial Applications,* Woodhead Publishing Series in Civil and Structural Engineering, 1st ed., Elsevier, 2009, pp. 267–293.

[13] M. J. A. Mijarsh, M. A. Megat Johari, and Z. A. Ahmad, "Synthesis of geopolymer from large amounts of treated palm oil fuel ash: Application of the Taguchi method in investigating the main parameters affecting compressive strength," *Construction and Building Materials*, vol. 52, pp. 473–481, Feb. 2014, https://doi.org/10.1016/j.conbuildmat.2013.11.039.

[14] J. Moon *et al.*, "Characterization of natural pozzolan-based geopolymeric binders," *Cement and Concrete Composites*, vol. 53, pp. 97–104, Oct. 2014, https://doi.org/10.1016/j.cemconcomp.2014.06.010.

[15] M. A. Gómez-Casero, C. De Dios-Arana, J. S. Bueno-Rodríguez, L. Pérez-Villarejo, and D. Eliche-Quesada, "Physical, mechanical and thermal properties of metakaolin-fly ash geopolymers," *Sustainable Chemistry and Pharmacy*, vol. 26, May 2022, Art. no. 100620, https://doi.org/10.1016/j.scp.2022.100620.

[16] Z. Luo, B. Zhang, J. Zou, and B. Luo, "Sulfate erosion resistance of slag-fly ash based geopolymer stabilized soft soil under semi-immersion condition," *Case Studies in Construction Materials*, vol. 17, Dec. 2022, Art. no. e01506, https://doi.org/10.1016/j.cscm.2022.e01506.

[17] E. Yavuz, N. I. Kul Gul, and N. U. Kockal, "Characterization of class C and F fly ashes based geopolymers incorporating silica fume," *Ceramics International*, vol. 48, no. 21, pp. 32213–32225, Nov. 2022, https://doi.org/10.1016/j.ceramint.2022.07.163.

[18] G. Ogwang, P. W. Olupot, H. Kasedde, E. Menya, H. Storz, and Y. Kiros, "Experimental evaluation of rice husk ash for applications in geopolymer mortars," *Journal of Bioresources and Bioproducts*, vol. 6, no. 2, pp. 160–167, May 2021, https://doi.org/10.1016/j.jobab.2021.02.008.

[19] S. Detphan and P. Chindaprasirt, "Preparation of fly ash and rice husk ash geopolymer," *International Journal of Minerals, Metallurgy and Materials*, vol. 16, no. 6, pp. 720–726, 2009, https://doi.org/10.1016/S1674-4799(10)60019-2.

[20] M. S. K. Chaitanya, T. V. Nagaraju, L. V. K. R. Gadhiraju, V. R. Madepalli, and S. Narayana Raju Jampana, "Strength and micro-structural performance of geopolymer concrete using highly burned rice husk ash," *Materials Today: Proceedings*, May 2023, https://doi.org/10.1016/j.matpr.2023.04.617.

[21] L. Kuang, G. Li, J. Xiang, W. Ma, and X. Cui, "Effect of seawater on the properties and microstructure of metakaolin/slag-based geopolymers," *Construction and Building Materials*, vol. 397, Sep. 2023, Art. no. 132418, https://doi.org/10.1016/j.conbuildmat.2023.132418.

[22] A. Gupta, "Investigation of the strength of ground granulated blast furnace slag based geopolymer composite with silica fume," *Materials Today: Proceedings*, vol. 44, pp. 23–28, 2021, https://doi.org/10.1016/j.matpr.2020.06.010.

[23] N. Ranjbar, M. Mehrali, A. Behnia, U. J. Alengaram, and M. Z. Jumaat, "Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar," *Materials & Design*, vol. 59, pp. 532–539, Jul. 2014, https://doi.org/10.1016/j.matdes.2014.03.037.

[24] J. Liu, J.-H. Doh, D. E. L. Ong, H. L. Dinh, Z. Podolsky, and G. Zi, "Investigation on red mud and fly ash-based geopolymer: Quantification of reactive aluminosilicate and derivation of effective Si/Al molar ratio," *Journal of Building Engineering*, vol. 71, Jul. 2023, Art. no. 106559, https://doi.org/10.1016/j.jobe.2023.106559.

[25] K. Nazir, O. Canpolat, M. Uysal, A. Niş, and Ö. F. Kuranlı, "Engineering properties of different fiber-reinforced metakaolin-red mud based geopolymer mortars," *Construction and Building Materials*, vol. 385, Jul. 2023, Art. no. 131496, https://doi.org/10.1016/j.conbuildmat.2023.131496.

[26] Y. Zhang, H. Liu, T. Ma, G. Gu, C. Chen, and J. Hu, "Understanding the changes in engineering behaviors and microstructure of FA-GBFS based geopolymer paste with addition of silica fume," *Journal of Building Engineering*, vol. 70, Jul. 2023, Art. no. 106450, https://doi.org/10.1016/j.jobe.2023.106450.

[27] G. Liang, H. Zhu, H. Li, T. Liu, and H. Guo, "Comparative study on the effects of rice husk ash and silica fume on the freezing resistance of metakaolin-based geopolymer," *Construction and Building Materials*, vol. 293, Jul. 2021, Art. no. 123486, https://doi.org/10.1016/j.conbuildmat.2021.123486.

[28] M. O. M. Mashri, M. A. M. Johari, Z. A. Ahmad, and M. J. A. Mijarsh, "Enhancing the properties of UPOFA-based geopolymer mortar via the incorporation of eggshell ash and silica fume," *Journal of Building Engineering*, vol. 65, Apr. 2023, Art. no. 105677, https://doi.org/10.1016/j.jobe.2022.105677.

[29] U. Zakira, K. Zheng, N. Xie, and B. Birgisson, "Development of high-strength geopolymers from red mud and blast furnace slag," *Journal of Cleaner Production*, vol. 383, Jan. 2023, Art. no. 135439, https://doi.org/10.1016/j.jclepro.2022.135439.

[30] A. Kumar, Rajkishor, N. Kumar, A. K. Chhotu, and B. Kumar, "Effect of Ground Granulated Blast Slag and Temperature Curing on the Strength of Fly Ash-based Geopolymer Concrete," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13319–13323, Apr. 2024, https://doi.org/10.48084/etasr.6874.

[31] B. Ilic, A. Mitrovic, and L. Milicic, "Thermal treatment of kaolin clay to obtain metakaolin," *Hemijska industrija*, vol. 64, no. 4, pp. 351–356, 2010, https://doi.org/10.2298/HEMIND100322014I.

[32] K. L. Konan, C. Peyratout, A. Smith, J.-P. Bonnet, S. Rossignol, and S. Oyetola, "Comparison of surface properties between kaolin and metakaolin in concentrated lime solutions," *Journal of Colloid and Interface Science*, vol. 339, no. 1, pp. 103–109, Nov. 2009, https://doi.org/10.1016/j.jcis.2009.07.019.

[33] A. Alujas, R. Fernández, R. Quintana, K. L. Scrivener, and F. Martirena, "Pozzolanic reactivity of low grade kaolinitic clays: Influence of calcination temperature and impact of calcination products on OPC hydration," *Applied Clay Science*, vol. 108, pp. 94–101, May 2015, https://doi.org/10.1016/j.clay.2015.01.028.

[34] A. M. Rashad, "Metakaolin as cementitious material: History, scours, production and composition – A comprehensive overview," *Construction and Building Materials*, vol. 41, pp. 303–318, Apr. 2013, https://doi.org/10.1016/j.conbuildmat.2012.12.001.

[35] E. Badogiannis, G. Kakali, and S. Tsivilis, "Metakaolin as supplementary cementitious material: Optimization of kaolin to metakaolin conversion," *Journal of Thermal Analysis and Calorimetry*, vol. 81, no. 2, pp. 457–462, Jul. 2005, https://doi.org/10.1007/s10973-005-0806-3.

[36] Y. M. Liew *et al.*, "Optimization of solids-to-liquid and alkali activator ratios of calcined kaolin geopolymeric powder," *Construction and Building Materials*, vol. 37, pp. 440–451, Dec. 2012, https://doi.org/10.1016/j.conbuildmat.2012.07.075.

[37] C. M. Ruzaidi *et al.*, "Study on Properties and Morphology of Kaolin Based Geopolymer Coating on Clay Substrates," *Key Engineering Materials*, vol. 594–595, pp. 540–545, Dec. 2013, https://doi.org/10.4028/www.scientific.net/KEM.594-595.540.

[38] P. Nuaklong, V. Sata, and P. Chindaprasirt, "Properties of metakaolin-high calcium fly ash geopolymer concrete containing recycled aggregate from crushed concrete specimens," *Construction and Building Materials*, vol. 161, pp. 365–373, Feb. 2018, https://doi.org/10.1016/j.conbuildmat.2017.11.152.

[39] N. A. Jaya, L. Yun-Ming, M. M. A. B. Abdullah, H. Cheng-Yong, and K. Hussin, "Effect of Sodium Hydroxide Molarity on Physical, Mechanical and Thermal Conductivity of Metakaolin Geopolymers," *IOP Conference Series: Materials Science and Engineering*, vol. 343, Mar. 2018, Art. no. 012015, https://doi.org/10.1088/1757-899X/343/1/012015.

[40] M. Sarkar and K. Dana, "Partial replacement of metakaolin with red ceramic waste in geopolymer," *Ceramics International*, vol. 47, no. 3, pp. 3473–3483, Feb. 2021, https://doi.org/10.1016/j.ceramint.2020.09.191.

[41] O. Ayeni, A. P. Onwualu, and E. Boakye, "Characterization and mechanical performance of metakaolin-based geopolymer for sustainable building applications," *Construction and Building Materials*,

vol. 272, Feb. 2021, Art. no. 121938, https://doi.org/10.1016/j.conbuildmat.2020.121938.

[42] T. Bakharev, "Geopolymeric materials prepared using Class F fly ash and elevated temperature curing," *Cement and Concrete Research*, vol. 35, no. 6, pp. 1224–1232, Jun. 2005, https://doi.org/10.1016/j.cemconres.2004.06.031.

[43] Department of Civil Engineering, Universiti Teknologi Petronas, Seri Iskandar, Malaysia and E. Al. Nurruddin, "Methods of curing geopolymer concrete: A review," *International Journal of Advanced And Applied Sciences*, vol. 5, no. 1, pp. 31–36, Jan. 2018, https://doi.org/10.21833/ijaas.2018.01.005.

[44] S. Pangdaeng, T. Phoo-ngernkham, V. Sata, and P. Chindaprasirt, "Influence of curing conditions on properties of high calcium fly ash geopolymer containing Portland cement as additive," *Materials & Design*, vol. 53, pp. 269–274, Jan. 2014, https://doi.org/10.1016/j.matdes.2013.07.018.

[45] 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.

[46] 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.

[47] 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, Sep. 2017, https://doi.org/10.1016/j.conbuildmat.2017.06.067.

[48] 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.

[49] R. Gao, W. Yang, Z. Duan, H. Liu, Q. Deng, and M. Hua, "Effect of Ordinary Portland Cement on Mechanical Properties and Microstructures of Metakaolin-Based Geopolymers," *Materials*, vol. 15, no. 24, Dec. 2022, Art. no. 9007, https://doi.org/10.3390/ma15249007.

[50] D. De Klerk, A. Naghizadeh, S. O. Ekolu, and M. Welman-Purchase, "Recycled cement use to produce fly ash – based geopolymer binders suitable for ambient curing: Comparison with slag effects," *Construction and Building Materials*, vol. 468, Mar. 2025, Art. no. 140394, https://doi.org/10.1016/j.conbuildmat.2025.140394.

[51] C. Y. Heah *et al.*, "Curing Behavior on Kaolin-Based Geopolymers," *Advanced Materials Research*, vol. 548, pp. 42–47, Jul. 2012, https://doi.org/10.4028/www.scientific.net/AMR.548.42.

[52] B. Mo, H. Zhu, X. Cui, Y. He, and S. Gong, "Effect of curing temperature on geopolymerization of metakaolin-based geopolymers," *Applied Clay Science*, vol. 99, pp. 144–148, Sep. 2014, https://doi.org/10.1016/j.clay.2014.06.024.

[53] C. Y. Heah *et al.*, "Effect of Curing Profile on Kaolin-based Geopolymers," *Physics Procedia*, vol. 22, pp. 305–311, 2011, https://doi.org/10.1016/j.phpro.2011.11.048.

[54] Q. Li *et al.*, "Effect of Curing Temperature on High-Strength Metakaolin-Based Geopolymer Composite (HMGC) with Quartz Powder and Steel Fibers," *Materials*, vol. 15, no. 11, Jun. 2022, Art. no. 3958, https://doi.org/10.3390/ma15113958.

[55] M. Criado, A. Palomo, A. Fernández-Jiménez, and P. F. G. Banfill, "Alkali activated fly ash: effect of admixtures on paste rheology," *Rheologica Acta*, vol. 48, no. 4, pp. 447–455, May 2009, https://doi.org/10.1007/s00397-008-0345-5.

[56] B. Nematollahi and J. Sanjayan, "Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer," *Materials & Design*, vol. 57, pp. 667–672, May 2014, https://doi.org/10.1016/j.matdes.2014.01.064.

[57] F. Muhammad *et al.*, "Strength evaluation by using polycarboxylate superplasticizer and solidification efficiency of Cr 6+, Pb 2+ and Cd 2+ in composite based geopolymer," *Journal of Cleaner Production*, vol. 188, pp. 807–815, Jul. 2018, https://doi.org/10.1016/j.jclepro.2018.04.033.

[58] T. T. Nguyen, C. I. Goodier, and S. A. Austin, "Factors affecting the slump and strength development of geopolymer concrete," *Construction and Building Materials*, vol. 261, Nov. 2020, Art. no. 119945, https://doi.org/10.1016/j.conbuildmat.2020.119945.

[59] G. Xiong and X. Guo, "Effects and mechanism of superplasticizers and precursor proportions on the fresh properties of fly ash – slag powder based geopolymers," *Construction and Building Materials*, vol. 350, Oct. 2022, Art. no. 128734, https://doi.org/10.1016/j.conbuildmat.2022.128734.

[60] *Requirements for Structural Concrete for Buildings*, SNI 2847:2019, National Standardization Agency of Indonesia, 2019.