

Original Article

# Coupled Mechanical and Transport Performance of Concrete Incorporating Alkali-Activated GGBS Aggregates and Recycled Electronic Waste

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**Abstract** - The rapid growth of infrastructure development has placed an unprecedented strain on natural aggregate resources, accelerating their depletion and intensifying the environmental impact of conventional concrete production. Simultaneously, the increasing burden of Electronic Waste (e-waste) is a significant sustainability issue because of the troublesome nature of its materials and the few avenues for recycling it. This study explores the use of combined alkali-activated GGBS-based manufactured artificial aggregates with recycled e-waste aggregates as a substitute for natural coarse aggregate in structural concrete. An extensive experimental program was carried out on M25 concrete containing combined manufactured GGBS and e-waste aggregates at 0%, 20%, 40%, 60%, 80%, and 100% replacement by volume. Workability in the fresh state was assessed with slump and compaction factor tests. The mechanical properties of the hardened concrete were assessed with compressive strength and static modulus of elasticity tests. The transport-related durability property was assessed using the RCPT, which was performed after 28 days of curing. The concrete performances demonstrated a non-linear relationship with aggregate replacement level that was highly dependent on the relative stiffness of the different types of aggregates used, their morphologies, and those of the paste-aggregate transition zones. The optimum replacement level was found to be 20%, where workability was improved, compressive strength was significantly increased, and chloride ion penetrability was much reduced compared to conventional concrete, owing to the increased particle packing, bonding efficiency, and partial microstructural densification provided by the alkali-activated GGBS aggregates. Although the mechanical performance of the concretes decreased with increasing replacement level, leading to increased heterogeneity and reduced stiffness, this provides a focus for future work. The study demonstrates that controlled incorporation of GGBS-based artificial aggregates and recycled e-waste can produce mechanically efficient concrete with enhanced durability, thereby establishing a scientifically grounded pathway to resource-efficient, sustainable aggregate engineering.

**Keywords** - Alkali-Activated GGBS Aggregates, Chloride Ion Penetrability, Recycled Electronic Waste, Sustainable Aggregate Engineering.

## 1. Introduction

Concrete is the world's most widely used engineering material, serving as the structural basis for an immense range of transport, buildings, and infrastructures. Its material use is second only to water and is supported by the rapid pace of urbanization and intensive infrastructural development. The continuing demand for concrete in the construction sector has driven natural aggregate extraction to unprecedented levels, since around 70-75% of the concrete mixture by volume consists of aggregates. The gradual depletion of high-quality aggregate sources, combined with the harmful environmental

effects of quarry or river sand extraction, has made the search for aggregates focused on securing long-term aggregate supplies a concern.

Simultaneously, the cement and concrete sector is under increasing pressure to reduce its environmental impact. Cement production is responsible for a large fraction of anthropogenic carbon dioxide emissions, while aggregate extraction has a variety of adverse localized environmental effects. Therefore, contemporary concrete science has shifted from a strength-oriented to a performance-oriented approach,



developing resource-efficient concrete designs that incorporate industrial by-products and recycled materials. Within this approach, artificial and artificial aggregates derived from secondary materials are emerging as a leading alternative to natural aggregates for coarse aggregate replacement.

GGBS is a waste product of the iron and steel industry that has been extensively investigated and processed into an SCM. A more recent development in the utilization of GGBS is using it as a precursor for artificial aggregates in the form of alkali-activated manufactured aggregates. This process promises the waste valorization of an abundant secondary material, avoiding reliance on stone-based natural aggregates. Manufactured aggregates differ from crushed stone aggregates in their particle shape, internal porosity, and interfacial behaviour, all of which impact not only the fresh and mechanical properties of concrete but also its resistance to damage due to transport processes. However, the mechanical performance of manufactured aggregates in concrete is sensitive to their production parameters, curing times, and replacement levels. Thus, they need to be evaluated under realistic conditions in which they are employed in structural applications.

Another raw material for the production of resource-efficient concrete is Electronic Waste (e-waste). The production and replacement of electronic devices is at an explosive level. E-waste products have multi-material, multi-component product characteristics and few environmentally sound disposal options. In particular, the non-metallic fractions cannot be recycled by standard procedures. If disposed of incorrectly, they can leach undesirable constituents and represent a threat to soil and groundwater. In terms of material characteristics, processed e-waste has low density, a heterogeneous surface topography, and is less stiff than mineral aggregates. These characteristics allow for the potential to use e-waste as a partial aggregate replacement for concrete, provided the appropriate performance criteria are satisfied.

Limited studies have shown that it is possible to use e-waste as coarse aggregate in concrete without catastrophic loss of its mechanical performance, thus providing a route to form a resource-efficient concrete that reduces the burden of e-waste. However, the use of e-waste in combination with manufactured mineral aggregates has not yet been investigated.

The incorporation of two different non-conventional aggregate systems creates competing effects relating to stiffness-mismatched interfacial transition zones and the connectivity of porous connectives that govern mechanical behavior and durability. The literature that is available examines these different approaches to using non-conventional aggregates for concrete formation in isolation from one another.

Though there are a number of investigation studies regarding both e-waste aggregates and alkali-activated GGBS-based aggregates separately, there are no studies that investigate the use of such aggregates in combination with one another. The interaction between the low-stiffness aggregates derived from polymeric e-waste and the porous structure of alkali-activated GGBS-based aggregates is particularly complex and different from the effects seen with other aggregates. Additionally, most existing studies on such aggregates focus primarily upon the compressive strength of the resultant concretes, with little investigation into other parameters, such as elastic modulus and chloride permeability. Therefore, a general understanding of the effects of such concretes with these types of aggregates is lacking in the existing literature.

This study investigates the effects of using these types of aggregate concretes on properties such as workability, strength, stiffness, and permeability, and determines an optimal strategy for the replacement of aggregates with these types of concretes.

## 2. Literature Review

The rapidly expanding Electronic Waste (e-waste) stream has emerged as a global environmental issue due to the increasing rates of consumption of electronic goods and the decreasing periods during which those goods are usable [1, 5]. E-waste streams are naturally heterogeneous, containing polymeric plastics, glass fibers, ceramics, and trace amounts of heavy metal contaminants, including lead, Cadmium, Mercury, and Antimony [3, 8]. The toxic leachate resulting from the disposal of e-waste has been associated with devastating environmental outcomes, such as the pollution of soils and groundwaters, and long-term threats to the affected ecosystems and their human inhabitants [3]. Various publications have reported that a very small fraction of e-waste is processed through environmentally responsible recycling, and that the bulk of e-waste is either informally recycled or landfilled, especially in developing countries [1, 8].

From a materials engineering perspective, the disposal of e-waste presents challenges due to its compositional heterogeneity and variable chemical composition, which limit conventional waste recovery methodologies [8]. Urban studies have shown highly elevated concentrations of heavy metal contaminants in soils surrounding informal e-waste operations, with contaminant concentrations up to hundreds of times greater than the background concentrations typically found in municipal solid waste [8]. The studies indicate a need for alternative, high-volume use pathways for e-waste, which can immobilize its hazardous components and reduce the reliance of e-waste streams on landfilling.

The construction industry has been identified as a potential market sector for the valorization of e-waste since

concrete applications in construction have a high demand for aggregates, and the concrete matrix itself can physically encapsulate heterogeneous waste streams [21]. Partial replacement of coarse aggregate in concrete mixes with one processed fraction of e-waste has been the focus of a number of experimental investigations [18, 19]. The findings of these studies typically indicate that low levels of replacement, about 10% to 15% of coarse aggregate, do not adversely affect the compressive strength of the concrete that is produced; some studies have even found that the use of e-waste material can improve the tensile and flexural strengths [18, 19]. Higher levels of replacement (above 15%), though, do have a negative effect on compressive strength and elastic modulus in all published studies, as a result of the low stiffness properties, variable geometries of the irregularly-shaped particles, and relatively poor properties of the interfacial bonds that form between particles and the matrix in which they are embedded [18].

In addition to research on e-waste-derived aggregates, a significant body of research has been published on artificial and manufactured aggregates that are produced from industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), quarry dust, and metallurgical residues [9, 12]. Of these by-products, GGBS has been of particular interest due to its latent hydraulic properties, which make it chemically compatible with traditional cementitious materials [10]. GGBS has traditionally been used as an SCM; however, it has also been used as a precursor for the manufacture of artificial coarse aggregates through pelletizing or cold bonding processes that are typically alkali activated [13, 14].

Concrete that incorporates GGBS-based artificial aggregates as a replacement for coarse aggregates has shown mechanical properties that are similar to traditional concrete at moderate replacement levels [13, 14]. Various studies have indicated that reductions in compressive strength that result from the low weight of artificial aggregates can be partially offset by the careful management of both curing and particle grading practices [13]. The porous microstructure of these manufactured aggregates also provides beneficial effects such as enhanced workability and internal curing [12]. However, increased absorption rates and reduced elastic stiffness remain challenges that need to be addressed at elevated replacement ratios [14].

The durability performance of concrete that incorporates artificial aggregates has also been investigated, with the literature reporting mixed results. For example, while increased ionic transport may result from the internal porosity of manufactured aggregates, the refinement of the paste/aggregate interface that results from pozzolanic reactions within an optimized matrix design may offset this effect under certain conditions [13, 17]. These competing processes suggest that ionic transport phenomena such as

chloride ion penetration should be viewed holistically rather than solely in terms of mechanical strength measurements.

Despite extensive research on the mechanical properties of concrete that incorporates e-waste-derived aggregates and artificial aggregates produced from GGBS, few research publications appear to have investigated the two types of aggregate together in a common concrete matrix. The combined incorporation of GGBS-based artificial aggregates and low-stiffness e-waste aggregates presents new challenges related to issues such as stress-transfer efficiency, interfacial transition zones, and pore connectivity [20]. Most existing studies have investigated these two aggregate types separately; thus, little is known about their combined effects on mechanical and durability performances.

Moreover, existing research studies appear to evaluate concrete performance primarily in terms of compressive strength, rather than elastic stiffness or ionic transport resistance. In practice, however, elastic modulus and ion permeability are performance parameters that are important for the longevity and usability of reinforced concrete structures [21]. Existing research gaps have not yet been addressed; thus, no study appears to have systematically assessed fresh-state properties, elastic moduli, and chloride penetration depths for various levels of combined replacement of ordinary Portland cement by alkali-activated GGBS binders.

To fill these gaps in the literature, this study investigates the mechanical and durability performances of concrete that incorporates combined replacements of alkali-activated GGBS artificial aggregate particles and e-waste-derived aggregate particles. By measuring concrete workability, compressive strength, and elastic modulus, as well as the rapid chloride ion permeability of matrices with different combined replacement levels, this study aims to identify an effective combined replacement level at which the structure still demonstrates acceptable mechanical properties but becomes more durable with fewer engineered resources.

While the studies on alkali-activated GGBS aggregates showed an improvement in the durability of the aggregates, the studies on the e-waste aggregates presented a reduction in stiffness and strength of those aggregates. However, these studies have all examined the individual aggregates without considering the effect that they may have upon the other type of aggregate.

Through incorporating these two types of aggregates into the cements, it is possible to see that the alkali-activated GGBS compensates for the weakness of the e-waste aggregates, leading to a cement with an interaction between these two components that has not been presented before in the literature. Thus, this study represents a step forward in the creation of these types of materials.

### 2.1. Research Gap

Considerable research has been conducted into the use of industrial by-products and recycled materials as a partial replacement for conventional materials in concrete. The specific use of Electronic Waste (e-waste) as a replacement for natural coarse aggregates has been explored as a separate avenue of investigation, with the conclusion that replacement of natural aggregates with moderate levels of e-waste does not result in a catastrophic loss of compressive strength properties, though it greatly reduces elastic stiffness and durability with higher replacement rates due to poor interface bonding and modulus of the aggregates.

Relatedly, Ground Granulated Blast Furnace (GGBS) has been similarly and extensively explored as a supplementary cementitious material, and has also more recently been investigated for its use as a precursor to the manufacture of artificial coarse aggregates via alkali activation or pelletization processes. GGBS-based manufactured aggregates have been shown to have aggregate engineering properties that enhance the microstructural properties of concrete and improve its durability, but their effect on the elastic response properties and transport mechanisms of the concrete have been shown to be highly variable depending upon replacement rate, method of manufacture, and use.

The combined use of GGBS-based manufactured aggregates and e-waste aggregates in a single concrete matrix, however, has not yet been observed in the literature. The reviewed literature tends to investigate these aggregates separately, without considering the possibility of interactive effects that may be created by the use of two different aggregate types with varying porosities, elastic stiffness, and surface chemistry within the same concrete. Additionally, however, existing literature that has investigated GGBS-based manufactured aggregates usually does so with a focus upon compressive strength alone; relatively few studies have considered the elastic modulus of such concrete, and even fewer still have correlated that modulus with permeability and permeability-related transport mechanisms. Thus, there is a gap in knowledge regarding the research topic of systematically investigating the fresh properties, strength, elastic modulus, and permeability or permeability-related transport mechanisms of hybrid aggregate system concrete that incorporates both alkali-activated GGBS-based manufactured aggregates and recycled e-waste aggregates across a range of replacement rates.

### 2.2. Objectives of the Study

The objectives of the present study are to investigate the feasibility and performance effects related to the use of both alkali-activated GGBS-based manufactured aggregates and recycled e-waste aggregates as partial replacements for natural coarse aggregates in structural concrete. More specific objectives can be listed as follows:

- The characterization of natural, GGBS-based manufactured, and e-waste aggregates according to relevant standards.
- The investigation of the effect of combined replacement on the fresh properties of concrete (especially slump and compaction).
- The investigation of the effect of aggregate replacement rate on compressive strength, split tensile strength, and modulus of elasticity.
- The evaluation of the durability performance of hybrid aggregate concrete (resistance to chloride ion permeability).
- The determination of an optimum replacement rate that can reduce reliance upon natural coarse aggregate without sacrificing mechanical performance, elastic modulus, and permeability-related durability.

### 2.3. Novelty of the Present Work

Most existing studies independently evaluate the properties of either e-waste or GGBS-based manufactured aggregates.

While most previous studies have found that the increase in e-waste replacement levels leads to a reduction in the strength of the concrete, and the use of GGBS-based aggregates improves the durability of the concrete, the combined use of these aggregates leads to a non-linear response of the concrete.

The novelty of this study lies in the development of a framework that evaluates the coupled mechanical and transport performance of the concrete containing these two types of aggregates, rather than the evaluation of the uniaxial strength of the concrete.

## 3. Materials

The materials used in the experimental program were selected for consistency, reproducibility, and adherence to relevant Indian Standards. The materials employed included ordinary Portland cement, fine and coarse natural aggregates, Ground Granulated Blast-Furnace Slag (GGBS), manufactured aggregates, recycled e-waste aggregates, and potable water.

### 3.1. Cement

Ordinary Portland Cement (OPC) of 53-grade (IS 12269:2013) was used as the sole binding material in the study. OPC 53 was selected because of its improved early-age strength and consistent characteristics that permit achieving the desired mechanical performance within known curing durations.

Limiting the study to a single binding material type enabled the performance variation between mixtures to be directly attributed to the effects of the replacement aggregates.

### 3.2. Fine Aggregate

M-sand conforming to Zone II was selected as fine aggregate. M-sand was selected as a sustainable replacement for river sand because of its consistent grading, angularity, and inter-particle friction, which increase its packing efficiency and paste-aggregate interactions; these factors affect the concrete's properties while in a fresh state and after curing.

### 3.3. Coarse Aggregates

#### 3.3.1. Natural Coarse Aggregate

The natural coarse aggregate used was machine-crushed granite stones with a nominal maximum size of 20 mm that conforms to IS 383:2016. Coarse aggregates were selected for their inherent strength, durability, and angularity to ensure adequate physical interlocking within the concrete matrix. Natural aggregates acted as the performance control in the study.

#### 3.3.2. Manufactured Coarse Aggregate (GGBS-Based)

Artificial aggregates were manufactured using GGBS as the sole precursor material. The aggregates conformed to M25-grade concrete mix design and were used to replace natural coarse aggregate partially.

GGBS was used in this instance to enable value addition to this otherwise waste material. The GGBS-based aggregates did, however, exhibit particular physical properties related to porosity and texture that influence their performance (e.g., workability, strength, durability).

### 3.4. Water

Potable water that is free from harmful contaminants was used to mix and cure all concrete samples, in accordance with the requirements for concrete production of relevant codes.

### 3.5. GGBS

GGBS is produced by rapidly cooling molten iron ore slag with water or steam to form a granular glassy material that is then dried and milled. GGBS mainly contains Calcium Oxide (CaO), Silicon Oxide (SiO<sub>2</sub>), Aluminum Oxide (Al<sub>2</sub>O<sub>3</sub>), and Magnesium Oxide (MgO); concentrations of individual oxides vary based on the mixture of raw materials charged into the furnace.

Unlike conventional Portland cement manufacture, GGBS production requires orders of magnitude less energy input and has a significantly lower carbon footprint. In a cementitious system, GGBS has latent hydraulic and pozzolanic properties that lead to strength gain over time.

Though GGBS is typically added as a partial replacement for cementitious binders in a ratio of between 20% and 50%, the specific application of GGBS in the current study refers not to its replacement of a binder but rather its use as a precursor for manufactured coarse aggregates.

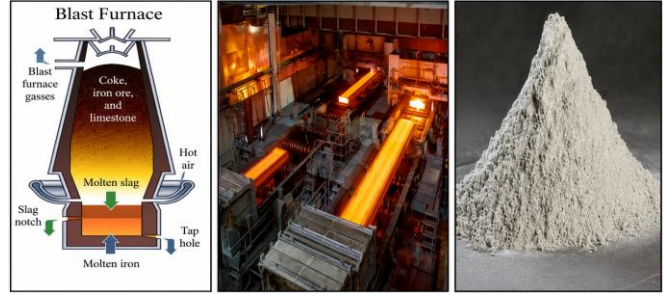


Fig. 1 The source and processing route of GGBS

Figure 1 depicts the integrated iron and steel manufacturing process, which begins with the reduction of raw materials in a blast furnace to produce molten iron and slag, and then continues with the creation of steel through high-temperature rolling processes. The resulting granulated blast furnace slag is then ground into a fine powder and used as an additional cementitious material, increasing cement's strength and durability while lessening its negative environmental effects.

### 3.6. Electronic Waste (E-Waste)

Electronic Waste (e-waste) aggregates were derived from discarded electronic materials that contained excess polymeric casing or remnants of polymeric material on printed circuit boards after the recovery of metallic components.

The physical properties of e-waste aggregates differ from those of mineral aggregates in various aspects, such as stiffness, homogeneity, and surface morphology.

These differences impact mechanisms such as load transfer, transition zones between aggregates and binders, and overall mechanical response when e-waste aggregates are integrated into concrete products that exhibit techno-economic benefits. In this instance, treated e-waste aggregates were partially replaced with natural coarse aggregates, with which they were combined with GGBS-based manufactured aggregates to investigate the effect of the different aggregate mixtures on the fresh-state behavior, mechanical performance, and durability of the concrete.

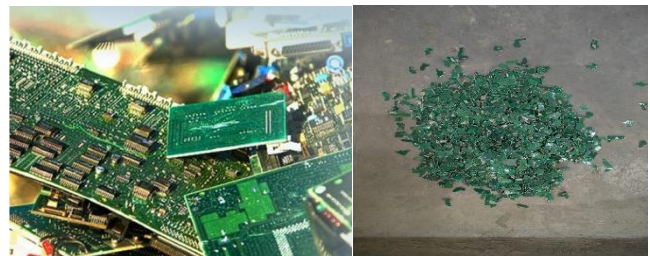


Fig. 2 Electronic waste

The image illustrates crushed Printed Circuit Boards (PCBs) and motherboard waste, consisting of fragmented epoxy resin, fiberglass, and embedded metallic components.

Such processed e-waste can be utilized as a partial replacement material in cementitious composites, promoting sustainable waste recycling and reducing environmental burden.

#### 4. Method and Materials Used for the Experimentation

The experimental program used to achieve the set objectives and to answer the posed research questions was designed to evaluate the influence of replacing coarse aggregates with alkali-activated manufactured and e-waste aggregates on the workability, strength, and durability of the resulting concretes. Consideration was given to isolating the effects of the aggregates by keeping the binder, water, and curing conditions the same across the test mixtures.

##### 4.1. Characterization of the Components of the Concretes Used

The components of the concrete used in the study were characterized in accordance with the relevant Indian Standards prior to concrete production in order to ensure that they conformed to the required limits and to characterize their physical and mechanical properties.

###### 4.1.1. Cement

OPC of 53 grade was used in all experimentations as per IS 12269:2013 specifications. The cement was tested for normal consistency, specific gravity, setting time, fineness, and compressive strength using mortar cubes of dimensions 70.6 × 70.6 × 70.6 mm. The resulting properties were found to conform to the defined limits, thus confirming both the suitability of the cement for structural concrete and the consistency of its properties across all test mixtures.

Table 1. Properties of the cement

SI No	Details	Results	Permissible Value as per IS: 12269-2013
1	Normal consistency (%)	34%	----
2	Specific Gravity	3.1	3.15
3	S <sub>T</sub>	45	≥ 30
4	F <sub>T</sub>	425	≥ 600
5	Fineness	281 m <sup>2</sup> /kg	225 m <sup>2</sup> /kg (minimum)
6	Fineness of Cement (retained on 90µ sieve)	2.5%	Less than 10%

According to the test results, the cement has appropriate consistency, specific gravity, setting qualities, and fineness, and it generally meets the physical specifications given in IS: 12269-2013.

Table 2. Compressive Strength (MPa) (70.6 X 70.6X 70.6) mm Cubes

Strength in days	Results	Permissible Value
3	29.3	≥27
7	41.2	≥37
28	53.5	≥53

Table 2 indicates that the cement mortar cubes' compressive strength findings at 3, 7, and 28 days meet the minimal specifications outlined by the applicable standards. The cement's good strength development properties and proper hydration are confirmed by the strength's progressive increase with curing age.

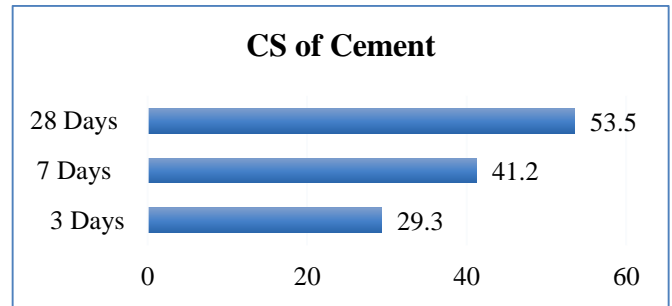


Fig. 3 Compressive strength of cement mortar

Figure 3 shows values of 29.3 MPa at 3 days, 41.2 MPa at 7 days, and 53.5 MPa at 28 days, showing how cement's compressive strength increases with curing age. This pattern shows adequate hydration and validates that the cement develops the necessary strength in accordance with standard requirements.

###### 4.1.2. Natural Coarse Aggregate

The coarse aggregate employed was machine-crushed granite of nominal maximum size 20 mm. Its physical, mechanical, and shape characteristics were determined according to IS 2386 (Parts I-IV) and found to conform to the strength, durability, and shape criteria to serve as the control aggregate in the experiment.

Table 3. Characteristics of Coarse Aggregate

SI No	Specifications	Results	IS 2386-4
1	Specific gravity	2.7	-----
2	Water absorption (%)	0.6	
3	Loose bulk density (kg/m <sup>3</sup> )	1400	1500-1600
4	Crushing value	16.5	Less than 30%
5	Impact Value	10	Less than 30%
6	Abrasion value	16.2	Less than 35%
7	Flakiness index	13	Less than 30%
8	Elongation Index	19	Less than 30%

Table 3 incorporates the Aggregate test results, showing acceptable mechanical and physical characteristics in compliance with IS 2386 (Part 4):1963 specifications. The aggregates' suitability for use in concrete and other structural

applications is confirmed by their low water absorption and strength-related indices, crushing, impact, and abrasion values.

4.1.3. Fine Aggregate

Zone II fine aggregate that conformed to IS 383:2016 was used as manufactured sand. The fine aggregate was sifted through a 4.75 mm sieve before use and was also tested for its specific gravity, water absorption, fineness modulus, and bulk density. The values obtained from these tests ensured that the sand was adequately graded and consistent for the intended use of concrete.

Table 4. Characteristics of Fine Aggregate

Sl No	Physical properties	Results
1	FA Specific Gravity	2.7
2	Percentage of Water Absorption	1.01
3	Fineness modulus	2.9
4	Loose bulk density (kg/m <sup>3</sup> )	1550

Table 4 indicates the physical properties of fine aggregate, which indicate acceptable specific gravity, water absorption, and grading characteristics suitable for concrete production. The fineness modulus and bulk density values confirm good particle distribution and workability performance in cementitious mixes.

4.2. Production of GGBS-Based Manufactured Coarse Aggregate

Coarse manufactured aggregates were produced because of the alkali activation of Ground Granulated Blast Furnace Slag (GGBS). Sodium hydroxide (NaOH) solutions and Sodium Silicate (Na<sub>2</sub>SiO<sub>3</sub>) solutions were separately prepared at the required concentrations. The two solutions were then mixed, and an SS/SH ratio of 2.5 was achieved. The resulting alkaline solution was added to dry GGBS and was mixed in a rotating drum mixer at 55 rpm. Pelletized agglomeration resulted in near-spherical geopolymer aggregates that were formed as pellets, and these pellets were collected from the mixing container and allowed to cure for 1 day at the ambient temperature of the laboratory (27 ± 2 °C). The areas were then air-dried. Sifting through the manufactured aggregates was then performed to ensure that they were adequately sized after drying in accordance with the traits of the natural coarse aggregates.

The selected palletization-based manufacturing process was simple and scalable, thus ensuring that the size distribution and surface texture of the manufactured aggregates could be controlled.

The flowchart illustrates the step-by-step procedure for geopolymer concrete production, shown in Figure 4, starting

with the preparation of alkaline activator solutions and ending with the collection of the final product. It highlights controlled mixing, aggregate addition, and curing stages, emphasizing the systematic process required to achieve consistent geopolymer concrete properties.

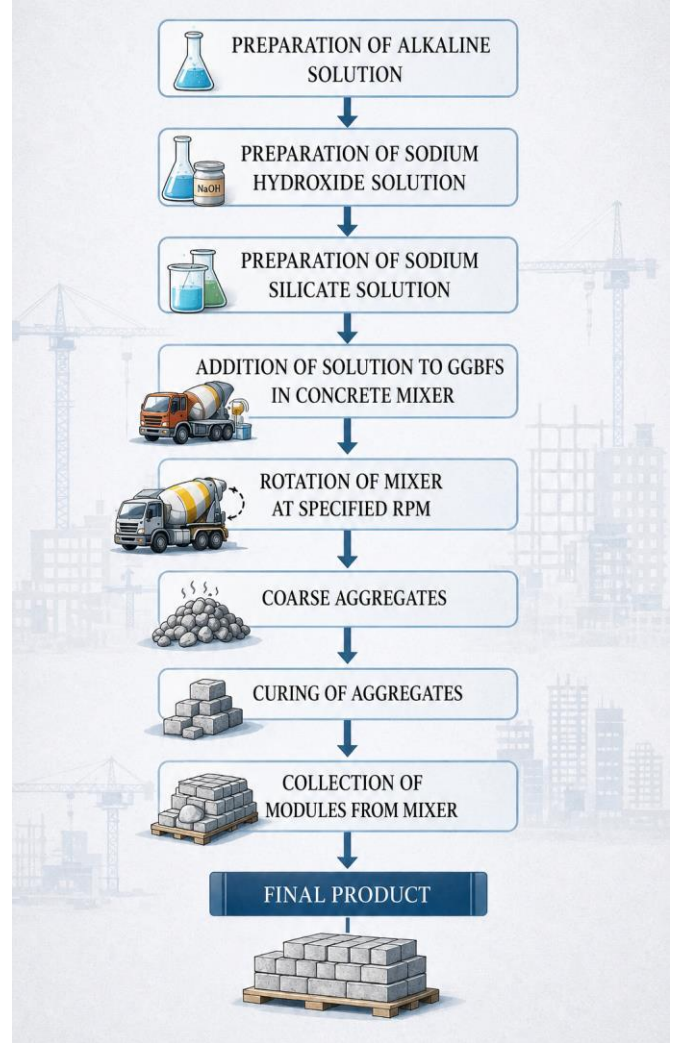


Fig. 4 Flow diagram 1 of the manufacturing of coarse aggregate



Fig. 5 Manufactured Aggregate

Figure 5 shows different sizes and gradations of coarse aggregates arranged for visual comparison. Such variation in aggregate size distribution plays a crucial role in influencing the strength, workability, and packing density of concrete.

**4.3. Properties of Manufactured Aggregates**

The physical properties of GGBS-based manufactured aggregates were assessed after curing and were compared with natural coarse aggregates through various tests, including water absorption, loose bulk density, crushing value, impact value, abrasion value, flakiness index, and elongation index—all performed according to IS 2386 standards. The results of the various tests determined that the rate of water absorption and loose bulk density of the manufactured aggregates were both higher than for natural aggregates; the properties measured, however, were still within limits that allow for use as structural concrete.

**Table 5. Characteristics of Manufactured aggregates**

Sl No	Properties	GGBS Aggregate	According to IS:2364-1963
1	Water absorption	3.25	
2	Loose bulk density(kg/m <sup>3</sup> )	897	1500-1600
3	Crushing value	26	< 30%
4	Impact Value	14	<30%
5	Abrasion value	89	< 35%
6	Flakiness index	0	< 30%
7	Elongation Index	0	<30%

According to IS 2364-1963, the test results show that the GGBS aggregate has appropriate strength-related characteristics, including crushing, impact, flakiness, and elongation indices. The higher abrasion value and lower bulk density, however, point to differences in physical properties that could affect durability and should be taken into account in mix design applications.

**4.4. Concrete Mixture Design and Preparation**

Concrete mixtures were designed according to IS 10262:2019 as a mixture of M25-grade concretes. Natural coarse aggregates in each of the concrete mixtures were partially replaced with manufactured aggregates (GGBS-based) and e-waste aggregates at different replacement levels: 0% (control), 20%, 40%, 60%, 80%, and 100% (where natural aggregates were directly replaced by alternative aggregates). Cement (coupled with an established water-cement ratio) and fine aggregates were held constant within each concrete mixture. Concrete was mixed in a concrete mixer for each mixture. Freshly mixed concrete samples from each mixture were subjected to workability tests before casting any test specimens.

**4.5. Properties of Freshly Mixed Concretes**

Freshly mixed concrete properties were evaluated for each mixture using different methods:

**4.5.1. Slump Test**

The slump test for the freshly mixed concrete was performed according to IS 1199:1959 methods by casting slump cones using samples from each of the mixtures; the slumps were then measured accordingly.



**Fig. 6 Slump flow test for concrete**

To determine if fresh concrete is workable, a slump cone test is performed, as seen in Figure 6. The concrete mix's consistency and ease of installation are indicated by the measured slump value.

**4.5.2. Compaction Factor Test**

The compaction factor test was performed according to IS 1199:1959 methods; this test produced results regarding the compaction factor of each mixture under specific conditions.



**Fig. 7 Compaction Factor Test for Concrete**

Figure 7 shows a cement or mortar mixer being used to prepare a uniform concrete/mortar mix in a laboratory or batching setup. Proper mixing ensures homogeneous distribution of materials, which is essential for achieving consistent strength and performance of the concrete.

**4.6. Compressive Strength Test**

Compressive strength tests were performed on cube samples of dimensions 150 × 150 × 150 mm according to IS 516:1959 test procedures. The compressive strength test specimens were demoulded after waiting a period of 24 hours, during which they were cured underwater. Compressive strength tests are performed on each of the replacement levels after being underwater cured for a designed period (28 days).



Fig. 8 Concrete mixing and mould preparation

Figure 8 shows a pan mixer in operation, used for mixing concrete or geopolymer concrete ingredients to achieve a uniform and homogeneous mix. Efficient mixing in a pan mixer enhances material dispersion, leading to improved workability and consistent mechanical properties.

#### 4.7. Modulus of Elasticity

Static modulus of elasticity values were also evaluated on cube-shaped test specimens following IS 516:1959 test procedures in order to obtain modulus of elasticity measurements for what are expected to be artificially created low-modulus-strength concretes resulting from replacing traditional aggregates with aggregates with known low modulus-of-elasticity values; modulus of elasticity measurements should be performed on each level of mixture replacement.



Fig. 9 Modulus of elasticity test of concrete

Figure 9 shows a modulus of elasticity test setup used to evaluate the stress–strain behaviour of concrete specimens under axial compression. The attached strain-measuring device records deformation, enabling the determination of the elastic modulus of concrete.

#### 4.8. RCPT Test

The Rapid Chloride Penetration Test (RCPT) is a type of durability test that is performed according to ASTM C1202 procedures. RCPT will be performed on disc-shaped specimens at scheduled times, providing differing results regarding the expected rapid chloride penetration in the resulting concretes at varying replacement levels.



Fig. 10 RCPT of concrete

RCPT, which measures concrete's resistance to chloride ion penetration, is depicted in Figure 10. Concrete durability and corrosion susceptibility to reinforcement are shown by the total charge that passes through the specimen.

## 5. Results and Discussion

The results from this investigation are presented in this section, along with discussions on the fresh, mechanical, elastic, and durability performance of concrete with replacements of natural coarse aggregate with GGBS-based manufactured aggregates and e-waste aggregates. All of the results are presented with consideration of the governing material properties in question.

### 5.1. Fresh Properties

#### 5.1.1. Slump

The slump results of concrete with both manufactured and e-waste aggregates exhibited a non-monotonic trend with increased replacement rates. At low replacement rates (20-40% replacement), the slump that was measured was at least as high as, if not higher than, that of the control concrete. Such a tendency can be explained in relation to the relatively smooth texture of e-waste aggregates, as well as the high degree of control over the particle morphology of GGBS-based manufactured aggregates, which both reduce friction between and allow for the increased mobility of those aggregate particles in the fresh concrete mixture.

At high levels (beyond 40%) of aggregate replacement, slump levels in both systems of aggregates exhibited a general decrease. Such a decrement can be explained in relation to the increased water absorption and porosity of manufactured aggregate particles, as well as in the irregularly shaped particles of e-waste aggregates, both of which increased the demand for water in the concrete mixture at the expense of available free water within the mixture. The slump that was measured in concrete with 100% replacements of the aggregates also experienced a steep fall in value, which reflects the decreased workability of the concrete mixture in its fresh state.

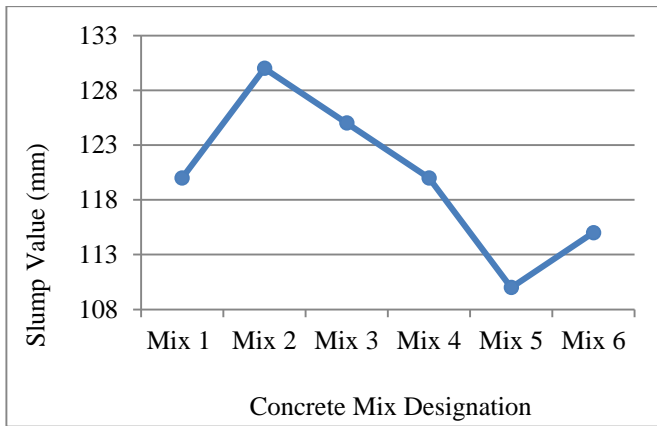
These results, therefore, indicate that the limited replacement of aggregate with either manufactured aggregates or e-waste aggregates does not negatively impact workability, but that increased amounts of replacement do require some

optimization of the concrete mixture to regain those favorable properties.

**Table 6. Slump test of concrete**

SI No	Replacement of Natural aggregate (%)	E waste aggregate Slump value (mm)	GGBS aggregate Slump value (mm)
Mix 1	0	120	80
Mix 2	20	80	81
Mix 3	40	81	85
Mix 4	60	77	79
Mix 5	80	76	78
Mix 6	100	71	72

The slump test results indicate a reduction in workability with increasing replacement of natural aggregates by both e-waste and GGBS aggregates. Overall, mixes containing GGBS aggregate exhibit relatively consistent slump values compared to E-waste aggregate mixes, indicating better workability retention.



**Fig. 11 Slump Cone test**

The slump test results demonstrate that Mix 1 achieved the highest workability, with values within the 100–150 mm range, indicating a highly plastic and cohesive concrete mix. A progressive reduction in slump from Mix 2 to Mix 6 suggests that increasing levels of material replacement adversely affected the rheological properties and flow characteristics of the concrete.

**5.1.2. The Compaction Factor**

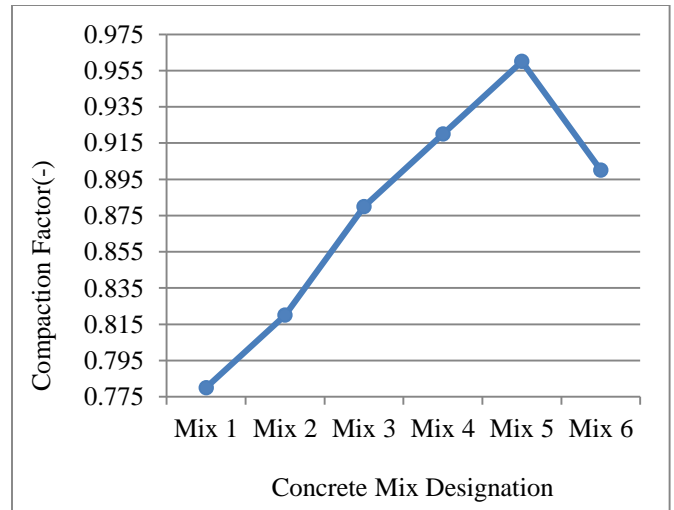
The compaction factors were measured for each of the different concrete mixture proportions, which only exhibited minor differences between one another, remaining within a range that indicates that all of the mixtures were able to remain workable and compactable. The slight improvement in compaction factor that was measured at moderate levels of replacement (20-40%) can be attributed to the increased packing of angular natural aggregates relative to the nodules of GGBS-based manufactured aggregate particles.

Slight reductions in compaction factor were observed at high levels of aggregate replacement (40-100%), which corresponds to an increase in the internal surface roughness of those aggregate systems. Similar to the case with slump results, the overall similarity among the compaction factor results indicates that all types of concrete that were tested were still able to retain their workability when compacted.

**Table 7. Compaction factor test of Manufactured Aggregate and E-Waste-based Concrete**

SI No	Replacement of Natural aggregate (%)	Compaction Factor of E-waste aggregate (mm)	Compaction Factor of GGBS Aggregate (mm)
Mix 1	0	0.86	0.88
Mix 2	20	0.87	0.86
Mix 3	40	0.89	0.9
Mix 4	60	0.87	0.89
Mix 5	80	0.85	0.86
Mix 6	100	0.84	0.85

Across all mixes, the compaction factor values, which varied from 0.84 to 0.90, indicated medium workability. The compaction factor for E-waste aggregate and GGBS aggregate reached 0.89 and 0.90, respectively, at 40% replacement, indicating optimal workability. However, as replacement levels increased, workability gradually decreased because of increased angularity and surface roughness that affected particle packing and internal friction.



**Fig. 12 Compaction factor for GGBS and E-waste-based aggregates**

Improved compaction properties of the mix are indicated by the compaction factor graph in Figure 12, which indicates an increase in workability up to 40% replacement. A progressive decline is seen above this point, indicating decreased workability as a result of higher internal friction and particle irregularity.

**5.2. Mechanical Performance**

**5.2.1. Compressive Strength**

The compressive strength results show that compressive strength progressively decreases with increasing replacements of natural coarse aggregates with replacement aggregates at rates of 20%, 40%, 60%, and 80%. Even at the relatively low replacement rate of 20%, however, compressive strength was still within acceptable levels for M25-grade concrete, especially with concrete containing GGBS-based manufactured aggregates performing relatively better than its e-waste equivalent.

The loss of compressive strength at high levels of aggregate replacement compared to natural aggregates, such as granite, can be attributed to the low strength and stiffness of both types of aggregate. In e-waste aggregates, the low strength and stiffness can be attributed to their polymeric composition and the unequal bonding effect that their different components exert on one another. In manufactured aggregates, the low tensile strength is a result of the porosity of the aggregates and the low bulk density of the particles, both of which result in their failure at specific yield points when tensile forces are applied.

Despite the compressive strength results, however, the findings indicate that up to 20% replacements of natural aggregates can be tolerated without losing structural applicability of concrete for its standard uses, especially in relation to concrete structures in which the concrete is not a major load-bearing component.

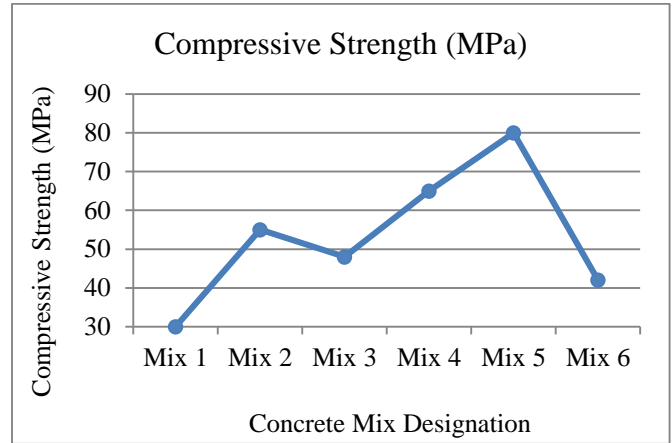
**Table 8. Compressive Strength of Manufactured Aggregate and E-Waste Concrete**

Sl No	Replacement of Natural Aggregate (%)	CS of E-Waste in MPa	CS of Manufactured in MPa
Mix 1	0	36.2	36.2
Mix 2	20	27.32	29.52
Mix 3	40	26.56	27.52
Mix 4	60	19.45	20.52
Mix 5	80	18.65	19.61
Mix 6	100	15.56	18.68

The compressive strength in the above table results indicates that the control mix (0% replacement) achieved the highest strength of 36.2 MPa. A gradual reduction in compressive strength was observed with increasing replacement of natural aggregate, with mixes containing E-waste aggregate showing slightly lower strength compared to manufactured aggregate at all replacement levels.

The compression strength graph in Figure 13 shows that as natural aggregate replacement increases, compressive strength tends to decrease. As E-waste and manufactured aggregates were gradually substituted, the strength of the

control mix decreased, with E-waste mixes displaying somewhat lower values at higher replacement levels.



**Fig. 13 Compressive strength for GGBS and E-waste-based aggregates**

**5.2.2. Split Tensile Strength**

The split tensile strength results also exhibit a reduction in strength relative to the other compressive strength measurements. Similarly to compressive strength, only minor reductions in tensile strength were found at low levels of aggregate replacement (0-20% replacement). Even at these minor levels of decrease, both systems of manufactured aggregates seem to hold their capacity to help bond the concrete together and “bridge” over potential cracks in tension.

At relatively high levels of aggregate replacement (40-100%), however, the reduction in tensile strength was more obvious due to the higher levels of heterogeneity within the concrete mixtures at these levels of replacement. The relative inefficiency of the bond that is formed between the paste and the manufactured aggregates or e-waste aggregates also negatively impacted the tensile strength of the concrete with either type of replacement aggregate. The relatively better results that were found in concrete with GGBS-based manufactured aggregates can once again be attributed to the previous addition of surface roughness and chemical compatibility, which enhanced bond formation at these interfaces.

**Table 9. Split tensile strength of Manufactured Aggregate and E-Waste Concrete**

Sl No	Replacement of Natural Aggregate (%)	Split tensile strength of E-Waste in MPa	Split tensile strength of Manufacture d in MPa
Mix 1	0	3.44	3.37
Mix 2	20	3.38	3.05
Mix 3	40	2.75	2.94
Mix 4	60	2.40	2.53
Mix 5	80	2.05	2.48
Mix 6	100	1.71	2.42

The split tensile strength results indicate that the control mix achieved the highest tensile strength, and a gradual reduction was observed with increasing replacement of natural aggregate.

At all replacement levels, concrete containing manufactured aggregate exhibited comparatively higher tensile strength than E-waste aggregate, particularly at higher percentages of replacement.

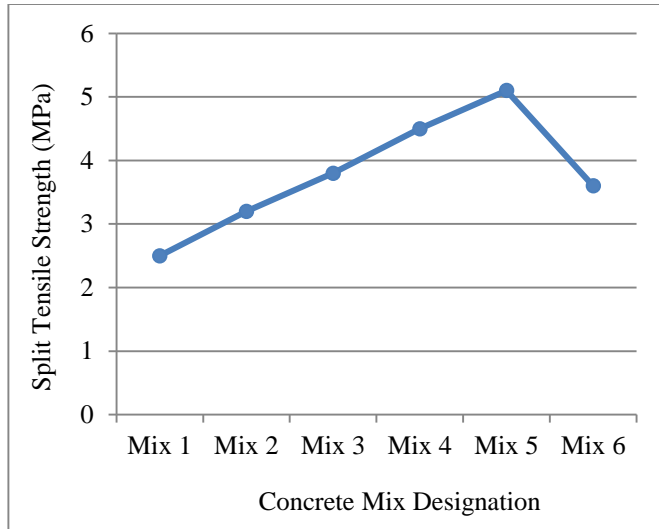


Fig. 14 Split tensile strength for GGBS and E-waste-based aggregates

As more natural aggregate is substituted, the split tensile strength graph in Figure 14 exhibits a declining trend. Higher replacement levels led to decreased tensile performance, but manufactured aggregate mixes maintained considerably greater strength than E-waste aggregate mixes. The control mix showed the maximum tensile strength.

**5.3. Modulus of Elasticity**

The static modulus of elasticity was also shown to decrease with increasing rates of replacement of coarse aggregates. The observed behavior is consistent with other research that shows that the stiffness of coarse aggregates governs the response of concrete as a whole to elasticity.

Both e-waste aggregates and manufactured aggregates have lower values of modulus of elasticity relative to natural granite aggregates, which resulted in a lower modulus of elasticity on a macro scale when each was used in its formation.

The initially low rates of reduction that were recorded in relation to modulus of elasticity were still found to be present due to the relatively high contribution of natural aggregates at lower levels of replacement (up to 20%). At higher levels of replacement (at 100%), however, those previously beneficial natural aggregates were absent.

Table 10. Modulus of elasticity

SI No	Replacement of Natural Aggregate (%)	Modulus of Elasticity of E-Waste	Modulus of Elasticity of Manufacture d aggregate
Mix 1	0	23300	22300
Mix 2	20	22100	22700
Mix 3	40	22500	23500
Mix 4	60	21500	22500
Mix 5	80	20700	21700
Mix 6	100	20200	20500

The results of the modulus of elasticity show that the control mix was stiffer, with values falling as the amount of natural aggregate replaced increased. The elastic modulus generally decreased at higher percentages, with manufactured aggregate mixes exhibiting relatively better stiffness retention than E-waste aggregate mixes, despite slight variations at intermediate replacement levels.

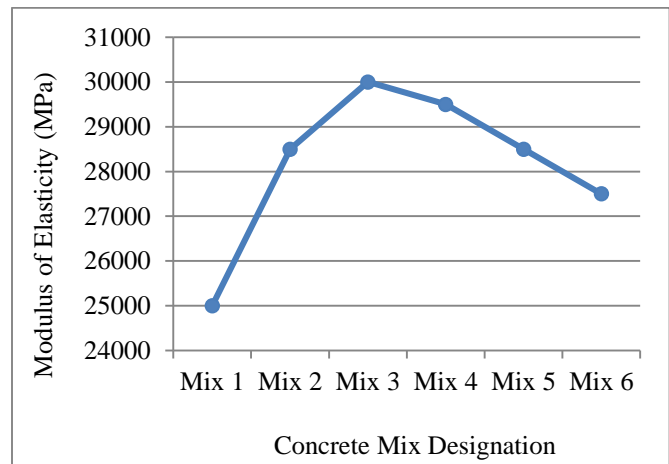


Fig. 15 Modulus of elasticity

As more natural aggregate is substituted, the modulus of elasticity graph in Figure 15 shows a progressive reduction in stiffness. Higher replacement percentages lead to a lower elastic modulus, with manufactured aggregate mixes exhibiting relatively superior stiffness than E-waste aggregate mixes, while minor variances are seen at intermediate replacement levels.

**5.4. Durability Performance: Rapid Chloride Permeability Test**

The chloride permeability test results that were obtained from GGBS-based manufactured aggregate concrete showed a drastically decreased total charge passed compared to control concrete (100% natural aggregate) at replacement rates of 100% for manufactured aggregates. Overall results for both types of concrete showed relatively decreased charge levels.

The decreased levels of chloride permeability can be attributed to microstructural refinement that was caused by the geopolymerism of GGBS-based manufactured aggregate concrete, especially around the interfacial paste-aggregate transition zones. The absorption of non-conductive phases with polymeric components likely also positively impacted the performance of e-waste recycled aggregate concrete despite its intermediate levels of chloride permeability.

Using the values as criteria for classifying chloride penetrability, conventional concrete can be categorized as being at moderate levels of chloride penetrability, while manufactured aggregate concrete can be categorized as being at low levels of penetrability (as one type/grade of environmentally friendly concrete product).

The reduction of chloride permeability is due to the densification of the microstructure within the ITZ. The alkali-activated GGBS aggregates lead to the formation of secondary C-S-H phases that reduce the porosity of the aggregate and reduce the number of capillary pores.

Additionally, the heterogeneous interface created by the e-waste aggregates creates a level of tortuosity within the system. Though not performed in this study, characterization of the microstructure of these samples would help to confirm the mechanisms of densification of these alkali-activated systems.

manufactured aggregate concrete, whereas conventional concrete demonstrated the maximum chloride ion penetration.

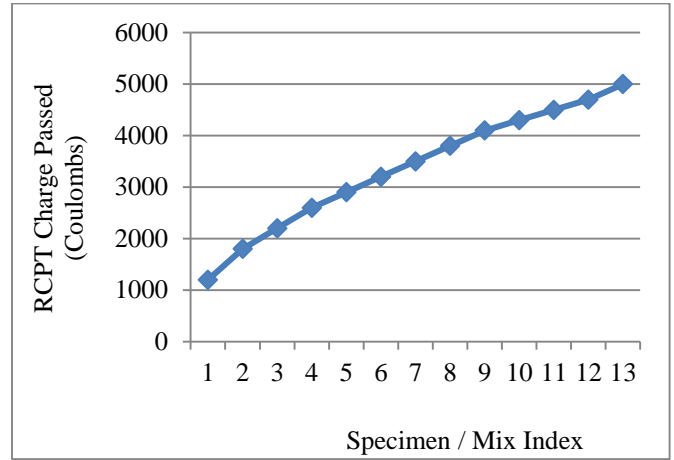


Fig. 16 Rapid Chloride Permeability Test

The RCPT graph shown in Figure 16 illustrates a steady increase in charge passed over time for all concrete mixes. Conventional concrete recorded the highest coulomb values, indicating greater chloride ion permeability, whereas E-waste and manufactured aggregate concretes demonstrated comparatively lower charge values, reflecting improved resistance to chloride penetration.

5.5. Overall Performance Evaluation

The overall evaluations that were performed on the concrete mixtures with regards to their fresh, mechanical, elastic, and durability performances all indicate that although manufactured and e-waste aggregates have different behaviours when they are subjected to different conditions or when they experience increases in the rates of replacement with other aggregates, their performance is relatively unaffected by moderate (up to 20%) rates of replacement of natural coarse aggregates. The performance measurements also indicate that limitations can still be maintained regarding high levels (40-100%) of replacement while still retaining certain ranges of desirable performances for use with concrete in certain contexts or with certain applications (i.e., non-structural elements).

The conclusions overall validate the potential benefits of using GGBS-based manufactured aggregates for increasing concrete’s durability performance and also indicate that e-waste aggregates possess beneficial properties as an alternative aggregate resource that can be utilized without losing their viability as an environmentally friendly building material.

5.6. Sustainability Assessment

The use of alkali-activated GGBS aggregates and recycled e-waste helps to reduce the dependence on natural aggregates. Since GGBS is an industrial by-product, it has

Table 11. Rapid Chloride Permeability Test

SI No	Times in minutes	Conventional concrete in Coulombs	E-Waste Aggregate concrete in Coloumbs	Manufacture d Aggregate concrete in Coloumbs
1	0	550	345	100
2	30	720	680	469
3	60	970	900	625
4	90	1276	1050	980
5	120	1925	1345	1230
6	150	2256	1895	1750
7	180	2750	2210	2000
8	210	2900	2562	2430
9	240	3250	2645	2520
10	270	3400	2892	2750
11	300	3540	3000	2900
12	330	3680	3100	3052
13	360	3800	3400	3200

The findings of the fast chloride permeability test show that for all concrete mixes, the charge passed (measured in coulombs) increased over time. E-waste and made aggregate concretes displayed relatively lower charge values, suggesting enhanced resistance to chloride permeability, especially in

lower embodied carbon than natural aggregates. Furthermore, utilizing recycled e-waste reduces the amount of e-waste that would have otherwise ended up in landfills.

The use of this type of aggregate will lead to a reduction in the environmental impact of aggregates as a result of the following: the reduction in the amount of industrial and electronic waste, the reduction of quarrying activities, and the improvement in the durability of the aggregates. Thus, the use of this type of aggregate creates a more sustainable construction industry.

### 5.7. Statistical Analysis

For the assessment of the reliability and consistency of the obtained results, a statistical analysis was performed on the determined mechanical and elastic properties of the concretes, such as compressive strength and modulus of elasticity. The mean, Standard Deviation (SD), and Coefficient of Variation (CV) were calculated for each type of concrete.

The compressive strength of the E-waste aggregate concretes was found to be 23.29 MPa with a standard deviation of 7.60 MPa (CV = 32.6%), while the manufactured aggregate concretes displayed a higher strength of 25.34 MPa with a lower standard deviation of 6.93 MPa (CV = 27.3%). These results demonstrate that the E-waste aggregate concretes exhibited higher variability in the compressive strength values.

The modulus of elasticity values for both types of concretes had a lower coefficient of variation with CV values of 5.1% and 4.5% for E-waste and manufactured aggregate concretes, respectively. These results indicate that the elastic properties of the concretes were less affected by the characteristics of the aggregates used to produce the concretes.

The Analysis of Variance (ANOVA) was performed to determine the statistical significance of the effect of the percentage of replacement of aggregates on the mechanical properties of the concretes. The ANOVA analysis showed that the effect of the percentage of replacement was statistically significant on both the compressive strength and modulus of elasticity of the concretes ( $p < 0.05$ ). These results indicate that these variables are governed by the characteristics of the materials as opposed to chance occurrences during the testing of these materials.

While the use of individual replacement materials for SCC typically results in a monotonic reduction in the strength of the SCC, the SCC containing the described hybrid system exhibits a non-linear trend in its strength. The improved strength of the SCC at 20% replacement is due to improvements in the packing of the particles, the bonding between the particles and matrix, and the reduction of the number of pores within the SCC matrix.

## 6. Conclusion

This research has studied the performance of alkali-activated GGBS-based manufactured aggregates and recycled e-waste aggregates when used as controlled partial replacements for natural coarse aggregates in an M25 concrete mix. Based on the results of the fresh, mechanical, elastic, and durability tests that were conducted, the following conclusions can be made:

The physical and mechanical properties of natural, manufactured, and e-waste aggregates all conformed to the relevant Indian Standard specifications, which establish their suitability for controlled usage in structural applications in concrete.

The fresh performance of concrete was influenced by the level of replacement of natural aggregates. The slump and compaction factor results improved (to an extent) with lowered levels of replacement of natural aggregates, with optimal levels of workability (high slump & compaction factor results) being achieved at around a 20% replacement of natural coarse aggregates. Workability was reduced beyond this point due to the increased water absorption and internal porosity of the alternative aggregates.

The compressive and split tensile strength of the concrete decreased gradually with the increased replacement of natural aggregates; the strength that was achieved with a level of replacement up to 20% of natural coarse aggregates was still high enough for structural applications in concrete that contained manufactured aggregates, however. GGBS-based manufactured aggregates outperformed e-waste aggregates in the retention of strength at all levels of replacement.

The modulus of elasticity decreased with the increased replacement of natural aggregates, indicating the reduced stiffness of manufactured and e-waste aggregates in comparison to natural granite aggregates. The loss of stiffness, however, remained at acceptable levels for concrete containing up to 20% replacement of natural coarse aggregates, establishing its suitability for serviceability-controlled structural applications.

Finally, durability tests that were based on the rapid chloride permeability test determined that concrete containing GGBS-based manufactured aggregates exhibited increased resistance to chloride ion penetration, as indicated by the lowered charge that was passed in the test. This increase in durability can be attributed to the microstructural densification of the paste-aggregate interfacial transition zone.

The combined performance of concrete containing controlled aggregates suggests that the optimal level for replacement of natural coarse aggregates is 20% this performs comparably to traditional concrete while allowing for a significant reduction of natural aggregates in its production.

Although the study presented here investigates chloride permeability, future investigations in this area of study can investigate the long-term durability of the concrete in aggressive environments to fully evaluate the performance of these materials in service conditions.

The findings demonstrate that the use of HA concrete with 20% replacement is effective for construction applications. The use of industrial by-products and recycled materials is a cost-effective solution for sustainable construction. This is particularly beneficial for regions with scarce aggregates and increasing e-waste.

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