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Development of Alkali-Activated Artificial Aggregates Utilizing E-Waste

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Abstract - The global construction industry faces a critical shortage of natural aggregates due to the unsustainable rate of quarrying, leading to severe ecological degradation. Simultaneously, the rapid accumulation of electronic waste, particularly the non-metallic fraction (NMF) of printed circuit boards, presents a significant environmental challenge as these materials are traditionally non-biodegradable and difficult to recycle. This research aims to investigate the technical feasibility of synthesizing alkali-activated artificial aggregates by repurposing the non-metallic fraction of printed circuit boards and fly ash. The study is based on the hypothesis that the chemical synergy between the aluminosilicate precursors in fly ash and the glass-fiber-reinforced epoxy structure of NMF can produce a geopolymer matrix with mechanical properties comparable to natural crushed aggregates. To evaluate this, a systematic investigation was carried out involving the activation of precursors with an 8M sodium hydroxide and sodium silicate binary solution (SS/SH of 2.5:1), followed by a dual-stage ambient and thermal curing regime at 100°C. The experimental results demonstrate that the 75-25 and 50-50 FA-EW formulations achieved Aggregate Impact Values of 24.44% and 22.30%, respectively, alongside Los Angeles Abrasion values ranging from 22.75% to 27.11%. These findings indicate that the synthesized aggregates comfortably satisfy standard requirements for road base and sub-base applications, which typically mandate limits below 30%. This work provides a technically robust and energy-efficient solution for diverting hazardous electronic waste from landfills while simultaneously addressing the global scarcity of natural construction aggregates through the principles of a circular economy.

***Key Words*:** E-waste, Fly Ash, Geopolymerization, Artificial Aggregates, Sustainability.

1.INTRODUCTION

The rapid growth of infrastructure development worldwide has significantly increased the demand for natural aggregates, which are essential constituents in asphalt and concrete production. Perkins et. al. (2021) observes that approximately 50 billion tonnes of aggregates are consumed worldwide each year. However, the excessive extraction of these aggregates through mining and quarrying has resulted in severe environmental consequences, including ecosystem degradation, depletion of natural resources, and increased carbon emissions. In response, recent research has focused on developing sustainable alternatives such as artificial aggregates derived from industrial by-products and waste materials. Alkali-activated materials and geopolymer technologies, in particular, have gained attention due to their ability to convert waste into value-added construction materials with reduced environmental impact.

Parallel to this challenge is the escalating issue of electronic waste (E-waste), which is one of the fastest-growing waste streams globally. Printed Circuit Boards (PCBs), a major component of E-waste, consist of both metallic and non-metallic fractions. Duan et. al. (2016) notes that non-metallic fractions (NMFs) which are considered as waste, make up about three-quarters of the total mass of printed circuit board e-waste. While the metallic portion is often recovered due to its economic value, the non-metallic fraction (NMF), composed of resins, glass fibers, and polymers, is largely underutilized and frequently disposed of in landfills, posing long-term environmental and health risks.

Existing literature indicates that artificial aggregates can be synthesized using various techniques such as cold bonding, sintering, and alkali activation, primarily utilizing materials like fly ash and slag. However, the application of these techniques to E-waste, particularly non-metallic PCB fractions, remains limited and underexplored.

The present study aims to address this research gap by investigating whether non-metallic E-waste can be effectively utilized in the production of alkali-activated artificial aggregates. The central hypothesis is that artificial aggregates synthesized from E-waste using optimized alkali-activation techniques can achieve engineering properties comparable to conventional natural aggregates while enhancing sustainability. To test this hypothesis, the study adopts a systematic approach involving the development of manufacturing methodologies, optimization of process parameters and evaluation of aggregate properties through standard tests.

2. MATERIALS

1) Non-Metallic Fraction (NMF) of PCBs

NMF is the residual fraction obtained after metal recovery from waste PCBs, mainly composed of epoxy resins reinforced with glass fibers. It constitutes nearly 70% of PCB weight and exhibits heterogeneous, non-biodegradable characteristics. The material was procured from Jacsgreen Recycling Pvt. Ltd., Tamil Nadu. The particle size analysis categorized the pulverized NMF into two distinct types based on their gradation profiles. While the finer fraction shows significant 0.075 mm sieve passage at 32.70%, the coarser material is dominated by larger particles with 40% retained above 0.60 mm.

Fig -1: Non Metallic Fraction of PCBs

2) Sodium Hydroxide (NaOH)

Sodium hydroxide is a strong alkaline activator used to dissolve aluminosilicate materials and initiate geopolymerization. It is highly hygroscopic and releases significant heat upon dissolution, forming Na^+ and OH^- ions. It was obtained from laboratory suppliers.

3) Distilled Water

Distilled water is used as a solvent for preparing NaOH solution. It enables accurate molarity and formation of a homogeneous alkaline medium. It was sourced from laboratory equipment suppliers.

4) Sodium Silicate liquid

Sodium silicate (Na_2SiO_3), acts as a key binder enhancing geopolymerization through silica enrichment and the acceleration of polycondensation. It was procured from Maheshwari Industries, Amravati.

Fig -2: Sodium Silicate liquid

5) Fly Ash

Fly ash is a pozzolanic industrial by-product rich in silica, alumina, and iron oxides, widely used as a geopolymer precursor. Fly ash demonstrates a high degree of fineness, as 58.20% of the material successfully passes through a 0.075 mm sieve. It was obtained from a local fly ash brick manufacturer.

Fig -3: Fly ash

6) Superplasticizer

Fosroc Auramix 300 is a polycarboxylate ether-based superplasticizer used to enhance workability and reduce liquid demand in the mix. It was used at 1.5% by weight of binder.

2. METHODOLOGY

Two types of artificial aggregates were synthesized, first with 75% fly ash and 25% PCB NMF powder (75-25 FA -EW), while second being 50% fly ash and 50% PCB NMF powder (50-50 FA -EW). Geopolymer paste was prepared and casted into cubes, which were crushed after curing in order to make artificial aggregates. Similar method is used by Ago et. al. (2023).

To optimize economic feasibility, an 8M sodium hydroxide (NaOH) solution was employed as the alkaline activator. Liquid to binder ratio of 0.35 is used for making geopolymer paste. In alignment with the findings of Karyawan et. al. (2019), which identified a 2.5 sodium silicate to sodium hydroxide ratio as the optimal threshold for minimizing water absorption, a 2.5:1 ratio was adopted for this study.

1. Alkaline Activator Synthesis and Stabilization

The primary alkaline activator was prepared by dissolving sodium hydroxide (NaOH) pellets in distilled water to achieve an 8M concentration. This exothermic process required continuous stirring until complete dissolution, followed by a 24-hour stabilization period at ambient temperature. This aging step is critical to ensure ionic hydration equilibrium and thermal stability, thereby preventing the risk of flash setting during the subsequent geopolymerization reaction.

2. Preparation of the Binary Alkaline Binder

The binary activator was synthesized by blending the stabilized NaOH solution with liquid sodium silicate at a predefined mass ratio. Mass-based proportioning was strictly maintained to account for the high density of the silicate component. The mixture was homogenized through manual stirring for 5 minutes, ensuring the removal of localized concentration gradients and entrapped air, allowing for chemical equilibration between the silicate and hydroxide.

3. Precursor Homogenization and Dry Blending

The solid precursor system comprised Fly Ash and PCB-NMF. To ensure uniform reactivity, the fly ash was de-agglomerated via a 150 micron sieve to remove coarse residues. A sandwich layering was done during dry blending, placing the PCB-NMF between two layers of fly ash, to mitigate fiber displacement and ensure a homogenous distribution of the lighter NMF particles within the denser spherical ash matrix prior to liquid activation.

Fig -4: Dry blending of percusors

4. Mixing, Casting, and Specimen Fabrication

Geopolymer paste was synthesized by incorporating the binary activator into the dry precursor blend. To enhance workability in less fluid mixes, a 1.5% dosage of Fosroc Auramix superplasticizer was introduced with 300 mL of water. The mixture was homogenized at medium-high speed before being cast into molds pre-treated with a thin film of release agent. Specimens were cast to a depth of 5 cm for the ease of crushing. The mix was consolidated via manual tamping until a glossy surface appeared, ensuring the removal of entrapped air and stabilization of fiber orientation while avoiding matrix bleeding.

Fig -5: Mixing

Fig -6: Compaction

5. Two-Stage Curing

A dual-stage curing regime was implemented to facilitate structured polycondensation. Initially, specimens underwent a 3-day ambient rest period to initiate slow-phase geopolymerization. This was followed by thermal activation in a thermostatically controlled oven at 100°C for 6.5 hours daily over three consecutive days. To mitigate thermal shock and micro-cracking, specimens were cooled gradually within the oven chamber to room temperature before further processing.

Fig -7:Casted geopolymer paste specimens

6. Fragmentation and Surface Encapsulation

Hardened geopolymer blocks were manually fragmented using controlled impact blows and subsequently graded via sieve analysis. To enhance durability and reduce water absorption, the resulting aggregates underwent surface encapsulation. A low-viscosity geopolymer slurry (L/S ratio of 0.4) was formulated to promote capillary penetration into micro-pores. The graded aggregates were submerged in the slurry, vigorously stirred to ensure uniform wetting, and then kept at ambient temperature for overnight, thereafter they are subjected to a final thermal treatment at 100°C for 6 hours in oven.

Fig -8: Hammer Crushing

Fig -9: Geopolymer slurry

Fig -10: Geopolymer coated aggregates

3. TESTING AND RESULTS

1. Aggregate Impact Value Assessment

The Aggregate Impact test was conducted to evaluate the mechanical toughness and resistance of the artificial aggregates to sudden shock or dynamic loading. Standardized specimens, passing a 12.5-mm sieve and retained on a 10-mm sieve were compacted in three layers within a cylindrical steel cup and subjected to 15 free-fall blows from a 13.5–14.0 kg hammer at a constant drop height of 380 mm. The resulting fines passing a 2.36-mm IS sieve were quantified as a percentage of the initial sample weight, where a lower impact value signifies superior impact resistance and structural integrity.

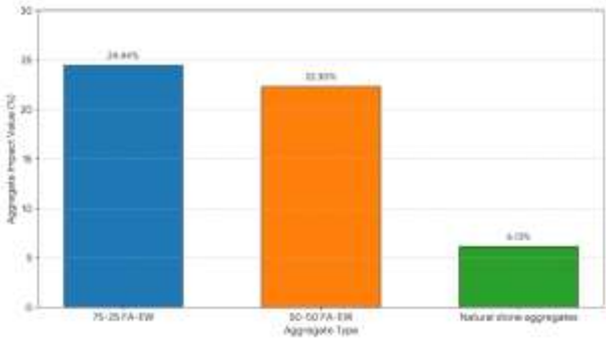

Fig -11: Results of Aggregate Impact test

The results indicate that the geopolymer aggregates (FA-EW) exhibit higher impact values compared to natural stone aggregates. Specifically, the 75-25 FA-EW and 50-50 FA-EW mixes yielded impact values of 24.44% and 22.30%, respectively. While these values are higher than the 6.13% observed for natural stone, both geopolymer variations remain well within the standard permissible limits for use in road sub-base and base course applications (typically less than 30 %). The slight reduction in aggregate impact value for the 50-50 FA-EW compared to the 75-25 FA-EW suggests that a higher proportion of NMF may contribute to a marginal increase in the toughness of the geopolymer matrix.

2. Los Angeles Abrasion Resistance Analysis

The Los Angeles Abrasion test was employed to determine the surface hardness and resistance of the aggregates to degradative wear caused by abrasion. “A” graded sample of dried aggregate was placed within a rotating hollow steel cylinder along with a specified charge of steel spheres, operating at 30 to 33 rpm for a set number of revolutions. After rotation, the material was extracted and sieved through a 1.70-mm IS sieve to calculate the weight loss percentage. This metric serves as a primary indicator of the aggregate's durability against mechanical grinding and surface wear encountered during service life.

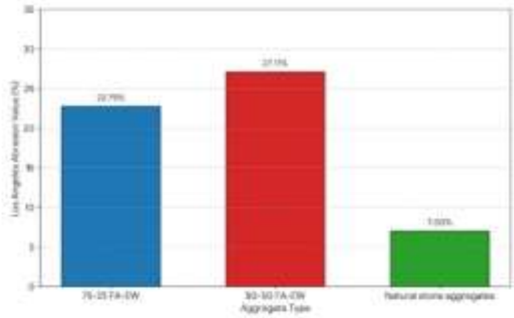

Fig -12: Results of Los Angeles Abrasion test

The Los Angeles Abrasion test results characterize the mechanical durability and resistance of the aggregates to surface attrition. The 75-25 FA-EW aggregate yielded an abrasion value of 22.75%, while the 50-50 FA-EW variant showed a higher loss at 27.11%.

However, both geopolymer formulations satisfy the standard requirement for high-quality road aggregates, which typically mandates an Los Angeles abrasion value of less than 40%. In comparison, the natural stone aggregates exhibited a significantly lower value of 7%, reflecting the inherent density and hardness of natural geological formations compared to composite artificial aggregates

4. CONCLUSIONS

The experimental investigation into the development of artificial aggregates using the non-metallic fraction (NMF) of printed circuit boards and fly ash confirms the technical viability of geopolymerization as a sustainable waste-management strategy. By utilizing 8M NaOH and sodium silicate binary activator of SS/SH of 2.5:1, the study successfully transformed hazardous industrial waste into a high-performance construction material. Both the 75-25 and 50-50 FA-EW formulations demonstrated robust mechanical properties. The Aggregate Impact Values (24.44% and 22.30%) and Los Angeles Abrasion values (22.75% and 27.11%) consistently satisfied the stringent requirements for base course. The 50-50 mix showed a slight improvement in impact resistance (toughness) compared to the 75-25 mix, whereas the 75-25 mix exhibited superior resistance to surface abrasion. This suggests that while fiber reinforcement from the NMF enhances toughness.

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