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Durability Performance of E-Waste Plastic Incorporated Ambient-Cured Metakaolin–Fly Ash Geopolymer Concrete

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Abstract

The disposal of electronic waste (e-waste) and the environmental burden associated with Portland-cement production are two complementary sustainability challenges for the construction sector. This study experimentally investigates the durability of e-waste plastic (EWP) incorporated ambient-cured metakaolin–fly ash geopolymer concrete (MK–FA GPC). An optimized binary geopolymer matrix containing 60% metakaolin and 40% fly ash was developed using 10 M NaOH, a liquid-to-binder ratio of 0.60 and a sodium-silicate-to-sodium-hydroxide ratio of 2.5. EWP, characterized in the thesis as a low-density, predominantly flaky/elongated material with a maximum size of 10 mm, specific gravity of 1.10 and water absorption of 0.10%, was used as partial coarse-aggregate replacement at 0, 2.5, 5, 7.5, 10, 12.5 and 15%. Durability was assessed using water absorption, sorptivity, rapid chloride permeability, 5% sulphuric-acid exposure, sodium-sulphate exposure and saltwater exposure. Mechanical properties and non-destructive measurements were used to establish the engineering trade-off associated with increasing EWP. Water absorption decreased from 4.97% for the control to 4.38% at 5% EWP and 3.45% at 15% EWP; 120-min sorptivity decreased from 0.060 to 0.047 and 0.031, respectively. Ninety-day RCPT charge decreased from 881 C for the control to 863 C at 5% and 803 C at 15% EWP. At 120 days, 5% EWP reduced sulphuric-acid mass loss from 25.35 to 21.54% and strength loss from 28.92 to 22.88%; sodium-sulphate strength loss decreased from 9.56 to 8.23%; and saltwater mass and strength losses decreased from 2.31 to 1.80% and 8.16 to 7.15%, respectively. In contrast, 28-day compressive strength decreased from 42.31 MPa for the control to 39.34 MPa at 5% and 26.86 MPa at 15% EWP. The results demonstrate that EWP can improve selected transport and chemical-exposure indicators while progressively reducing mechanical strength. Within the investigated range, 5% EWP provided the most balanced performance and retained an M30-level compressive strength. The findings support the feasibility of EWP utilization in ambient-cured MK–FA GPC but also demonstrate that lower absorption or chloride charge alone cannot establish comprehensive durability. Polymer-specific characterization, leaching,

thermal/fire performance, long-term diffusion, coupled exposures and life-cycle assessment are required before field-scale implementation.

Keywords: *E-waste plastic; geopolymer concrete; metakaolin; fly ash; durability; sorptivity; chloride permeability; sulphuric acid; sulphate attack; saltwater; ambient curing; recycled aggregate.*

1. Introduction

The construction industry is under increasing pressure to reduce its dependence on Portland cement and virgin mineral resources while maintaining long-term performance. Geopolymer concrete (GPC) provides one pathway because aluminosilicate-rich materials such as fly ash and metakaolin can be activated with alkaline solutions to produce cementless binders. Metakaolin is particularly useful in ambient-cured systems because of its high reactivity, while fly ash can contribute resource efficiency and favorable fresh-state characteristics. The thesis underlying this study optimized a binary metakaolin–fly ash system before introducing e-waste plastic as a coarse-aggregate replacement.

E-waste presents a separate waste-management challenge. Electronic products contain metals, glass, ceramics and polymeric components, and the polymer fraction is difficult to manage when discarded. The present study does not use e-waste plastic as a geopolymer precursor; rather, it uses processed EWP as partial replacement of natural coarse aggregate. This distinction is important because the plastic phase modifies the aggregate skeleton, density, water transport and interfacial transition zone rather than directly participating in the principal aluminosilicate geopolymer reaction.

Recent literature indicates growing interest in waste plastic and e-waste as aggregate in geopolymer and cement-based concrete. A 2024 Journal of Environmental Management review synthesized fresh, physical, mechanical, durability and microstructural behavior of plastic-supplemented geopolymer concrete and highlighted the need for standardized characterization of plastic types and thermal behavior. A 2025 Heliyon study of e-waste plastic aggregate concrete reported strength reductions with increasing replacement but improved selected durability indicators and identified 15% as optimum for its particular conventional-concrete system. A 2025 Construction and Building Materials study further showed that silica fume could improve the performance of e-waste plastic aggregate concrete by improving bonding and reducing acid-related deterioration.

Despite these developments, comparatively limited evidence is available for EWP in an ambient-cured binary MK–FA geopolymer system in which water transport, chloride permeability and multiple chemical exposures are investigated together. The thesis provides such a dataset. The objective of the present paper is therefore to isolate and critically evaluate the durability implications of EWP addition, while retaining mechanical performance as a necessary engineering constraint.

2. Research Gap and Objectives

The thesis identified EWP use in geopolymer concrete as an underdeveloped area, particularly for coarse-aggregate replacement in dual-binder systems. It also identified the need for durability evaluation under water, chloride, acid, sulphate and saltwater environments. The present paper is organized specifically around that durability gap.

- To establish the optimized ambient-cured MK–FA geopolymer matrix used as the reference concrete.
- To investigate the effect of 0–15% EWP replacement on water absorption and sorptivity.
- To evaluate the effect of EWP on electrical chloride permeability using RCPT at 28 and 90 days.
- To quantify mass and strength loss under sulphuric-acid, sodium-sulphate and saltwater exposures.
- To compare durability gains with the associated loss of mechanical strength.
- To identify an application-oriented optimum EWP content rather than maximizing waste incorporation.

3. Materials and Experimental Programme

3.1. Geopolymer binder

The reference geopolymer matrix was optimized in the thesis before EWP replacement. The selected binder contained 60% metakaolin and 40% fly ash. The optimum NaOH concentration was 10 M, the liquid-to-binder ratio was 0.60 and the sodium-silicate-to-sodium-hydroxide ratio was 2.5. The selected matrix achieved a 28-day compressive strength of 42.306 MPa.

3.2. E-waste plastic aggregate

The EWP used in the study had a maximum particle size of 10 mm, specific gravity of 1.10 and water absorption of 0.10% and was predominantly flaky/elongated. These characteristics distinguish it from conventional mineral coarse aggregate and provide the physical basis for the observed changes in workability, density, stiffness and water transport.

3.3. Mix proportions

Table 1: EWP replacement levels used in the experimental programme

Mix ID	EWP replacement (%)
BR60	0
EWP2.5	2.5
EWP5	5
EWP7.5	7.5
EWP10	10
EWP12.5	12.5
EWP15	15

EWP replacement was investigated over a sufficiently broad range to identify the point at which durability improvements were offset by unacceptable mechanical degradation. The control BR60 represents the optimized MK–FA geopolymer matrix without EWP.

3.4. Durability testing

Water absorption and sorptivity were measured after curing. Chloride permeability was assessed using ASTM C1202-based RCPT at 28 and 90 days. Sulphate resistance was evaluated using ASTM C1012-2015. Acid exposure used 5% H_2SO_4, and saltwater was prepared according to ASTM D1141-1998. The experimental programme also included petrographic image analysis, SEM, EDS and elemental mapping.

Table 2: Durability tests, exposure conditions and reported ages

Property	Exposure/measurement	Ages reported
Water absorption	Absorption test	7 and 28 d
Sorptivity	Capillary absorption	Up to 120 min
RCPT	ASTM C1202	28 and 90 d
Acid resistance	5% H_2SO_4 immersion	28, 60 and 120 d
Sulphate resistance	Na_2SO_4; ASTM C1012	28, 60 and 120 d
Saltwater resistance	ASTM D1141 solution	28, 60 and 120 d
Microstructure	Petrography, SEM, EDS, mapping	Selected mixes

4. Results and Discussion

4.1. Fresh-state behavior

Increasing EWP content increased slump from 78 mm for BR60 to 116 mm for EWP15. The thesis attributes this trend to the hydrophobic character and very low water absorption of the plastic particles. Workability remained classified as medium through EWP10 and became high at EWP12.5 and EWP15.

Table 3: Slump and workability classification of EWP mixtures

Mix	EWP (%)	Slump (mm)	Classification
BR60	0	78	Medium
EWP2.5	2.5	86	Medium
EWP5	5	90	Medium
EWP7.5	7.5	97	Medium
EWP10	10	98	Medium
EWP12.5	12.5	99	High
EWP15	15	116	High

The improvement in workability is relevant to durability because improved flow may support better compaction; however, excessive workability in a low-density aggregate system can also increase segregation risk. No independent segregation measurement was reported in the thesis, so this possibility should be investigated in future work.

4.2. Mechanical strength as the durability constraint

The 28-day compressive strength decreased monotonically with EWP content, from 42.31 MPa for BR60 to 39.34 MPa at EWP5 and 26.86 MPa at EWP15. The 5% replacement caused approximately 7.0% strength loss, whereas 15% caused approximately 36.5% loss.

Table 4: Compressive strength and 28-day strength loss

Mix	7-d compressive (MPa)	28-d compressive (MPa)	Loss at 28 d (%)
BR60	32.34	42.31	0
EWP2.5	31.96	40.9	3.3
EWP5	30.82	39.34	7.0
EWP7.5	27.26	37.72	10.8
EWP10	25.73	32.54	23.1
EWP12.5	22.14	27.26	35.6
EWP15	21.95	26.86	36.5

The thesis attributes strength loss mainly to replacing stiff mineral aggregate with weaker, flaky and elongated plastic particles. This creates a stiffness mismatch and a less effective load-transfer skeleton. The data establish an important interpretation rule for the durability results: the fact that water transport and

chemical-exposure losses improve at high EWP contents does not make high EWP contents suitable for structural concrete if the strength margin becomes inadequate.

4.3. Split tensile and flexural strength

At 28 days, split tensile strength decreased from 3.77 MPa for BR60 to 3.48 MPa at EWP5 and 2.76 MPa at EWP15. Flexural strength decreased from 3.83 MPa to 3.59 MPa and 2.84 MPa, respectively. The thesis reports that the reduction remains comparatively small up to 5% but becomes more pronounced beyond that level.

This behavior supports the use of 5% as an engineering compromise. The durability improvements are obtained without creating the large tensile and flexural penalties observed at higher replacement levels.

4.4. Non-destructive evaluation

The rebound number decreased from 34 for BR60 to 31 for EWP5 and 14 for EWP15. UPV decreased from 3.58 km/s to 3.28 km/s and 1.83 km/s, respectively. The thesis classified BR60–EWP5 as good, EWP7.5–EWP12.5 as fair and EWP15 as poor under the adopted interpretation.

The NDT results are consistent with the strength trend and show that high EWP replacement alters internal stiffness and continuity. Importantly, the lower UPV at high EWP content should not be interpreted as evidence of poor durability by itself; it primarily indicates a change in the elastic wave path caused by the low-stiffness plastic phase and associated interfaces.

4.5. Water absorption

Water absorption decreased systematically as EWP increased. At 28 days, absorption decreased from 4.97% for BR60 to 4.38% at EWP5 and 3.45% at EWP15. The thesis attributes this behavior to the hydrophobic and low-density characteristics of EWP, which can hinder water uptake.

Table 5: Water absorption of EWP mixtures at 7 and 28 days

Mix	7-d absorption (%)	28-d absorption (%)
BR60	5.23	4.97
EWP2.5	5.08	4.7
EWP5	4.72	4.38
EWP7.5	4.56	4.05
EWP10	4.29	3.98
EWP12.5	4.12	3.78
EWP15	3.98	3.45

Relative to BR60, the 28-day absorption reduction was approximately 11.9% at EWP5 and 30.6% at EWP15. The result indicates that plastic incorporation can reduce measured water uptake even though it simultaneously reduces mechanical strength. This apparent divergence is a central finding of the study.

4.6. Sorptivity

Sorptivity decreased from 0.060 for BR60 to 0.047 at EWP5 and 0.031 at EWP15 at 120 min. The 5% mixture therefore showed approximately 21.7% lower sorptivity than the control. The thesis explains the trend through the hydrophobic nature and low density of EWP and the associated reduction in water absorption.

Table 6: Sorptivity at 120 minutes

Mix	Sorptivity at 120 min
BR60	0.06
EWP2.5	0.057
EWP5	0.047
EWP7.5	0.041
EWP10	0.034
EWP12.5	0.032
EWP15	0.031

Sorptivity is an important indicator but should not be equated with comprehensive durability. The thesis itself notes that lower sorptivity does not establish the absence of interconnected voids, leaching or thermal degradation.

4.7. Chloride permeability

RCPT charge passed decreased with EWP content. At 28 days, the control and EWP5 values were 1118 and 1096 C, respectively; at 90 days they were 881 and 863 C. EWP15 reached 1019 C at 28 days and 803 C at 90 days. The thesis classified the 28-day results as low and the 90-day results as very low under ASTM C1202.

Table 7: RCPT charge passed at 28 and 90 days

Mix	RCPT 28 d (C)	RCPT 90 d (C)
BR60	1118	881
EWP2.5	1107	872
EWP5	1096	863
EWP7.5	1075	847
EWP10	1045	823
EWP12.5	1023	806
EWP15	1019	803

The 90-day RCPT reduction relative to BR60 was approximately 2.0% at EWP5 and 8.9% at EWP15. The trend is consistent with the water-transport results. However, RCPT is an electrical conductance test rather than a direct chloride diffusion measurement, and the ionic conductivity of geopolymer pore solutions can differ from that of OPC. Therefore, the present data support lower electrical permeability but should not be interpreted as direct diffusion coefficients.

4.8. Sulphuric-acid resistance

The acid exposure used 5% H_2SO_4 and evaluated mass and strength loss after 28, 60 and 120 days. Increasing EWP reduced both measures of deterioration. The thesis explains that sulphuric acid attacks the geopolymer gel while the plastic fraction is comparatively resistant under the selected exposure, so increasing the fraction of EWP reduces the fraction of acid-sensitive mineral aggregate and geopolymer surface.

Table 8: Sulphuric-acid resistance at 120 days

Metric at 120 d	BR60	EWP5	Change at EWP5
Mass loss (%)	25.35	21.54	15.0% lower
Strength loss (%)	28.92	22.88	20.9% lower

The improvement is significant at the material level but should be interpreted carefully. EWP itself is not a geopolymer binder and does not prevent deterioration of the surrounding gel. Rather, the plastic fraction is comparatively resistant to the selected aqueous acid exposure and changes the exposed composite surface and transport path. Long-term behavior of the specific e-waste polymer, including additives and contaminants, requires independent characterization.

4.9. Sulphate resistance

Sulphate resistance was evaluated according to ASTM C1012-2015 using sodium sulphate. The control exhibited 6.40% mass loss and 9.56% strength loss at 120 days. EWP5 exhibited 4.90% mass loss and 8.23% strength loss, while EWP15 reached 3.62% mass loss and 7.14% strength loss.

Table 9: Sodium-sulphate resistance: mass and strength loss

Mix	Mass loss 28 d	Mass loss 60 d	Mass loss 120 d	Strength loss 28 d	Strength loss 60 d	Strength loss 120 d
BR60	2.47	2.73	6.4	7.14	8.58	9.56
EWP2.5	1.9	2.18	5.63	6.63	7.39	8.78
EWP5	1.79	2.05	4.9	6.05	6.98	8.23
EWP7.5	1.69	1.98	4.58	5.94	6.67	8.05
EWP10	1.56	1.84	4.14	5.45	6.47	7.64
EWP12.5	1.34	1.72	3.78	4.08	6.18	7.42
EWP15	1.28	1.58	3.62	3.95	5.97	7.14

4.10. Saltwater resistance

Saltwater resistance was evaluated using a solution prepared according to ASTM D1141-1998. The thesis reports progressively lower mass and strength losses with increasing EWP. At EWP5, 120-day mass loss was 1.80% and strength loss was 7.15%, compared with 2.31% and 8.16% for BR60.

Table 10: Saltwater resistance: mass and strength loss

Mix	Mass loss 28 d	Mass loss 60 d	Mass loss 120 d	Strength loss 28 d	Strength loss 60 d	Strength loss 120 d
BR60	1.14	1.86	2.31	5.17	6.24	8.16
EWP2.5	0.98	1.71	2.03	5.1	5.78	7.58
EWP5	0.89	1.57	1.8	5.0	5.3	7.15
EWP7.5	0.85	1.25	1.63	4.72	4.87	6.74
EWP10	0.7	1.07	1.33	4.63	4.73	6.59
EWP12.5	0.63	0.98	1.16	4.42	4.61	6.32
EWP15	0.52	0.86	1.08	4.16	4.31	6.05

4.11. Integrated durability–strength response

The central observation is a divergence between mechanical and durability indicators. Compressive strength, tensile strength, flexural strength, rebound number and UPV all decreased with EWP content, whereas water absorption, sorptivity, RCPT charge and chemical-exposure losses generally decreased. This is physically consistent with the different functions of the phases: plastic is low-density, hydrophobic and relatively resistant to the selected aqueous chemical exposures, but it is less stiff and provides weaker load transfer than mineral coarse aggregate.

Table 11: Integrated durability and strength indicators

Indicator	BR60	EWP5	EWP15	Trend
28-d compressive strength (MPa)	42.31	39.34	26.86	Decreases
28-d split tensile	3.77	3.48	2.76	Decreases

Indicator	BR60	EWP5	EWP15	Trend
strength (MPa)				
28-d flexural strength (MPa)	3.83	3.59	2.84	Decreases
28-d water absorption (%)	4.97	4.38	3.45	Decreases
120-min sorptivity	0.06	0.047	0.031	Decreases
90-d RCPT (C)	881	863	803	Decreases
120-d acid mass loss (%)	25.35	21.54	Not tabulated here	Decreases
120-d acid strength loss (%)	28.92	22.88	Not tabulated here	Decreases
120-d sulphate strength loss (%)	9.56	8.23	7.14	Decreases
120-d saltwater strength loss (%)	8.16	7.15	6.05	Decreases

EWP15 generally gives the lowest measured durability losses, but it also produces the lowest mechanical performance. EWP5 is therefore the optimum only when structural strength is included as a binding criterion. This distinction is essential for a scientifically defensible optimization claim.

5. 5. Durability Mechanisms

5.1. Water transport

The reduction in water absorption and sorptivity is consistent with the very low water absorption of EWP and its hydrophobic surface. The thesis also reports that low-density EWP can accumulate toward specimen surfaces, which may hinder water uptake.

5.2. Chemical resistance

The chemical exposure results indicate that the plastic phase remained comparatively resistant under the selected aqueous acid, sulphate and saltwater conditions. The surrounding geopolymer gel remained the primary phase susceptible to dissolution or chemical modification. Thus, EWP changes the volume fraction and exposed area of chemically reactive material. This mechanism is specific to the EWP used and should not be generalized to all electronic polymers.

5.3. Interfacial transition zone

The mechanical reduction at increasing EWP content is consistent with a weaker plastic–geopolymer interface. The thesis microstructural programme used SEM, EDS and elemental mapping to investigate this interface. The available dataset supports a comparatively continuous matrix at 5% EWP and more low-stiffness inclusions and discontinuities at higher replacement, but does not provide a quantitative interfacial bond-strength measurement.

6. Statistical and Engineering Interpretation

The thesis reported polynomial relationships between EWP content and several properties. For 28-day compressive strength, the reported regression was $y = -0.2463x^2 - 0.9016x + 43.808$ with $R^2 = 0.9592$. For slump, the reported relationship was $y = 0.2143x^2 + 3.5714x + 76.286$ with $R^2 = 0.909$.

These regressions describe the observed trends over the tested 0–15% range and should not be extrapolated beyond it. For SCIE-level reporting, future work should additionally report replicate numbers, standard deviations, confidence intervals and formal significance testing from laboratory records if available.

7. Comparison with Recent Literature

The present results are broadly consistent with recent literature showing that plastic or e-waste aggregate can increase workability and reduce mechanical strength while improving selected durability indicators. A 2024 review of plastic-supplemented geopolymer concrete synthesized fresh, mechanical, durability and microstructural changes and highlighted the absence of a global standard for waste-plastic characterization.

A 2025 experimental study using 0–20% e-waste aggregate in conventional concrete reported mechanical-strength reductions with increasing replacement and improved water-permeability/electrical-resistivity indicators, with 15% identified as optimum for its particular system. The difference between that optimum and the 5% optimum in the present MK–FA GPC study illustrates that replacement percentage cannot be transferred between binder systems, particle forms or performance criteria.

A 2025 Construction and Building Materials study reported that silica fume improved bonding in e-waste plastic aggregate concrete and reduced sulphuric-acid deterioration. This supports a future direction for the present MK–FA system: interfacial modification may allow greater EWP replacement without sacrificing mechanical strength.

Recent work on e-waste aggregates in ambient-cured geopolymer concrete has also shown that optimum replacement depends on whether e-waste is used as fine or coarse aggregate, with substantially different optimum levels reported for the two forms.

8. Sustainability and Practical Significance

The use of EWP in MK–FA GPC offers two complementary resource benefits: diversion of a difficult waste stream and reduction of natural coarse-aggregate demand. The geopolymer binder also replaces Portland cement with metakaolin and fly ash. However, sustainability cannot be inferred from material substitution alone. Alkaline activator manufacture, metakaolin calcination, e-waste collection, sorting, cleaning, shredding and transportation all contribute to environmental impact.

The thesis conducted a cost analysis but did not perform a full life-cycle assessment. The study also did not evaluate leaching or ecotoxicity. These limitations are particularly important for e-waste because electronic polymers may contain additives and residues. Recent reviews identify the absence of global standards for waste-plastic characterization and the need to assess fire behavior and polymer-specific effects.

9. Limitations

- The EWP feedstock was heterogeneous and was not reported as a polymer-by-polymer mass balance.
- Long-term leaching and environmental safety were not investigated.
- Fire and elevated-temperature behavior of the EWP-containing GPC was not experimentally quantified.
- RCPT was used as an electrical permeability indicator; direct chloride diffusion was not measured.
- The chemical exposures were finite-duration laboratory exposures and did not represent all coupled field conditions.
- The optimum 5% EWP content is specific to the selected 60:40 MK–FA binder, 10 M NaOH, 0.60 liquid/binder ratio, 2.5 SS/SH ratio and EWP particle characteristics.
- Life-cycle assessment was not performed; cost analysis alone cannot establish environmental superiority.

- Statistical uncertainty, replicate variability and formal significance testing should be expanded for journal publication.

10. Future Research

- Identify polymer composition using FTIR, DSC/TGA and systematic sorting of the EWP feedstock.
- Investigate mineral coating, surface treatment or coupling strategies to improve the EWP–geopolymer interface.
- Extend chloride assessment to bulk diffusion, migration coefficients and reinforcement-corrosion monitoring.
- Investigate carbonation, wet–dry cycling, freeze–thaw and thermal cycling.
- Quantify fire performance and polymer decomposition products.
- Perform leaching tests for metals and relevant organic additives associated with e-waste.
- Use response-surface methodology or machine learning only after assembling a sufficiently large, replicated dataset.
- Conduct cradle-to-gate and cradle-to-grave LCA including e-waste processing and alkaline activator production.
- Validate the 5% optimum at beam, slab or other structural scale.
- Investigate whether interface modification can increase allowable EWP replacement above 5% while retaining structural strength.

11. Conclusions

This study investigated the durability of ambient-cured MK–FA geopolymer concrete containing 0–15% EWP as partial coarse-aggregate replacement. The principal conclusions are:

- A 60:40 metakaolin–fly ash binder activated with 10 M NaOH, a liquid-to-binder ratio of 0.60 and a Na_2SiO_3/NaOH ratio of 2.5 provided the optimized reference matrix.
- Water absorption and sorptivity decreased progressively with EWP. At 5% EWP, 28-day absorption decreased from 4.97 to 4.38% and 120-min sorptivity from 0.060 to 0.047.
- RCPT charge decreased with EWP, from 881 C for BR60 to 863 C at EWP5 and 803 C at EWP15 at 90 days.
- At 120 days, EWP5 reduced sulphuric-acid mass loss from 25.35 to 21.54% and strength loss from 28.92 to 22.88%; sodium-sulphate strength loss decreased from 9.56 to 8.23%; and saltwater mass and strength losses decreased from 2.31 to 1.80% and 8.16 to 7.15%.
- Mechanical performance decreased monotonically with EWP. At 28 days, compressive strength decreased from 42.31 MPa for BR60 to 39.34 MPa at 5% and 26.86 MPa at 15%.
- The opposing trends demonstrate that EWP improves selected transport and chemical-exposure indicators while reducing stiffness and load-bearing capacity.
- Within the investigated range, 5% EWP provides the most balanced engineering performance because it retains 39.34 MPa compressive strength while providing measurable improvements in water absorption, sorptivity, chloride charge and chemical-exposure resistance.
- 5% should therefore be described as the optimum for the studied performance criteria and material system, not as a universal optimum for all EWP geopolymer concretes.

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