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An Experimental Study on the Performance Enhancement of Geopolymer Concrete using E-Waste Particulates

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ABSTRACT: The growing volume of electronic waste and the environmental impact of cement production have encouraged interest in alternative, resource -efficient construction materials. This study evaluates the potential of incorporating processed non-metallic e -waste as a partial replacement for fine aggregate in fly ash -GGBS -based geopolymer concrete. Four mixes with They made four amounts of e-waste: 0 percent, 5 percent, 10 percent and 15 percent e-waste. They wanted to see how these different amounts of e-waste behaved when they were subjected to compressive and split tests, on the e-waste. tensile and flexural strength testing. Durability performance was examined using water absorption, porosity, acid resistance and TCLP leachability analysis for important heavy metals was used to confirm environmental safety, whereas quick chloride permeability tests were used. The findings demonstrate that a number of performance metrics may be improved by introducing e-waste in regulated amounts. The constant 10% e-waste mixture produced lower permeability and greater strength than the control, mostly as a result of a more refined pore structure and better packing density. After this point, the particles' non-reactive nature started to break the binder's continuity, which led to a decrease in strength and a modest increase in permeability. All mixes showed leachate concentrations far below regulatory criteria in spite of these variances, demonstrating the geopolymer matrix's efficacy in immobilising hazardous ions. Overall, the study shows that using processed e-waste in moderation is a sensible and ecologically friendly approach. 10% of Replacement level supports its usage in sustainable building applications by providing the optimal balance between mechanical performance, durability, and environmental safety.

KEYWORDS: fly ash, silica fume, geopolymer, greenhouse gas, e-waste, split tensile strength, and compressive strength.

1. INTRODUCTION

Alternative low-carbon binders are becoming more popular since the manufacture of concrete has long been linked to significant carbon emissions and extensive use of natural resources. The alkaline activation of aluminosilicate by-products creates geopolymer concrete, which offers increased durability and much lower impact on the environment as comparison to regular Portland cement [1]. Geopolymer systems show excellent resistance to chemical assault, thermal stress, and long-term deterioration, according to several reviews [2]. Because fly ash and GGBS complement aluminosilicate and calcium, they are among the most effective precursor combinations. chemistry, which encourages stable gel formation and increases early strength [3]. Calcium and aluminosilicate chemistry, which improves early strength and encourages stable gel formation [3]. Their significance in waste-valorisation research is further reinforced by their capacity to immobilise hazardous ions [4]. Parallel to this, the growing volume of Global electronic trash has sparked worries about recycling and safe disposal. Particularly under harsh exposure circumstances, geopolymer systems enhanced with GGBS and recycled components have promising mechanical and durability features [5]. Additionally, steady performance at high temperatures has been demonstrated by GGBS-based geopolymers, indicating applicability for structural and thermal applications [6]. Research has shown that adding fly ash, silica fume, and GGBS to geopolymer binders increases their strength and improves their microstructural integrity [7]. Glass fibres, polymers, and trace metals included in electronic trash, especially printed circuit boards, make disposal more difficult. Finely ground PCB waste may be used to cementitious and geopolymer systems in acceptable amounts, according to recent research on the use of processed PCB wastes [8]. Further research demonstrates that, when employed appropriately, PCB fibres can enhance strength qualities [9], and previous experiments on crushed PCB particles verified that they can be successfully immobilised inside geopolymer matrices [10]. The geopolymer Manufactured sand and e-waste mixtures have also shown respectable mechanical performance and workability [11]. E-waste additions have demonstrated potential advantages in ductility and fracture resistance beyond mechanical behaviour, particularly in blended systems [12]. A basis for comprehending ideal binder proportions in geopolymer mix design is provided by research comparing various fly ash-GGBS ratios [13]. Recent research on geopolymer chemistry has shed light on gel formation, ion-binding, and long-term structural stability at the material level [14]. Geopolymer binding-based heavy-metal stabilisation has also drawn interest, with many studies confirming the immobilisation of cadmium, lead, and chromium in matrices activated by alkali [15]. Researchers have shown that properly treated e-waste may provide usable mixtures with consistent strength by testing coarse PCB particles in geopolymer concrete [16]. Similar results have been found in other studies employing PCB-derived fine aggregate when replacement amounts are maintained moderate [17]. A thorough analysis of concrete's e-waste reveals that Incorporating non-metallic PCB components can enhance resource efficiency, lower thermal conductivity, and promote circular economy objectives [18]. Furthermore, research utilising industrial and biological waste confirms that geopolymer matrices may hold hazardous ions without observable leaching [19]. Current analyses summarise the significance of durability and microstructural analysis when incorporating unusual elements into geopolymer systems [20].

Despite these advancements, no research has integrated fly ash-GGBS geopolymer systems with processed e-waste while assessing mechanical behaviour, durability indices, and environmental safety jointly. This study fills this gap by investigating heavy-metal resistance, permeability, strength development, and acid resistance. leachability in geopolymer concrete with progressive replacement amounts of e-waste. Unlike earlier research that only concentrated on using different recovered materials or only looked at certain areas of e-waste, This paper provides an assessment of processed materials connected to cementitious systems that are not made of metal. The paper examines processed non-metallic materials in these cementitious systems and focuses on systems. waste as a partial substitute for fine aggregate in fly ash geopolymer concrete based on GGBS. The study creates four mixtures with 0%, 5%, 10%, and 15% e-waste and tests their mechanical capabilities using flexural, split-tensile, and compressive strengths. This work broadens the scope beyond mechanical behaviour by investigating water absorption, durability responses, porosity, and fast chloride permeability and sulphuric acid resistance as well as by assessing environmental safety using TCLP (Toxicity Characteristic leachability analysis) leaching process. This research provides a comprehensive performance profile and determines the ideal e-waste composition for real-world use by combining technical and environmental factors. This comprehensive approach sets the current study apart from previous research and offers fresh perspectives on how processed e-waste might help create low-impact, sustainable building materials.

2. MATERIALS AND METHODOLOGY:

2.1. MATERIALS

2.1.2. Ground Granulated Blast Furnace Slag (GGBS): Ground -granulated blast -furnace slag (GGBS or GGBFS) is obtained by quenching molten iron slag (a byproduct of iron and steel -making) from a blast furnace When we use water or steam it makes a glassy and granular product. This product is then. Ground into a fine powder. Ground glass is what we get from this process. We use water or steam to make the glassy and granular product, which is dried and ground into a fine powder. granulated blast furnace slag is highly cementitious and high in CSH (calcium silicate hydrates) which is a strength enhancing compound which improves the strength, durability and appearance of the concrete. Replacement of PC with GGBFS ultimately leads to a significant increase in the compressive strength of the mix.

2.1.3. Fly Ash: Fly ash is a coal combustion product that is composed of the particulates (fine particles of burned fuel) that are driven out of coal -fired boilers together with the flue gases. Fly ash has proven to be an excellent building and structural material th at actually can enhance the properties of concrete and other construction resources. Owing to its pozzolanic properties, fly ash is used as a replacement for Portland cement in concrete. Fly ash can significantly improve the workability of concrete.

2.1.4. M-Sand: M Sand is nothing but artificial sand made from crushing of rock or granite for construction purposes in cement or concrete. M sand differs from natural river sand in its physical and mineralogical properties. It is proved that M sand provides greater Durability, Strength, Workability to the Concrete. It is Eco friendly and Economical than the River Sand.

2.1.5. Coarse Aggregate: Materials that are large enough to be retained on the 4.7mm sieve size usually constitute coarse aggregates and can reach a maximum size of 63mm. Coarse aggregates of 20mm size range have used in this project. Coarse is naturally occurring and can be obtained by blasting quarries or crushing them by hand or crushers. It is imperative to wash them before using them for producing concrete. Their angularity and strength affect the concrete in numerous ways. Needless to say, the selection of these aggregates is a very important process.

2.1.6. Printed Circuit Board (PCB): A printed circuit board mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non -conductive substrate. PCBs is one of the kinds of E waste which is generated in large amount and it is Recycled as a building material by reducing it into 20mm size and partially replacing it with Coarse aggregate.

2.1.7. Alkaline Solution: An alkaline solution is a mixture of base solids dissolved in water. The NaOH solution of 12 Molarity is prepared. After 24 hours it is Mixed with Sodium Silicate solution to form alkaline solution which is added to dry mix of Geopolymer Concrete and it hydrates the Concrete and imparts binding properties to the Concrete.

2.2. METHODOLOGY:

In this study, the methodology follows a systematic and well -structured sequence beginning with the careful selection of raw materials required for producing both conventional concrete and geopolymer concrete. These materials' physical and chemical properties are carefully inspected to guarantee their appropriateness, uniformity, and dependability. Geopolymer concrete is made using alkaline after characterisation. activator solutions with different molarities, which aids in comprehending how alkaline concentration affects the final product's durability and strength. Next, the ease of mixing, pouring, and compacting both conventional and geopolymer concrete is evaluated. Conventional concrete and geopolymer concrete specimens are cast when the mix designs are completed. Standard cube, cylinder, and beam specimens with the specified dimensions 150 × 150 × 150 mm cubes, 150 mm × 300 mm cylinders, and beams with a 150 mm cross-section and 700 mm length are made using the appropriate curing and compaction techniques. In order to get precise and trustworthy findings, these specimens are next put through a number of mechanical tests, such as compressive strength, split tensile strength, and flexural strength, utilising a testing equipment with a 300-ton capacity. To examine the mixes' long-term performance in harsh environments, further durability tests such water absorption, porosity, RCPT, and acid resistance are carried out.

Table 1 shows the proportions of materials used in the geopolymer concrete mixes, including the varying replacement levels of e -waste powder (0–15%), the binder combinations of fly ash and GGBS, and the alkaline activator solution. Table 2 lists the IS codes and relevant standards followed for all materials and testing procedures, including fly ash, GGBS, aggregates, water quality, and the TCLP method used for assessing e -waste leachability.

Table 1: Proportion of Replaced Materials

Material	**Purpose**	**Replacement (%)**
Fly ash	Main binder (geopolymer precursor)	60-70% of total binder
GGBS	Strength enhancer	30-40% of total binder
E-Waste Powder	Partial fine aggregate replacement	0%, 5%, 10%, 15%
River sand	Fine aggregate replacement	Balance
NaoH + Na2Sio3	Alkaline activator	100% of activator
Coarse Aggregate	Structure strength	Standard proportion
Water	Mixing and curing	As required

Table 2: IS Code References for Material Standards

Material	**Is Code**
Fly Ash	IS 3812 (Part 1): 2013
GGBS	IS 12089: 1987
Coarse & Fine Aggregates	IS 383: 2016
Water For Mixing & Curing	IS 456: 2000, Clause 5.4
Sodium Hydroxide & Sodium Silicate	No specific IS code (Use ASTM or industrial grade standards)
Testing of Hardened Concrete	IS 516 (Part 1): 2021
Toxicity Leaching (for e-waste)	EPA Method 1311 (TCLP) (International Standard)

2.2.1. Preparation Of Alkaline Activator

An alkaline activator solution was prepared by dissolving sodium hydroxide (NaOH) pellets in distilled water to obtain an 8M solution. The solution was allowed to cool for 24 hours to stabilize its properties. Subsequently, sodium silicate (Na_2SiO_3) was mixed with the NaOH solution in a weight ratio of 2.5:1 to form the final activator solution. This blended solution was left to equilibrate to ensure homogeneity before being incorporated into the concrete mix.

2.2.2 Mix Design and Proportions

Due to the lack of standardized IS codes for geopolymer concrete mix design, a trial -and-error method was the binder content was made up of a mix of fly ash and GGBS. This mix was seventy percent fly ash and thirty percent GGBS, by weight. The activator was used with this binder content that had fly ash and GGBS in it. to-binder (A/B) ratio was maintained at 0.5, while the NaOH molarity was kept constant at 8M. To improve workability, a water -to-binder ratio of 0.2 was used where necessary. Pulverized e -waste was incorporated as a partial replacement for fine aggregate at four different levels: 0%, 5%, 10%, and 15% by weight. The mixes were designated as GPC -0 (control), GPC -5, GPC -10, and GPC -15 based on the percentage of e -waste used as shown in table 3.

Table 3: Materials mix proportion

Mix Id	**Fly Ash (%)**	**Ggbs (%)**	**E-Waste Replacement (% Of Sand)**	**Curing Type**
GPC-0	70	30	0%	Heat + Ambient
GPC-5	70	30	5%	Heat + Ambient
GPC-10	70	30	10%	Heat + Ambient
GPC-15	70	30	15%	Heat + Ambient

2.2.3. Batching, Mixing and Casting

The dry materials comprising the binder, natural aggregates, and e -waste were first mixed thoroughly to achieve a uniform blend. The prepared alkaline activator solution was then gradually added to the dry mix to initiate the geopolymerization process. The fresh concrete was poured into standard 150 mm cube moulds for compressive strength testing, along with cylindrical and beam moulds for tensile and flexural strength tests, respectively.

3. ENVIRONMENTAL SAFETY ASSESSMENT

To ensure the safe use of e -waste in construction materials, an environmental leachability assessment was performed using the Toxicity Characteristic Leaching Procedure (TCLP), in accordance with EPA Method 1311. Powdered samples of the hardened geopolymer concrete containing e -waste were tested for the presence of heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu). The leachate concentrations of these metals were compared against permissible limits to verify the environmental safety of the developed materials. The TCLP (Toxicity Characteristic Leaching procedure) test confirmed that heavy metal release remained far below regulatory limits in all mixes. The three -dimensional aluminosilicate network typical of geopolymers is known for its ability to immobilize contaminants. The presence of calcium from GGBS further improves binding stability. Even at 15% replacement, none of the mixes approached threshold limits. This ensures that incorporating e-waste, into geopolymer concrete is not only structurally viable but also environmentally responsible.

Table 4 presents the TCLP heavy -metal leachate results for geopolymer concrete mixes containing varying proportions of e -waste. As shown, the concentrations of Pb, Cd, Cr, and Cu for all mixes (GPC -0 to GPC -15) remain significantly below the respective permissible limits. This confirms that the incorporation of e -waste does not pose an environmental risk. The very low leachate values demonstrate the strong immobilisation capacity of the geopolymer matrix, further enhanced by the calcium -rich GGBS component, which promotes stab le binding of metal ions. Even at the highest replacement level (15%), none of the metals approach regulatory thresholds, validating the environmental safety of the developed materials.

Table 4: TCLP heavy-metal leachate (mg/L) and permissible screening limits

Metal	Permissible (Typical)	Gpc-0	Gpc-5	Gpc-10	Gpc-15
Pb	5.0 mg/L	0.15	0.13	0.12	0.14
Cd	1.0 mg/L	0.02	0.02	0.01	0.2
Cr	5.0 mg/L	0.11	0.09	0.08	0.12
Cu	5.0 mg/L	0.19	0.16	0.15	0.18

4. RESULTS AND DISCUSSION:

This section presents the experimental findings on geopolymer concrete incorporating e -waste materials as a partial replacement for fine aggregates. In order to determine the ideal e-waste content, the study assesses the created mixtures' mechanical qualities, durability, and microstructural traits. The slump value of geopolymer concrete decreases gradually with the increase in E -waste content. The control mix GPC -0 shows the highest workability (75 mm), while mixes containing 5%, 10%, and 15% E -waste show reduced slump values of 72 mm, 68 mm, and 60 mm respectively. This reduction occurs because E -waste particles are angular and lightweight, which decreases the flowability of the mix. Overall, concrete with up to 10% E -waste maintains acceptable workability, whereas 15% replacement shows a Table 5.

Table 5: Fresh Properties of concrete

Mix	E- Waste (%)	Slump (Mm)
GPC-0	0	76
GPC-5	5	74
GPC-10	10	66
GPC-15	15	61

The compressive strength of geopolymer concrete increases consistently with the addition of E -waste up to 10%, as shown in Table 6. The mix GPC -10 exhibits the highest strength at all curing ages, reaching 48.2 MPa at 28 days, which is higher than the control mix (44.5 MPa). This improvement is attributed to the filler effect and better particle packing provided by finely crushed E -waste. However, at 15% replacement, the strength decreases, indicating that excessive E -waste disrupts the matrix bonding. Overall, 10% E -waste replacement is found to be the optimum level for enhancing compressive strength.

Table 6: The compressive strength

Mix	7 Days	14 Days	28 Days
GPC-0	28.6	37.2	44.2
GPC-5	30.2	38.6	46.5
GPC-10	31.4	39.8	48.1
GPC-15	29.0	36.4	42.7

Based on the values presented in Table 7, the split tensile strength of geopolymer concrete shows a steady improvement from 7 to 28 days for all mixes. The mix GPC -10 consistently achieves the highest strength at every curing age, indicating the most effective bonding due to the optimal amount of E -waste. GPC-15, on the other hand, exhibits a discernible decline in strength, indicating that too much E-waste weakens the matrix and decreases cohesion. Overall, the findings demonstrate that replacing 10% of E-waste yields the greatest tensile performance, improving resilience without sacrificing structural soundness.

Table 7: Split tensile test of results.

MIX	7 Days	14 Days	28 Days
GPC-0	2.6	3.1	3.5
GPC-5	2.8	3.3	3.7
GPC-10	3.0	3.5	3.9
GPC-15	2.4	2.9	3.25

The gradual growth of the geopolymer matrix is confirmed by the flexural strength values shown in Table 8, which consistently rise from 7 to 28 days for all combinations. GPC-10 records the highest of all mixes. flexural strength at all ages, demonstrating an exceptional ability to withstand cracks because of the best filler effect of E-waste. In contrast, GPC-15 exhibits a decrease in strength, indicating that a larger E-waste percentage weakens the connection and decreases stiffness. Overall, the findings unequivocally show that the best way to improve the flexural behaviour of geopolymer concrete is to replace 10% of the E-waste.

Table 8: Flexural strength test of result.

MIX	7 Days	14 Days	28 Days
GPC-0	2.6	3.1	3.53
GPC-5	2.8	3.3	3.68
GPC-10	3.0	3.5	3.89
GPC-15	2.4	2.9	3.24

Table 9 shows that differences in the GPC mixes result in considerable changes in water absorption, porosity, and RCPT values. With the lowest water absorption (2.4%), porosity (9.8%), and smallest RCPT value (920 coulombs), which indicates superior density and chloride, the GPC-10 mix performs the best. defiance. The GPC-15 mix, on the other hand, has higher values in all three criteria, indicating less durability. Overall, Table 9 makes it quite evident that the GPC-10 mix has the best durability performance.

Table 9: water absorption, porosity and RCPT test results (after 24 hours)

Mix	Water Absorption (%) (After 24 Hours)	Porosity (%) (After 60-72 Hours)	Rcpt (Coulombs) (After 28 Days)
GPC-0	2.9	12.5	1220
GPC-5	2.7	11.4	1100
GPC-10	2.4	9.8	920
GPC-15	3.1	13.6	1400

Based on Table 10, the acid resistance of the GPC mixes improves noticeably as the mix composition changes. After 28 days of immersion, the GPC-10 mix exhibits the lowest mass loss of 2.1%, showing the strongest resistance against sulphuric acid assault. By contrast, GPC-0 shows the greatest mass loss (3.2%), indicating poorer chemical resilience. The improved stability and better performance of changed mixes in acidic environments are demonstrated by the progressive decrease in mass loss from GPC -0 to GPC -10. Overall, Table 2 makes it abundantly evident that of all the combinations, GPC-10 provides the highest acid resistance.

Table 10: Acid resistance (mass loss after 28 days immersion in 5% H_2SO_4)

Mix	Mass Loss (%)
GPC-0	3.15
GPC-5	2.8
GPC-10	2.12
GPC-15	4.12

5. CONCLUSIONS:

The viability of using e-waste to partially substitute fine aggregate in fly ash-GGBS based geopolymer concrete was effectively investigated in this work. The findings unequivocally demonstrate that adding e-waste to geopolymer concrete in moderation can improve its overall performance without sacrificing its structural or environmental soundness. The results of the experiment showed that:

1. Due to the angular and lightweight character of the particles, workability gradually declined with increasing e-waste concentration; nonetheless, mixtures containing up to 10% e-waste still had workable consistency. In every mechanical test, including split tensile, flexural, and compressive strength, the 10% At all curing ages, the replacement level consistently yields the greatest results. When e-waste is utilised in the ideal ratio, these improvements show improved particle packing and a denser internal matrix.
2. This pattern was further supported by durability evaluations. The GPC-10 mix showed the lowest porosity, chloride permeability, and water absorption, suggesting a more refined pore structure and greater resilience to harsh conditions.

Additionally, its outstanding results in the acid resistance test showed enhanced chemical stability in comparison to the combination under control. Even though the mechanical and durability attributes decreased at the 15% replacement level, these modifications highlighted how crucial it is to keep the amount of e-waste in the matrix balanced.

3. All mixtures, including those with the greatest e-waste percentage, discharged heavy metals much below legal limits, according to the environmental evaluation conducted using the TCLP test. This validates the geopolymer matrix's potent immobilisation capabilities and encourages the secure usage of e-waste in materials for building.
4. Overall, the results show that the best balance between mechanical performance, durability, and environmental safety may be achieved by partially replacing fine aggregates with 10% e-waste. This study emphasises how e-waste may be used as a sustainable substitute material in geopolymers. concrete, supporting the creation of more environmentally friendly building techniques as well as trash minimisation.

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