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Dimensional Stability of Ambient-Cured One-Part Geopolymer Concrete Activated by Powdered Sodium Metasilicate: Drying Shrinkage, Restrained Shrinkage and Creep

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Abstract

Dimensional stability is one of the key serviceability criteria for geopolymer concrete, especially when the binder is produced by a one-part route and cured at ambient temperature. This paper evaluates drying shrinkage, restrained shrinkage and compressive creep of one-part geopolymer concrete activated mainly with powdered sodium metasilicate anhydrous. The binder system was based on class F fly ash and ground granulated blast furnace slag (GGBFS), and the assessment focused on the effects of slag content, water-to-precursor ratio and solid activator composition. Five one-part mixtures were compared with an ordinary Portland cement concrete reference. Free shrinkage was monitored for one year together with mass loss and ultrasonic pulse velocity, while restrained shrinkage was measured on slab specimens by a photogrammetry-based procedure. Creep was evaluated under sustained compressive stress applied at 28 days. The slag-dominant mixture showed the highest one-year free shrinkage, reaching 1769 microstrain, whereas mixtures containing 60% fly ash and 40% GGBFS generally remained between 723 and 1091 microstrain. Lowering the water-to-precursor ratio from 0.45 to 0.35 reduced creep strain from about 1706 to 1551 microstrain and decreased the creep coefficient from 2.56 to 1.87. Restrained shrinkage of geopolymer mixtures was markedly lower than that of the Portland cement reference, with optimized mixtures remaining around 255-270 microstrain after one year. The results show that powdered sodium metasilicate can produce dimensionally stable one-part geopolymer concrete when slag content and water dosage are controlled to limit mesopore development, capillary pressure and early-age self-desiccation.

Keywords: One-part geopolymer concrete; powdered sodium metasilicate; drying shrinkage; restrained shrinkage; creep; GGBFS; fly ash; dimensional stability; pore structure.

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1. Introduction

Ordinary Portland cement concrete has a long record of predictable strength development, but its production is associated with high energy use and a considerable carbon footprint. Geopolymer and alkali-activated binders have therefore been studied as alternative binder systems in which aluminosilicate powders react in alkaline media to form hardened matrices with engineering properties comparable to conventional concrete [1,2]. Fly ash and GGBFS are among the most frequently used precursors because they are available industrial by-products and can form sodium aluminosilicate hydrate and calcium aluminosilicate hydrate type reaction products. The relative amount of these products governs not only strength, but also pore refinement, moisture transport and volume stability.

A practical limitation of conventional geopolymer concrete is the use of strongly alkaline liquid activators. Two-part systems based on sodium hydroxide and sodium silicate can develop high mechanical strength; however, they create problems related to corrosiveness, heat release during solution preparation, storage and handling requirements, and possible rapid setting. One-part geopolymer technology mitigates these challenges by combining the precursor powders with a solid alkaline activator. Water is then added during batching, which makes the process closer to ordinary concrete production and improves the possibility of wider industrial use [3].

The long-term dimensional behaviour of one-part geopolymer concrete requires special attention. Concrete shrinkage and creep influence cracking risk, serviceability and durability. In alkali-activated binders, shrinkage is not controlled solely by external moisture loss; it is also affected by self-desiccation, chemical rearrangement, capillary pressure in fine pores, activator chemistry and the amount of calcium-rich slag in the precursor [4-7]. These mechanisms may differ from those in Portland cement concrete, so conventional prediction models cannot be applied without verification. Powdered sodium metasilicate anhydrous is a promising activator for one-part fly ash/GGBFS systems because its low silica modulus can produce high alkalinity and sufficient soluble silicate for precursor dissolution under ambient curing. Nevertheless, excessive slag content may intensify autogenous deformation, whereas excessive water may leave connected capillary pores after evaporation. The same factors can also affect creep by changing the amount of mobile water and the degree of microstructural restraint under sustained load [8-12].

The aim of this paper is to assess the dimensional stability of ambient-cured one-part geopolymer concrete activated mainly with powdered sodium metasilicate. The study emphasizes three interconnected serviceability responses: free drying shrinkage, restrained shrinkage and compressive creep. The novelty of the assessment is the combined interpretation of these behaviours through precursor balance, water-to-precursor ratio, activator type, mass loss and pore-structure indicators rather than considering shrinkage or creep as isolated properties.

2. Methods

2.1. Materials and mixture design

The geopolymer binder consisted of class F fly ash and GGBFS. Powdered sodium metasilicate anhydrous was used as the principal solid alkaline activator. Two modified activator combinations were also considered: one mixture included partial replacement of sodium metasilicate with sodium hydroxide pellets, and another included partial replacement with sodium silicate Grade D powder. An ordinary Portland cement concrete mixture was used as the reference material.

The mixture matrix was selected to separate the effects of precursor ratio, water dosage and activator composition. G05-AN was a slag-dominant mixture containing 5% fly ash and 95% GGBFS. The G60 series contained 60% fly ash and 40% GGBFS. G60-AN and G60-AN-0.35 used sodium metasilicate anhydrous as the sole activator, while their water-to-precursor ratios were 0.45 and 0.35, respectively. G60-ANSH and G60-ANGD were used to evaluate binary solid activator systems. In all geopolymer concretes, the total solid activator dosage was maintained at 10% of the precursor mass.

Table 1. Mixture proportions of one-part geopolymer concrete and conventional concrete.

Mix ID	OPC	Fly ash	GGBFS	Sand	7 mm agg.	14 mm agg.	SM-AN	SH	SS-GD	W/P or W/C
G05-AN	0	20	380	600	600	600	40	0	0	0.45

G60-AN	0	240	160	600	600	600	40	0	0	0.45
G60-AN-0.35	0	240	160	600	600	600	40	0	0	0.35
G60-ANSH	0	240	160	600	600	600	28.5	11.5	0	0.45
G60-ANGD	0	240	160	600	600	600	20	0	20	0.45
OPC	400	0	0	600	600	600	0	0	0	0.45

Note: all material quantities are in kg/m3. SM-AN = sodium metasilicate anhydrous; SH = sodium hydroxide; SS-GD = sodium silicate Grade D; W/P = water-to-precursor ratio for geopolymer mixtures; W/C = water-to-cement ratio for the Portland cement reference.

2.2. Test program and curing regime

The test program was designed to describe volume change under three conditions. Free drying shrinkage was measured on 280 x 75 x 75 mm prisms. Length change was recorded from the time of demoulding and continued for one year. The first seven days were used to identify early-age deformation while the geopolymer specimens were sealed, and subsequent readings represented the combined drying response under controlled exposure. Mass loss and ultrasonic pulse velocity (UPV) were monitored to link volume change to moisture removal and microstructural integrity.

Restrained shrinkage was evaluated on 500 x 500 x 100 mm concrete slabs cast on grooved steel plates and restrained by internal bolts. A photogrammetry-based measurement system tracked target-point movement on the exposed surface for one year. This approach allowed surface deformation to be quantified without relying on embedded gauges and provided a closer representation of restrained drying than free-prism tests.

Compressive creep was measured on 150 x 300 mm cylinders. At 28 days, specimens were loaded to approximately 40% of their compressive strength. Companion unloaded specimens were used to subtract environmental length change. Creep strain, specific creep strain and creep coefficient were calculated from the measured load-induced deformations. Geopolymer specimens were cured under ambient laboratory conditions of approximately 23 +/- 3 °C after casting, while the Portland cement reference followed conventional water curing before testing.

3. Results And Discussion

3.1. Free shrinkage and early-age deformation

The free shrinkage response showed that precursor composition was the dominant factor governing dimensional stability. The slag-dominant G05-AN mixture reached a total one-year shrinkage of 1769 microstrain, while G60-AN reached 937 microstrain. Therefore, raising the GGBFS fraction from 40% to 95% nearly doubled the total length change. This behaviour indicates that high-calcium, highly reactive slag systems are more vulnerable to early-age self-desiccation and capillary-pressure-driven deformation.

The first seven days were particularly important because the specimens were still sealed and external drying was minimal. G05-AN developed 521 microstrain of shrinkage during this period, indicating that a large part of its deformation was autogenous or chemical rather than purely drying-induced. This interpretation was supported by the almost negligible mass loss during the sealed period. The finding is consistent with the expected rapid reaction of slag-rich binders, where calcium-bearing phases form dense but moisture-sensitive gels and generate internal suction before the matrix has gained sufficient resistance to deformation.

A more balanced fly ash/GGBFS binder clearly improved dimensional stability. G60-AN and G60-AN-0.35 showed similar one-year total free shrinkage values of 937 and 889 microstrain, respectively. The early-age length change of these mixtures was small: G60-AN showed only 16 microstrain of shrinkage, whereas G60-AN-0.35 showed a minor expansion of 26 microstrain. The presence of fly ash likely moderated early reaction, while unreacted spherical particles contributed a micro-aggregate effect that reduced internal deformation.

Changing the activator composition modified the early-age deformation path. Replacing part of sodium metasilicate with sodium hydroxide produced the lowest one-year total shrinkage among the G60 mixtures, 723 microstrain, and the specimen expanded by about 154 microstrain during the first seven days. By contrast, the mixture containing sodium silicate Grade D reached 1091 microstrain and showed early shrinkage of 174 microstrain. This difference suggests that not only alkalinity, but also the dissolution rate and silica modulus of the solid activator control the first stage of reaction and the final pore system.

Table 2. One-year free shrinkage and early-age volume-change indicators.

Mix ID	Main variable	Total free shrinkage after 1 year (microstrain)	First 7-day deformation	Observed implication
G05-AN	95% GGBFS	1769	521 microstrain shrinkage	High autogenous/chemical shrinkage
G60-AN	60% FA / 40% GGBFS	937	16 microstrain shrinkage	Balanced response
G60-AN-0.35	Lower W/P	889	26 microstrain expansion	Improved matrix uniformity
G60-ANSH	SM-AN + SH	723	154 microstrain expansion	Lowest total free shrinkage
G60-ANGD	SM-AN + SS-GD	1091	174 microstrain shrinkage	More early-age instability

Note: positive values indicate absolute shrinkage magnitude; early-age expansion is reported as expansion rather than negative shrinkage for clarity.

3.2. Moisture loss, UPV and pore-structure interpretation

Mass loss alone could not explain the shrinkage of the slag-rich mixture. After one year, G05-AN, G60-AN and the Portland cement reference lost approximately 4.69%, 4.80% and 4.19% of their initial mass, respectively. Despite this comparable moisture loss, G05-AN shrank much more than the other mixtures. The result indicates that the distribution of water within the pore network and the size of pores are more important than the absolute amount of evaporated water.

UPV measurements reinforced this interpretation. The slag-dominant mixture showed a 31% reduction in pulse velocity after the start of drying, which can be linked to the formation of pores and microcracks. In the G60 mixtures, reducing W/P from 0.45 to 0.35 decreased the one-year mass loss from 4.80% to 3.68% and improved the final UPV from 2.89 to 3.10 km/s. Thus, lower water dosage produced a more coherent matrix and limited the formation of connected voids after water evaporation.

The pore-structure evidence supports the observed shrinkage sequence. Mixtures with higher GGBFS content and mixtures containing sodium silicate Grade D developed larger mesopore volumes and higher internal surface area. These features increase capillary pressure and make the matrix more sensitive to internal moisture redistribution. In contrast, the low-water G60-AN-0.35 mixture exhibited a more refined structure and better long-term uniformity. Therefore, shrinkage resistance in one-part geopolymer concrete should be designed through a pore-structure-oriented approach rather than by strength grade alone.

3.3. Creep behaviour under sustained compression

The creep results showed that the same parameters controlling free shrinkage also influenced time-dependent deformation under sustained load. G05-AN exhibited the largest one-year creep strain, 2731 microstrain, and the highest creep coefficient, 5.15. This response is notable because G05-AN had relatively high compressive strength and instantaneous stiffness compared with some G60 mixtures. Its high creep was therefore attributed mainly to its pore structure, high mesopore volume and greater capacity for internal water movement under stress.

The balanced G60-AN mixture reached a one-year creep strain of approximately 1706 microstrain and a creep coefficient of 2.56. Lowering the water-to-precursor ratio to 0.35 improved the creep response: G60-AN-0.35 reached 1551 microstrain and a coefficient of 1.87. This represents a 9% reduction in creep strain and a 27% reduction in creep coefficient relative to G60-AN. Although the low-water mixture showed higher instantaneous strain when the load was applied, its denser microstructure provided better resistance to subsequent creep development.

Binary activator mixtures had intermediate behaviour. G60-ANSH showed a lower creep coefficient than G60-AN, while G60-ANGD showed a slight increase in creep strain, about 1846 microstrain after one year. The increase in G60-ANGD can be associated with the lower reactivity and higher silica modulus of sodium silicate Grade D compared with sodium metasilicate anhydrous. However, the presence of unreacted fly ash particles probably restricted a more severe creep increase by acting as rigid micro-inclusions within the binder matrix.

The Portland cement reference developed 2073 microstrain of creep in one year, which was higher than all G60 geopolymer mixtures but lower than the slag-dominant G05-AN mixture. The creep development pattern also differed: a major fraction of OPC creep occurred at early age, while geopolymer creep continued to grow at a more persistent rate. This explains why conventional creep prediction models may overestimate early geopolymer creep yet underestimate the longer-term trend.

Table 3. One-year creep performance of selected concrete mixtures.

Mix ID	Compressive strength at loading (MPa)	Applied stress (MPa)	Instantaneous strain (microstrain)	1-year creep strain (microstrain)	1-year creep coefficient
G05-AN	39.5	15.8	530	2731	5.15
G60-AN	36.0	14.4	662	1706	2.56
G60-AN-0.35	48.0	19.2	848	1551	1.87
G60-ANSH	26.5	10.5	659	~1550	2.35
G60-ANGD	38.0	15.2	790	1846	~2.34
OPC	50.0	20.3	426	2073	~4.87

Note: approximate coefficients were calculated from reported creep strain and instantaneous strain where exact rounded values were not tabulated separately.

3.4. Restrained shrinkage and cracking tendency

Restrained shrinkage differed substantially from free shrinkage. The Portland cement reference showed similar values in free and restrained conditions: its one-year free drying shrinkage after the start of drying was 844 microstrain, and its restrained shrinkage reached 951 microstrain. This suggests that the shrinkage gradient and restraint arrangement did not reduce the measured deformation in the cement reference.

The one-part geopolymer mixtures behaved differently. Their one-year restrained shrinkage ranged from 28% to 51% of the corresponding free shrinkage. G05-AN and G60-AN produced the highest restrained shrinkage values, 510 and 466 microstrain, respectively. The remaining G60 mixtures, G60-AN-0.35, G60-ANSH and G60-ANGD, remained close to each other at approximately 255-270 microstrain. Therefore, the optimized low-water and binary-activated mixtures showed much lower restrained deformation than the Portland cement reference.

The lower restrained shrinkage of geopolymer concrete can be explained by stress relaxation and microstructural gradation. Under restraint, shrinkage generates tensile stress. If the material has adequate tensile capacity and sufficient tensile creep, part of this stress can be relaxed before visible cracking occurs. The geopolymer mixtures had lower elastic modulus than the cement reference and, in many cases, higher specific creep under comparable stress. These characteristics can reduce the effective tensile stress generated by restraint.

Surface observations confirmed that high total shrinkage is not the only criterion for cracking. G05-AN developed a network of narrow microcracks, approximately 0.01 mm wide, which was consistent with its large early-age deformation and dry surface condition. In contrast, the other geopolymer slabs remained visually crack-free despite experiencing measurable restrained shrinkage. Early wet surface curing would therefore be particularly important for slag-dominant one-part mixtures, whereas balanced fly ash/GGBFS systems showed better intrinsic cracking resistance.

Table 4. Restrained shrinkage and surface cracking response after one year.

Mix ID	1-year restrained shrinkage (microstrain)	Relation to free shrinkage	Surface condition
G05-AN	510	High among GPC mixtures	Narrow microcrack network observed
G60-AN	466	Lower than free shrinkage	No visible surface cracking
G60-AN-0.35	255-270	Substantially lower than free shrinkage	No visible surface cracking
G60-ANSH	255-270	Substantially lower than free shrinkage	No visible surface cracking
G60-ANGD	255-270	Substantially lower than free shrinkage	No visible surface cracking in slab
OPC	951	Similar to free drying shrinkage	Reference behaviour

3.5. Implications for mixture design

The results indicate that dimensional stability of one-part geopolymer concrete should not be judged from compressive strength alone. G05-AN achieved a mature hardened matrix, but the very high slag content increased early-age self-desiccation, mesopore volume and shrinkage-related cracking susceptibility. In contrast, a 60/40 fly ash/GGBFS binder moderated early reaction and limited both free shrinkage and creep.

Water reduction produced two different effects. It shortened the processing window in the fresh state, but it also decreased mass loss, increased UPV retention and improved creep resistance. Hence, low W/P is beneficial for hardened stability only when the mixture still has enough workability for proper placement and compaction.

The activator type also matters. Sodium metasilicate anhydrous alone provided a stable baseline response in the 60/40 binder. Partial replacement with sodium hydroxide reduced free shrinkage and creep coefficient but lowered mechanical strength. Partial replacement with sodium silicate Grade D increased early shrinkage and creep slightly, probably because of a less reactive pore network. These results support using powdered sodium metasilicate anhydrous as the principal activator, while any binary activator modification should be justified by a clear serviceability target.

4. Conclusions

1. The dimensional stability of ambient-cured one-part geopolymer concrete was governed primarily by the

GGBFS content, water-to-precursor ratio and solid activator composition. The slag-dominant mixture experienced the largest free shrinkage and creep, despite showing adequate mechanical strength.

2. A balanced 60% fly ash and 40% GGBFS precursor system activated with powdered sodium metasilicate anhydrous provided a more stable free-shrinkage response than the slag-dominant system. The reduction in shrinkage was attributed to moderated reaction kinetics, lower early self-desiccation and the micro-aggregate effect of partially unreacted fly ash particles.
3. Reducing W/P from 0.45 to 0.35 improved long-term creep resistance. The low-water mixture had a one-year creep strain of 1551 microstrain and a creep coefficient of 1.87, compared with about 1706 microstrain and 2.56 for the corresponding mixture with W/P = 0.45.
4. Restrained shrinkage of the one-part geopolymer concretes was markedly lower than that of the Portland cement reference. Optimized geopolymer mixtures had one-year restrained shrinkage around 255-270 microstrain, whereas the conventional concrete reached 951 microstrain.
5. High free shrinkage did not automatically produce high restrained shrinkage, because stress relaxation, lower elastic modulus and possible tensile creep reduced restrained deformation in geopolymer slabs. However, the slag-dominant mixture still developed narrow surface microcracks, indicating the need for early moisture protection when GGBFS content is very high.
6. Powdered sodium metasilicate anhydrous can be considered an effective activator for dimensionally stable one-part geopolymer concrete if the precursor ratio and water dosage are optimized together. Future studies should validate the restrained-shrinkage and creep mechanisms on larger slabs and develop prediction models calibrated specifically for one-part geopolymer concrete.

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