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Experimental Investigation of E-Waste Plastic as Partial Coarse Aggregate Replacement in Ambient-Cured Metakaolin–Fly Ash Geopolymer Concrete

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Abstract

The construction sector requires substantial quantities of cementitious materials and natural aggregates, while the rapid turnover of electrical and electronic equipment generates an increasingly difficult waste stream. This study investigates the feasibility of incorporating processed e-waste plastic (EWP) as a partial replacement for natural coarse aggregate in ambient-cured metakaolin–fly ash geopolymer concrete (MK–FA GPC). The experimental programme first optimized the geopolymer matrix through sequential variation of binder ratio, sodium hydroxide molarity, liquid-to-binder ratio, and sodium silicate-to-sodium hydroxide ratio. The optimum matrix consisted of 60% metakaolin and 40% fly ash, 10 M NaOH, liquid-to-binder ratio of 0.60, and Na_2SiO_3/NaOH ratio of 2.5. EWP was subsequently introduced at 0, 2.5, 5, 7.5, 10, 12.5 and 15% replacement of natural coarse aggregate. The EWP had a maximum particle size of 10 mm, specific gravity of 1.10 and water absorption of 0.10%, and exhibited a flaky/elongated morphology. Increasing EWP increased slump from 78 to 116 mm, but progressively reduced mechanical strength. At 28 days, compressive strength decreased from 42.31 MPa for the control mixture to 39.34 MPa at 5% EWP and 26.86 MPa at 15% EWP. Corresponding split tensile and flexural strengths at 5% EWP were 3.48 and 3.59 MPa, respectively. In contrast, water absorption, sorptivity and chloride charge passed decreased with EWP addition. At 5% EWP, 28-day water absorption decreased from 4.97 to 4.38%, 120-min sorptivity decreased from 0.060 to 0.047, and 90-day RCPT charge decreased from 881 to 863 C. Acid, sulphate and saltwater exposure also showed lower mass/strength losses for EWP-containing mixtures. Petrographic, SEM, EDS and elemental-mapping observations indicated that the geopolymer matrix remained continuous and that the principal N–A–S–H/C–A–S–H gel system was not disrupted by 5% EWP, although the carbon-rich plastic fraction reduced the relative proportion of geopolymeric gel. The results indicate that 5% EWP provides the most balanced combination of mechanical performance and durability within the investigated range. The study demonstrates a technically feasible route for converting a selected e-waste plastic fraction into a construction material, while also identifying the need for polymer-specific characterization, leaching assessment, thermal testing and life-cycle analysis before field-scale deployment.

Keywords: e-waste plastic; geopolymer concrete; metakaolin; fly ash; recycled aggregate; durability; ambient curing; circular economy.

1. Introduction

Concrete is one of the most widely used engineered materials, and its production consumes large quantities of mineral resources. Conventional Portland cement manufacture is energy intensive and associated with substantial greenhouse-gas emissions. Geopolymer and alkali-activated binders have consequently received considerable attention because aluminosilicate-rich materials such as fly ash and metakaolin can be activated to form inorganic polymeric binders. The thesis underlying this manuscript identifies the environmental burden of cement production as a principal motivation for geopolymer concrete and notes the potential of waste-derived aluminosilicates to reduce dependence on Portland cement.

Electronic waste is a separate but complementary sustainability challenge. End-of-life electrical and electronic equipment contains metals, glass, ceramics and a heterogeneous polymer fraction. The uploaded thesis investigated discarded/cracked plastic panels, printed-circuit-board-related plastic fractions and other electronic plastics after size reduction. The material was used as a partial coarse-aggregate replacement rather than as a precursor to geopolymerization. This distinction is important because the engineering function of the EWP in the present study is primarily physical aggregate replacement.

Previous research has demonstrated that plastic aggregates can increase workability and reduce density while generally lowering mechanical strength as replacement increases. More recent studies have also shown that e-waste plastic aggregate concrete can benefit from interfacial modification and mineral additions. However, relatively limited experimental evidence is available for EWP in ambient-cured binary metakaolin–fly ash GPC, particularly when mechanical properties, non-destructive testing, multiple durability exposures and microstructural characterization are considered together. The present study addresses this gap using the experimental dataset contained in the thesis.

The main contribution is therefore not simply the use of waste plastic, but the development of an optimized ambient-cured MK–FA GPC matrix followed by systematic EWP replacement from 0 to 15%. The study evaluates the engineering trade-off between improved fresh-state/transport properties and the loss of mechanical performance, and identifies an application-oriented optimum rather than maximizing waste content.

2. Literature Context and Research Gap

Geopolymer performance is governed by precursor chemistry, activator concentration, silicate-to-hydroxide ratio, liquid-to-binder ratio, curing regime and aggregate characteristics. Metakaolin is highly reactive because calcination converts kaolinitic material into an amorphous aluminosilicate, while fly ash contributes a reactive silica–alumina phase and generally improves particle packing and workability. The thesis literature review reports that increasing NaOH concentration generally enhances aluminosilicate dissolution but can reduce workability, and that sodium silicate content strongly affects geopolymerization and setting.

The literature summarized in the thesis also indicates that metakaolin can help overcome the heat-curing requirement often associated with low-calcium fly-ash GPC. The selected binary system therefore targets ambient curing while retaining a high proportion of reactive metakaolin. This is particularly relevant to practical construction, where heat curing is difficult for cast-in-place applications.

The e-waste-plastic literature generally reports a workability increase because plastic particles absorb little water, accompanied by reductions in compressive, tensile and flexural strength as plastic content increases. The present thesis adds evidence that this trend persists in MK–FA GPC but that selected durability indicators improve. The key research question becomes whether the reduction in structural strength can be limited to an acceptable level while gaining waste-utilization and transport-resistance benefits.

Recent external literature reinforces the importance of this question. A 2024 review specifically examined waste plastic in geopolymer concrete, while a separate 2024 review considered non-metallic e-waste fractions, including e-plastic, in geopolymer systems. Recent 2025–2026 studies have further investigated e-waste plastic aggregates, silica-fume-assisted interface improvement, machine-learning prediction and life-cycle assessment. These studies suggest that the next step is not merely demonstrating feasibility, but quantifying performance trade-offs and establishing safe, source-specific processing routes.

3. Materials and Experimental Programme

3.1. Materials

Metakaolin obtained from Golden Micro Chemicals, Thane, Maharashtra, was used as the principal reactive aluminosilicate. The thesis reports a specific gravity of 2.52 and supplier-reported specific surface area of 12,000 m^2/kg. XRD identified anatase, cristobalite, hematite, kaolinite, mica and quartz as major phases. Class-F fly ash was used as the second binder component. Sodium hydroxide and sodium silicate were used as the alkaline activators. Natural sand and crushed coarse aggregate formed the conventional aggregate skeleton.

The EWP was obtained from local electronic-waste sources and processed into approximately 10-mm flaky/elongated particles. The thesis reports a fineness modulus of 6.1, specific gravity of 1.10, water absorption of 0.10%, abrasion value of 0.70% and impact value of 3.80%. XRD showed a broad feature near 22°, while FTIR indicated O–H, C–H, C=C, C=O, C–O and C–Br-related functional groups. Because the feedstock was heterogeneous electronic plastic, the material should be interpreted as a selected mixed e-waste polymer fraction rather than a single pure polymer.

Table 1: *Properties of the EWP aggregate.*

Property	E-waste plastic
Maximum particle size	10 mm
Fineness modulus	6.1
Water absorption	0.10%
Specific gravity	1.10
Abrasion value	0.70%
Impact value	3.80%
Morphology	Flaky/elongated

3.2. Mix optimization

A sequential optimization strategy was adopted. The metakaolin-to-fly-ash binder ratio was varied first, followed by NaOH molarity, liquid-to-binder ratio and $Na_2SiO_3/NaOH$ ratio. The optimized matrix was then used for EWP replacement. This sequential approach reduces the number of simultaneously varying parameters and allows the effect of EWP to be evaluated against a fixed reference matrix.

Table 2: *Principal design variables and selected optimum values.*

Parameter	Investigated range	Selected value
Metakaolin : fly ash	0:100 to 100:0	60:40
NaOH molarity	8–12 M	10 M

Liquid : binder	0.50–0.70	0.60
Na_2SiO_3 : NaOH	1.0–3.0	2.5
EWP replacement	0–15%	5% optimum
Curing	Ambient	Ambient
Target grade	M30	M30

3.3. EWP replacement mixtures

EWP replaced natural coarse aggregate at 0, 2.5, 5, 7.5, 10, 12.5 and 15%. For the EWP series, binder content and activator quantities were held constant. The control mixture BR60 contained 330 kg/m^3 metakaolin, 220 kg/m^3 fly ash, 526 kg/m^3 sand, 852 kg/m^3 natural coarse aggregate, 94 kg/m^3 NaOH and 176 L/m^3 sodium silicate. At 5% EWP, 43 kg/m^3 EWP replaced 43 kg/m^3 natural coarse aggregate, leaving 809 kg/m^3 natural coarse aggregate.

Table 3: *Mix proportions for the EWP series.*

Mix	EWP (%)	MK (kg/m^3)	FA (kg/m^3)	EWP (kg/m^3)	NCA (kg/m^3)	NaOH (kg/m^3)	Na_2SiO_3 (L/m^3)
BR60	0	330	220	0	852	94	176
EWP2.5	2.5	330	220	21	831	94	176
EWP5	5	330	220	43	809	94	176
EWP7.5	7.5	330	220	64	788	94	176
EWP10	10	330	220	85	767	94	176
EWP12.5	12.5	330	220	107	746	94	176
EWP15	15	330	220	128	724	94	176

3.4. Specimen preparation and testing

The thesis reports that at least three specimens were cast for each mix and each test. Compressive strength was determined on 150 × 150 × 150 mm cubes according to IS 516-1959 at 7 and 28 days. Split tensile strength was measured on 150 × 300 mm cylinders according to IS 5816-1999, and flexural strength was measured on 500 × 100 × 100 mm prisms. Fresh workability was measured using the slump test according to IS 1199-1959.

Non-destructive testing included rebound hammer testing according to IS 13311 (Part 2) and ultrasonic pulse velocity (UPV). Durability evaluation included water absorption, sorptivity, rapid chloride permeability testing (ASTM C1202), sulphuric-acid attack, sulphate attack and saltwater attack. Acid exposure used 5% H_2SO_4; sulphate testing followed ASTM C1012-2015; and saltwater was prepared according to ASTM D1141-1998. Microstructural characterization included petrographic image analysis, SEM, EDS and elemental mapping.

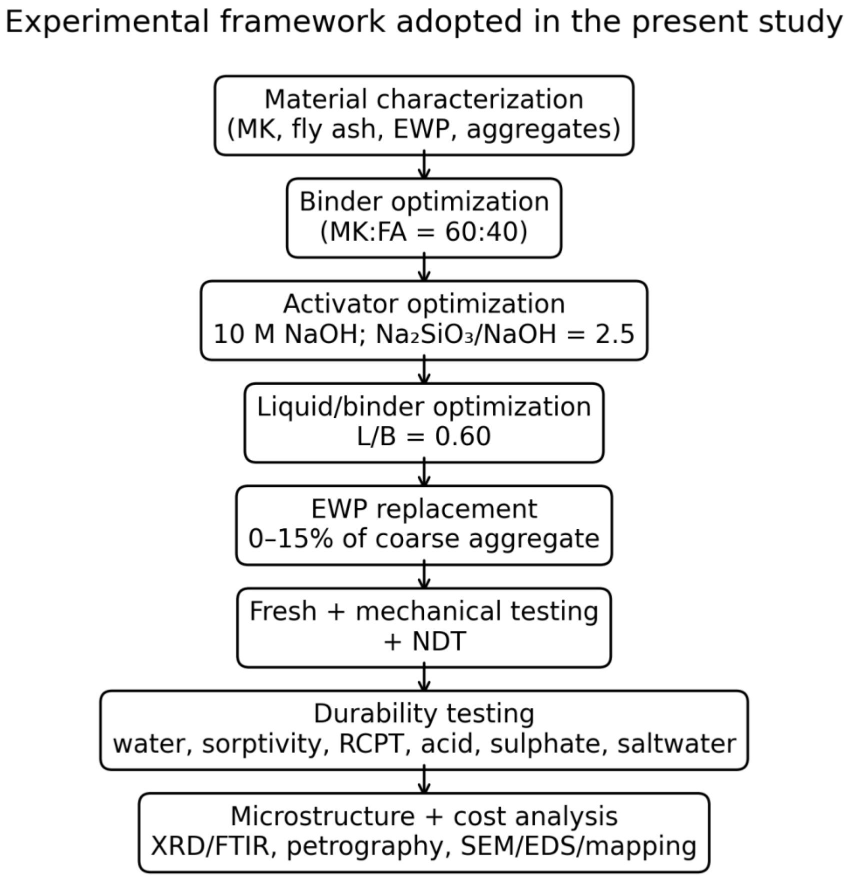

Figure 1: *Experimental framework used to develop and evaluate EWP-modified MK–FA GPC.*

4. Results and Discussion

4.1. Optimization of the geopolymer matrix

The thesis identified 60% metakaolin and 40% fly ash as the optimum binder combination. Relative to the all-fly-ash reference, the selected blend increased compressive, split tensile and flexural strength by approximately 39, 18 and 17%, respectively. Increasing metakaolin beyond 60% reduced the measured mechanical properties. The improvement is attributed to the higher reactivity of metakaolin and its contribution to geopolymerization under ambient curing.

The optimum NaOH concentration was 10 M. Increasing molarity improved strength up to this level, while additional increases produced only about 5–6% further strength gain. The liquid-to-binder ratio of 0.60 produced the highest 28-day compressive strength, 42.306 MPa, among the investigated ratios. The selected sodium-silicate-to-sodium-hydroxide ratio of 2.5 was also identified as optimum; further increases reduced the mechanical response. These results are important because they establish the reference matrix against which the EWP effect can be interpreted.

4.2. Fresh properties

Increasing EWP content increased slump continuously from 78 mm for BR60 to 116 mm for EWP15. The relationship reported in the thesis was $y = 0.2143x^2 + 3.5714x + 76.286$ ($R^2 = 0.909$), where x is EWP percentage. The observed increase is consistent with the very low water absorption of EWP and its hydrophobic surface, which allows the geopolymer paste to move around the plastic particles. The transition from medium to high workability occurred at 12.5% EWP according to the classification reported in the paper.

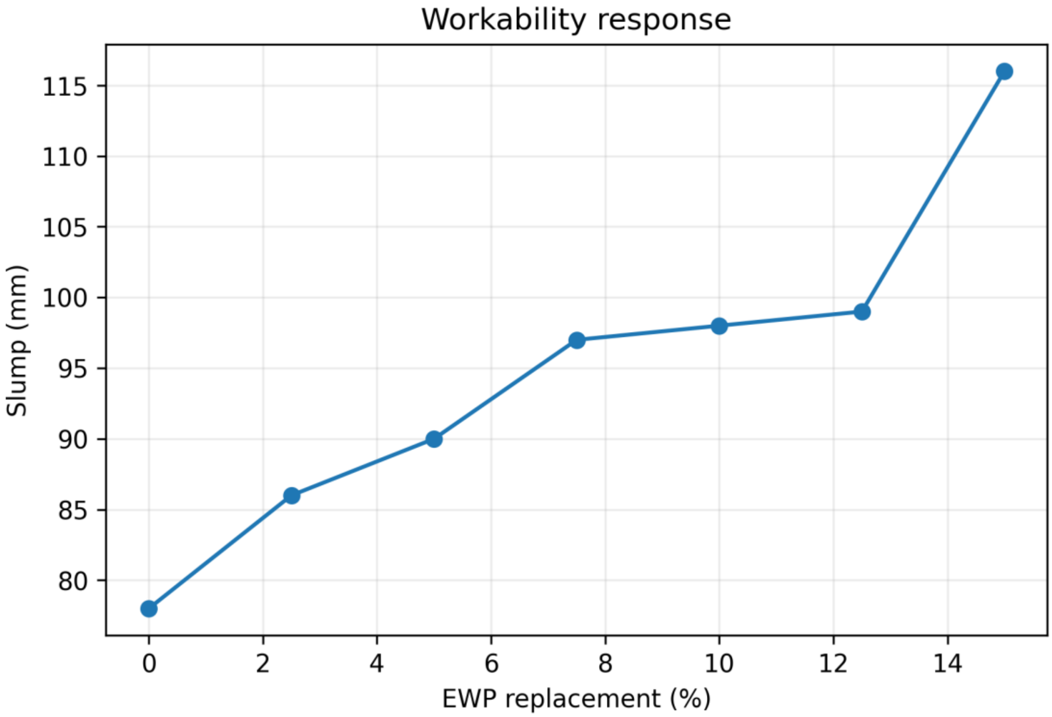

Figure 2: *Slump response of MK–FA GPC with increasing EWP content.*

Table 4: *Fresh-state workability of the EWP mixtures.*

Mix	EWP (%)	Slump (mm)	Workability classification
BR60	0.0	78.0	Medium
EWP2.5	2.5	86.0	Medium
EWP5	5.0	90.0	Medium
EWP7.5	7.5	97.0	Medium
EWP10	10.0	98.0	Medium
EWP12.5	12.5	99.0	High
EWP15	15.0	116.0	High

4.3. Compressive strength

The 28-day compressive strength decreased monotonically with EWP content. BR60 achieved 42.306 MPa, while EWP5 achieved 39.34 MPa and EWP15 achieved 26.86 MPa. The reduction at 5% was approximately 7.0% relative to the control, whereas the reduction at 15% was approximately 36.5%. The thesis attributes the strength loss primarily to replacement of strong mineral aggregate by weaker, flaky and elongated plastic particles. The 7-day strength followed the same trend, with 30.82 MPa at EWP5 and 21.95 MPa at EWP15.

The 28-day regression reported in the thesis was $y = -0.2463x^2 - 0.9016x + 43.808$ ($R^2 = 0.9592$). The strong fit describes the experimental trend within the tested range, but it should not be extrapolated outside the studied EWP percentages. The practical significance is that 5% EWP retained the M30 target while higher replacement levels progressively consumed the mechanical-strength margin.

Table 5: *Compressive strength of EWP-modified GPC.*

Mix	EWP (%)	7-day compressive (MPa)	28-day compressive (MPa)	28-day loss vs BR60 (%)
BR60	0.0	32.34	42.31	0.0
EWP2.5	2.5	31.96	40.90	3.3
EWP5	5.0	30.82	39.34	7.0
EWP7.5	7.5	27.26	37.72	10.8
EWP10	10.0	25.73	32.54	23.1
EWP12.5	12.5	22.14	27.26	35.6
EWP15	15.0	21.95	26.86	36.5

4.4. Tensile and flexural strength

Split tensile and flexural strengths showed the same directional response as compressive strength. At 28 days, split tensile strength decreased from 3.77 MPa for BR60 to 3.48 MPa for EWP5 and 2.76 MPa for EWP15. Flexural strength decreased from 3.83 MPa for BR60 to 3.59 MPa for EWP5 and 2.84 MPa for EWP15. Thus, the 5% mixture caused relatively small losses while higher EWP levels caused progressively larger reductions.

Table 6: *Tensile and flexural strength results (MPa).*

Mix	EWP (%)	7-day split tensile	28-day split tensile	7-day flexural	28-day flexural
BR60	0.0	3.36	3.77	3.38	3.83
EWP2.5	2.5	3.28	3.68	3.31	3.68
EWP5	5.0	3.08	3.48	3.20	3.59
EWP7.5	7.5	2.86	3.18	3.05	3.34
EWP10	10.0	2.62	2.92	2.86	3.26
EWP12.5	12.5	2.58	2.88	2.74	3.14
EWP15	15.0	2.48	2.76	2.56	2.84

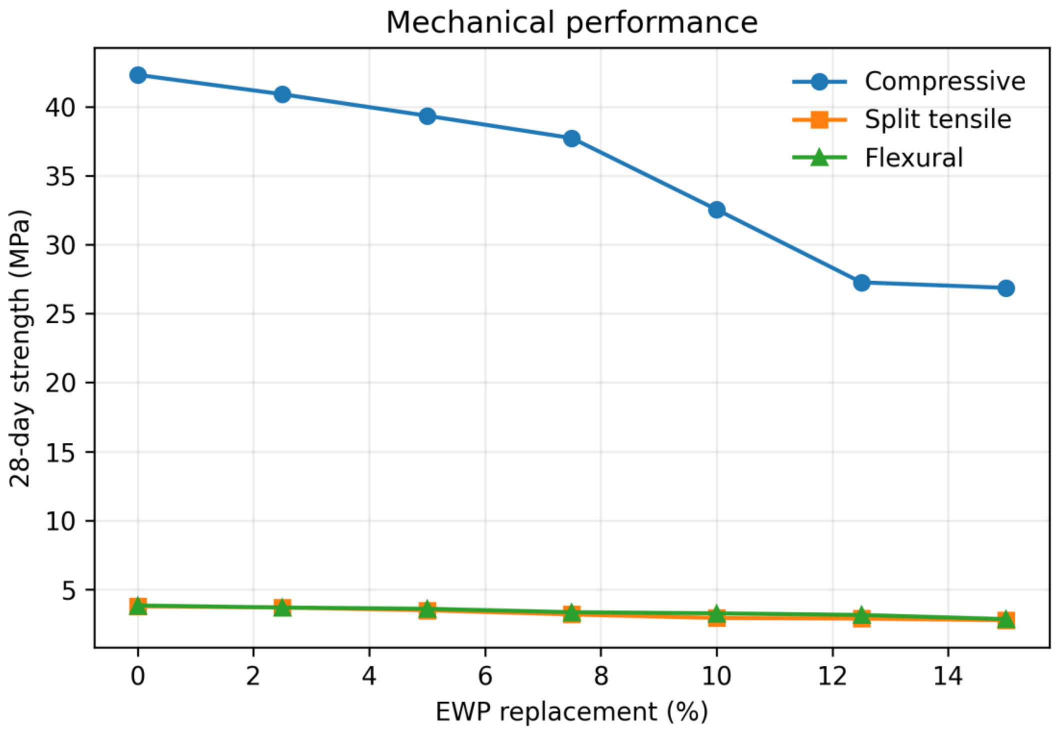

Figure 3: Effect of EWP content on 28-day mechanical properties.

4.5. Optimum EWP content

A multi-property interpretation identifies 5% EWP as the most balanced mixture. BR60 provides the highest mechanical strength, but EWP5 reduces compressive strength by only about 7.0% at 28 days while improving water absorption, sorptivity, chloride charge and chemical-exposure indicators. At 7.5% and above, mechanical degradation becomes progressively more pronounced. At 15%, compressive strength is only 26.86 MPa and the rebound number falls to 14, making this level less attractive for M30 structural applications despite its superior water-transport indicators.

The optimum should therefore be defined as a performance compromise rather than a single maximum. The 5% level is optimum within the investigated material, particle size, activator chemistry, curing condition and replacement range. It should not be generalized to all e-waste plastics or all geopolymer formulations without validation.

5. Conclusions

- A binary metakaolin–fly ash geopolymer concrete suitable for ambient curing was optimized at a 60:40 binder ratio, 10 M NaOH, liquid-to-binder ratio of 0.60 and Na_2SiO_3/NaOH ratio of 2.5.
- The EWP used in the study had a maximum size of 10 mm, specific gravity of 1.10 and water absorption of 0.10%, and was predominantly flaky/elongated.
- Increasing EWP from 0 to 15% increased slump from 78 to 116 mm, demonstrating improved fresh-state flow.
- Mechanical properties decreased with increasing EWP. At 28 days, compressive strength declined from 42.31 MPa for BR60 to 39.34 MPa at 5% EWP and 26.86 MPa at 15% EWP.

- At 5% EWP, the 28-day split tensile and flexural strengths were 3.48 and 3.59 MPa, respectively, representing relatively small losses compared with the control.
- Water absorption, sorptivity and RCPT charge decreased with increasing EWP. At 5% EWP, 28-day water absorption decreased by approximately 11.9% and 120-min sorptivity by approximately 21.7% relative to BR60.
- Acid, sulphate and saltwater exposure showed lower mass or strength losses for EWP-containing mixtures, with the EWP5 mixture showing 120-day acid strength loss of 22.88%, sulphate strength loss of 8.23% and saltwater strength loss of 7.15%.
- NDT results supported the mechanical-strength trend: the 28-day rebound number decreased from 34 to 31 at 5% EWP and 14 at 15% EWP; UPV decreased from 3.58 to 3.28 and 1.83 km/s, respectively.
- Microstructural analysis indicated that the geopolymer matrix remained developed in EWP5, with Na, Al, Si and Ca present in the matrix and increased carbon associated with the plastic fraction.
- Considering mechanical strength, durability and fresh properties together, 5% EWP was the most balanced replacement level within the investigated range.
- The cost analysis in the thesis indicated approximately 1.75% higher cost for MK-GPC and 12% higher cost for MK-GPC with EWP relative to the selected conventional-concrete benchmark.
- Before commercial deployment, source-specific e-waste characterization, leaching, thermal/fire performance and life-cycle assessment are required.

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Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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