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Ambient-Cured One-Part Geopolymer Concrete Activated by Powdered Sodium Metasilicate

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Abstract

This paper assesses ambient-cured one-part geopolymer concrete in which powdered sodium metasilicate is used as the principal alkaline activator. The material concept is based on a dry binder system where class F fly ash, ground granulated blast furnace slag (GGBFS) and solid activator are blended before water is added. Such a procedure reduces the dependence on strongly alkaline liquid solutions and brings the mixing sequence closer to ordinary concrete production. Five one-part geopolymer mixtures were examined and compared with an ordinary Portland cement reference in terms of setting behaviour, workability, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, water absorption, permeable void volume, drying shrinkage, creep, restrained shrinkage and pore-structure features. The 28-day compressive strength of the one-part mixtures ranged from 26.2 to 41.7 MPa, while flexural and splitting tensile strengths were 4.55-6.35 MPa and 3.65-5.05 MPa, respectively. The mixture containing 60% fly ash and 40% GGBFS, activated only with powdered sodium metasilicate anhydrous, provided the most balanced response. Reducing the water-to-precursor ratio to 0.35 improved strength, microstructural compactness and creep resistance, although it shortened the workable period. Compared with the cement reference, several geopolymer mixtures showed higher water absorption and free drying shrinkage; nevertheless, optimized formulations exhibited lower creep and restrained shrinkage. The findings confirm that powdered sodium metasilicate can be an effective single activator for ambient-cured one-part geopolymer concrete when precursor balance and water dosage are controlled together.

Keywords: One-part geopolymer concrete; powdered sodium metasilicate; ambient curing; fly ash; GGBFS; mechanical properties; drying shrinkage; pore structure.

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1. Introduction

Ordinary Portland cement remains the dominant binder in concrete technology because it provides predictable early strength, standardized quality control and broad industrial availability. However, cement production is energy-intensive and generates a significant carbon footprint. This has encouraged sustained research into alternative binders that can reduce clinker consumption

while retaining the engineering performance required in concrete elements [1-3].

Geopolymer binders are formed when reactive aluminosilicate powders dissolve and reorganize in an alkaline medium. Low-calcium fly ash and GGBFS are among the most widely used precursors because they are available industrial by-products and contain reactive silica, alumina and calcium-bearing phases. Their reaction products commonly include sodium aluminosilicate hydrate and calcium aluminosilicate hydrate type gels, and the balance between these products strongly affects strength, pore structure and dimensional stability [2,6-8].

Conventional geopolymer concrete is commonly prepared by mixing solid precursors with liquid alkaline solutions such as sodium silicate and sodium hydroxide. Although this two-part route can produce high strength, it creates practical difficulties related to corrosive liquids, heat generation during solution preparation, high viscosity, storage requirements and rapid setting in some compositions [3,4]. One-part geopolymer technology addresses these issues by using solid alkaline activators that are dry-blended with the precursor powders. Water is then added during batching, giving a "just add water" system with a simpler and safer production sequence [4,5].

Powdered sodium metasilicate anhydrous is one of the most promising solid activators for fly ash/GGBFS-based one-part systems. Its relatively low silica modulus can generate sufficient alkalinity and available silicate for precursor dissolution and gel formation under ambient curing. At the same time, its effect depends on the precursor ratio and water content: insufficient water may reduce workability, whereas excess water can leave capillary pores after evaporation and weaken the hardened matrix [4,5,10].

The objective of this paper is to evaluate the material performance of ambient-cured one-part geopolymer concrete activated mainly by powdered sodium metasilicate. The focus is not on a particular end-use element, but on the relationship between activator composition, fly ash/GGBFS balance, water-to-precursor ratio, mechanical properties, moisture transport, dimensional stability and pore structure. The novelty of the assessment lies in interpreting fresh, hardened and long-term behaviour as interconnected outcomes of a dry-activated binder system.

2. Methods

2.1. Materials and mixture design

The geopolymer binder system consisted of class F fly ash and GGBFS as aluminosilicate precursors. Powdered sodium metasilicate anhydrous was used as the main solid alkaline activator. Two modified activator systems were also considered: one in which part of sodium metasilicate was replaced with sodium hydroxide, and another in which part of it was replaced with sodium silicate GD powder. A Portland cement concrete mixture was used as a reference material for comparison.

The mixture matrix was selected to isolate three principal variables: precursor balance, activator type and water-to-precursor ratio. The G05-AN mixture was dominated by GGBFS, whereas the G60 mixtures contained 60% fly ash and 40% GGBFS. The G60-AN and G60-AN-0.35 mixtures used sodium metasilicate anhydrous as the sole activator, with water-to-precursor ratios of 0.45 and 0.35, respectively. G60-ANSH and G60-ANGD were included to evaluate the effect of replacing part of sodium metasilicate with another solid activator. In all geopolymer concretes, the total solid activator dosage was kept at 10% of the precursor mass.

Table 1. Mixture variables selected for dimensional stability assessment of one-part geopolymer concrete

Mix ID	Binder composition	Activator system	W/P or W/C	Primary variable examined for dimensional stability
G05-AN	5% fly ash / 95% GGBFS	SM-AN	0.45	Slag-dominant binder
G60-AN	60% fly ash / 40% GGBFS	SM-AN	0.45	Balanced fly ash-GGBFS reference
G60-AN-0.35	60% fly ash / 40% GGBFS	SM-AN	0.35	Reduced water-to-precursor ratio
G60-ANSH	60% fly ash / 40% GGBFS	SM-AN + SH	0.45	Sodium hydroxide-modified activator system
G60-ANGD	60% fly ash / 40% GGBFS	SM-AN + SS-GD	0.45	Sodium silicate powder-modified activator system
OPC	Portland cement	N/A (cement hydration)	0.45	Portland cement reference

Note. SM-AN = powdered sodium metasilicate anhydrous; SH = sodium hydroxide; SS-GD = Grade D sodium silicate powder; W/P = water-to-precursor ratio for geopolymer mixtures; W/C = water-to-cement ratio for the Portland cement reference; GGBFS = ground granulated blast-furnace slag; OPC = ordinary Portland cement concrete; N/A = not applicable.

2.2. Test program and curing regime

The fresh-state assessment covered initial setting time, mortar flowability, flow loss and concrete slump. These indicators were used to determine whether solid-activated mixtures had adequate open time and consistency before hardening. The hardened-state assessment included compressive strength at multiple ages, 7- and 28-day flexural strength, 28-day splitting tensile strength and modulus of elasticity.

Durability- and serviceability-related indicators were also included because the usefulness of one-part geopolymer concrete cannot be judged by compressive strength alone. Water absorption and volume of permeable voids were used to represent moisture transport. Drying shrinkage, creep and restrained shrinkage were followed for long-term dimensional behaviour. Pore-structure observations were considered to explain differences in strength, permeability and shrinkage. The geopolymer specimens were cured under ambient laboratory conditions of about 23 +/- 3 °C, whereas the cement reference followed conventional water curing before subsequent testing.

3. Results and Discussion

3.1. Fresh behaviour and activation kinetics

The use of powdered activators avoided the extremely rapid setting often observed in some liquid-activated geopolymer systems. Most one-part pastes had initial setting times greater than 110 min, which indicates that the dissolution of the solid activator introduced a slower reaction sequence. First, sodium metasilicate dissolved into the mixing water and increased alkalinity; then dissolution of fly ash and slag particles proceeded; finally, geopolymeric gels formed and the matrix stiffened. This stepwise reaction was beneficial because it reduced the risk of flash setting.

Water dosage controlled both reaction rate and workability. In the 60/40 fly ash/GGBFS system, reducing W/P from 0.45 to 0.35 shortened the initial setting time from roughly 375 min to around 115 min and caused greater flow loss during the first 30 min. The lower amount of water increased activator concentration and promoted faster precursor dissolution, but it also reduced the time available for handling. Therefore, the low-water mixture offered better hardened performance at the cost of a narrower processing window.

The precursor ratio also influenced fresh behaviour. The mixture with very high slag content showed lower spread and relative slump than the mixtures containing 60% fly ash. The angular shape and higher reactivity of slag particles increase interparticle contact and early binding, whereas spherical fly ash particles tend to improve flow. Consequently, a balanced fly ash/GGBFS blend was more favourable than a slag-dominant binder when fresh-state stability and workable consistency were considered together.

3.2. Mechanical performance and activator efficiency

The one-part geopolymer concretes achieved 28-day compressive strengths between 26.2 and 41.7 MPa. Although the cement reference reached 46.1 MPa, the best geopolymer mixture approached this level without heat curing and without liquid alkaline solutions. The 7-day-to-28-day strength gain ratios also showed rapid early development, especially for mixtures activated solely by sodium metasilicate anhydrous.

The highest geopolymer compressive strength was recorded for G60-AN-0.35. Its strength of 41.7 MPa was associated with a lower water-to-precursor ratio, higher activator concentration and improved compactness of the matrix. G60-AN, which had the same precursor and activator composition but higher water content, reached 39.9 MPa. This difference indicates that water reduction improves strength, although the magnitude of improvement was moderate within the tested W/P range. Activator composition had a stronger influence than water reduction. Partial replacement of sodium metasilicate anhydrous with sodium hydroxide reduced 28-day compressive strength to 26.2 MPa, while replacement with sodium silicate GD resulted in 29.1 MPa. The reduction can be attributed to changes in activator modulus, lower availability of reactive silicate, slower dissolution, heat-release differences and a higher probability of unreacted particles or microvoids. These results support the selection of sodium metasilicate anhydrous as a single activator for fly ash/GGBFS one-part geopolymer concrete.

Tensile-related performance followed the same general pattern. The flexural strength of the geopolymer mixtures ranged from 4.55 to 6.35 MPa, and the splitting tensile strength ranged from 3.65 to 5.05 MPa. G60-AN-0.35 reached the highest flexural strength among the geopolymer mixtures, showing that lower water content and a more compact pore structure are particularly important for resisting tensile cracking. The cement reference remained slightly higher in absolute terms, but

the optimized geopolymer mixture provided a comparable strength profile.

Table 2. Selected 28-day mechanical properties.

Mix ID	Compressive strength, MPa	7-d/28-d strength, %	Flexural strength, MPa	Splitting tensile strength, MPa
G05-AN	37.0 +/- 1.06	76	5.70 +/- 0.02	5.05 +/- 0.12
G60-AN	39.9 +/- 0.44	83	4.95 +/- 0.42	5.05 +/- 0.07
G60-AN-0.35	41.7 +/- 0.46	80	6.35 +/- 0.11	5.05 +/- 0.40
G60-ANSH	26.2 +/- 0.53	76	4.55 +/- 0.35	3.65 +/- 0.05
G60-ANGD	29.1 +/- 1.94	66	5.20 +/- 0.37	3.70 +/- 0.22
OPC	46.1 +/- 0.07	75	6.50 +/- 0.54	5.30 +/- 0.29

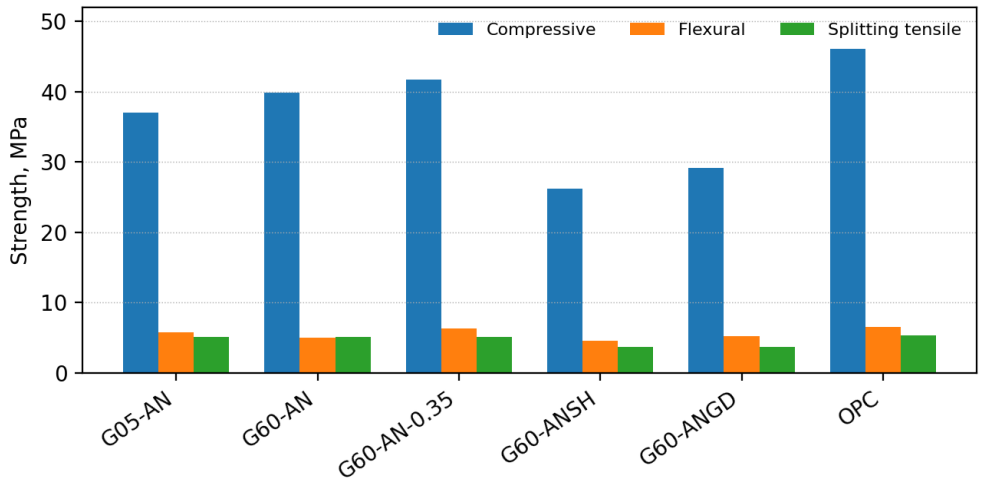

Figure 1. Comparison of 28-day compressive, flexural and splitting tensile strengths.

3.3. Moisture transport and pore-structure interpretation

Water absorption and permeable void volume were generally higher in the one-part geopolymer concretes than in the cement reference. This behaviour is linked to the role of water in geopolymerization. In cement hydration, a considerable part of the mixing water becomes chemically involved in hydration products. In geopolymer binders, a larger fraction remains physically held; during drying, this water can leave discontinuous pores and capillary channels. For this reason, water dosage must be treated as a microstructural design parameter rather than only as a workability adjustment.

The 60/40 fly ash/GGBFS mixtures produced a more favourable pore structure than the slag-dominant mixture. The fly ash fraction contributed sodium aluminosilicate gel and unreacted spherical particles that could act as microfillers, while GGBFS supplied calcium-rich phases that supported the formation of calcium aluminosilicate hydrate type products. This combination helped balance reactivity and matrix densification. In contrast, very high GGBFS content increased early reaction intensity and could produce higher mesopore volume, leading to greater capillary pressure and dimensional instability.

Microstructural observations also explain why the single-activator mixtures performed better than the binary activator mixtures. Lower pore and microcrack presence was associated with G60-AN-0.35, whereas the mixtures containing sodium hydroxide or sodium silicate GD showed less favourable pore development. In the sodium hydroxide-modified system, activator modulus decreased below the preferred range for this precursor combination. In the sodium silicate GD-modified system, hydrous composition and lower dissolution rate reduced reaction efficiency. Both cases led to a weaker and more porous matrix than the mixture activated only with sodium metasilicate anhydrous.

3.4. Shrinkage, creep and restrained deformation

Free drying shrinkage of the one-part geopolymer concretes was comparable to or higher than that of the cement reference, depending on precursor balance. The

slag-dominant G05-AN mixture was the most critical case, with one-year shrinkage substantially higher than the 60/40 fly ash/GGBFS mixtures. Its high early-age shrinkage can be attributed to rapid calcium-related reactions, internal self-desiccation and mesopore-induced capillary pressure. This confirms that excessive slag content may improve early reaction but can compromise dimensional stability.

The 60/40 fly ash/GGBFS mixtures showed more controlled shrinkage. G60-AN and G60-AN-0.35 had similar one-year shrinkage levels despite different water contents, indicating that pore-size distribution and reaction products were at least as important as total water dosage. The sodium silicate GD-modified mixture showed higher shrinkage than G60-AN, especially at early age, which agrees with its slower activation and more porous microstructure.

Creep behaviour also depended on water content and precursor balance. The low-water G60-AN-0.35 mixture recorded the lowest creep strain and creep coefficient among the geopolymer mixtures and the cement reference. Its improved performance is consistent with higher compressive strength, better ultrasonic pulse velocity, fewer microcracks and lower pore volume in the critical mesopore range. In contrast, the slag-dominant mixture had the highest creep response because its pore system provided more pathways for moisture movement and stress redistribution.

Restrained shrinkage was more favourable in optimized one-part geopolymer mixtures than in the cement reference. While free shrinkage was not always lower, the restrained deformation of several geopolymer mixtures was considerably reduced. This behaviour can be associated with a combination of lower modulus of elasticity, stress relaxation through creep, adequate tensile resistance and a layer-dependent pore profile. Therefore, dimensional performance of one-part geopolymer concrete should be evaluated under both free and restrained conditions rather than inferred from free shrinkage alone.

3.5. Material design implications

The results suggest that powdered sodium metasilicate anhydrous is most effective when it is used as the sole activator in a balanced fly ash/GGBFS binder. A 60/40 precursor ratio provided a better compromise than a slag-dominant system because it combined sufficient calcium-assisted reaction with lower shrinkage and improved fresh-state behaviour. The addition of sodium hydroxide or sodium silicate GD did not improve overall performance and instead reduced strength or increased pore-related defects.

For practical mixture design, the water-to-precursor ratio must be selected according to the target property. W/P = 0.45 provided more workable consistency and longer open time, whereas W/P = 0.35 improved strength, flexural response, pore compactness and creep resistance. Consequently, a low-water mixture may be preferable when high mechanical performance is required, but mixture adjustment or compatible admixture development may be needed to maintain sufficient workability.

Overall, the one-part geopolymer concept shows that ambient curing can be compatible with useful mechanical and serviceability performance when activator type, precursor ratio and water dosage are optimized together. The central design principle is pore-structure control: compositions that reduce connected capillary pores and microcracks tend to show higher strength, lower creep and better restrained deformation.

4. Conclusions

1. Ambient-cured one-part geopolymer concrete activated mainly by powdered sodium metasilicate can achieve a 28-day compressive strength range of 26.2-41.7 MPa without heat curing or liquid alkaline solutions.
2. The most balanced composition was the 60/40 fly ash/GGBFS binder activated solely with sodium metasilicate anhydrous. This mixture benefited from the coexistence of fly ash-derived aluminosilicate gel and slag-derived calcium-rich reaction products.
3. Reducing the water-to-precursor ratio from 0.45 to 0.35 improved compressive strength, flexural strength and creep resistance, but it also accelerated setting and increased early flow loss. Therefore, water content should be optimized jointly for fresh and hardened performance.
4. Partial replacement of sodium metasilicate anhydrous with sodium hydroxide or sodium silicate GD was not beneficial in the tested system. The modified activator systems produced lower compressive strength and less favourable microstructural characteristics.
5. The geopolymer mixtures generally showed higher water absorption and permeable void volume than the Portland cement reference, indicating that pore refinement remains a critical issue in one-part geopolymer concrete design.
6. Free drying shrinkage was strongly affected by slag content and pore-size distribution. The slag-dominant mixture showed the highest dimensional instability,

while the 60/40 fly ash/GGBFS mixtures gave more controlled shrinkage behaviour.

7. Optimized one-part geopolymer mixtures exhibited lower creep and restrained shrinkage than the cement reference, demonstrating that serviceability performance depends on the combined influence of stiffness, tensile resistance, stress relaxation and pore gradation.

8. Future studies should focus on compatible admixtures, curing moisture control, lower water-to-precursor ratios and microstructure-guided mixture design to further improve the reliability of powdered sodium metasilicate-activated one-part geopolymer concrete.

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