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EVALUATION OF STRENGTH CHARACTERISTICS OF GEOPOLYMER CONCRETE WITH FOUNDRY SAND AND RECYCLED COARSE AGGREGATE AS PARTIAL REPLACEMENTS

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Abstract

Reducing environmental pollution is one of the primary concerns for sustainable development, in which the construction industry is no exception. A clean construction revolution calls for less resource-consuming, more resource-efficient, less wasteful, and less polluting technologies that are still able to meet the pre-defined quality standards and regulatory requirements. Over the last decade or so, geopolymer concrete has caught the attention of the scientific community as a feasible green material that exhibits good mechanical performance and durability and is advantageous in terms of global warming potential compared with the standard Portland cement concrete. This work is meant to disclose the strength performance of a kind of geopolymer concrete where foundry sand (FS) and recycled coarse aggregate (RCA) agents are used as a partial replacement for natural fine and coarse aggregates, respectively. Foundry sand is an inevitable by-product of metal casting, while RCA is the product of the demolition of concrete buildings; thus, these materials reduce the waste generated by landfilling and play an active role in the circular construction economy. Geopolymer binder in this experiment was generated from a mixture of fly ash and ground granulated blast furnace slag (GGBFS) with an alkaline solution consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The reason for substituting natural sand with foundry sand at various percentages was to observe the mechanical performances in the case of a combination of both materials. The first research trial included compressive strength, split tensile strength, and flexural strength tests at ages of 7, 14, and 28 days of curing.

The author's experiment yielded data which demonstrated that the replacement of the controlled and optimized fine aggregates with foundry sand serves the purpose of densifying the packing and promotes the strengthening happening at the early ages. In an analogous fashion, partial substitution of natural coarse aggregates with RCA reveals excellent results with negligible decreases in properties of the material, if the replacement percentages do not go over the upper

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limits. Excessive percentages of FS and RCA, on the other hand, are likely to reduce the strength owing to inferior bonding, increased porosity, and higher water absorption, which are characteristics of recycled products. Thus, the research work enables the strength attainments of geopolymer concrete with FS and RCA to become at the same level as or even exceed those of traditional mixtures, which provide a feasible and environmentally friendly alternative solution that can be applied to structural and non-structural fields. It manifests how this research may serve as a call-to-action for the construction industry and, more generally, for the society, regarding the imperative usage of the industrial waste materials as ingredients in design formulations of the geopolymer concrete, thus continuing the chain of natural resource conservation, carbon emissions reduction, and the endurance of sustainable practices. Genuine concerns of study results, accordingly, are a source of invaluable information for urban planners, scientists, and industry professionals conducting in the field of infrastructure development, who are committed to solving the challenges of the materials' integration in the green transition of their contemporary work.

Keywords Geopolymer concrete; Foundry sand; Recycled coarse aggregate; Sustainable construction materials; Mechanical strength; Compressive strength; Split tensile strength.

I. INTRODUCTION

Concrete is the core of modern infrastructure and has been extensively used in various applications such as buildings, bridges, highways, and other civil engineering projects. Nevertheless, the prolonged use of typical Portland cement concrete has caused various environmental concerns[1]. For instance, the process of cement production alone is responsible for about one-eighth of the total CO_2 emissions made worldwide, and at the same time, the large-scale removal of natural river sand and gravel devastates ecosystems, riverbeds, and even the underground water supply. These problems have made the need for sustainable, eco-efficient, and resource-conserving solutions to the construction industry sector much more urgent. Over the last ten years, geopolymer concrete (GPC) is recognized as one of the most environmentally friendly materials. Geopolymer binders are not like regular cement; they are made by the alkali activation of aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS)[2]. The procedure, therefore, places less carbon emissions, uses less energy, and encourages the use of waste materials. Besides, geopolymer concrete also has very good mechanical strength, is durable, resistant to chemical attack, and has better thermal stability, therefore, it can replace cement-based concrete[3]. Besides using less cement, sustainable building also calls for the reduction of natural aggregate consumption. Fine and coarse aggregates together make up about 60–75% of the volume of the concrete, and their unrestrained mining is environmentally damaging. Hence, using waste or recycled materials as aggregate substitutes is a double-win strategy, on the one hand, it cuts down on the extraction of natural resources and on the other, it reduces the amount of industrial waste disposed of[33]. Foundry sand (FS) and recycled coarse aggregate (RCA) are particulate matter for which the technologies of sustainable concrete have a promising future[4]. Foundry sand is a by-product of the production process in the metal casting industry, it is created in large quantities and is mainly disposed of in lands intended for waste. Its even gradation, high silica

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content, and physical features make it the perfect candidate for natural fine aggregate substitution. In the same vein, recycled coarse aggregate from the demolition of concrete structures is a significant contributor to waste management and at the same time, supports the principles of a circular economy[5]. In RCA, the inclusion of adhered mortar is said to be the cause of increased porosity as well as water absorption, which in turn may have an effect on the mechanical properties of concrete. Nonetheless, when utilized in proper amounts, RCA can be a good replacement for natural aggregates thereby maintaining natural aggregate consumption at the same level without performance reduction[6-7].

Using foundry sand and recycled coarse aggregate together in a geopolymer concrete mix is, therefore, an innovative way to create a construction material that is less harmful to the environment. The combined effects of these two waste materials on the geopolymer matrix, behavior, interfacial bonding, and strength is a hot topic for a new study[8]. Besides, the replacement percentages, alkaline activator concentration, curing regime, and binder composition are some of the factors that can condition the GPC performance when FS and RCA are involved[9]. In light of this, it is indispensable to physically test the mechanical behavior of such mixtures for their ableuktia in the building sector to be acknowledged further[10]. This work is mainly aimed at examining the strength characteristics of the geopolymer concrete composed of foundry sand as the partial replacement of natural fine aggregates and recycled coarse aggregate as the substitution of natural coarse aggregates. The essential mechanical properties investigated were compressive strength, split tensile strength, and flexural strength at different curing ages (7, 14, and 28 days)[11]. The goal of the research was to pinpoint the optimum replacement levels that would either keep the GPCs structural performance at a certain level or even improve it while still maximizing the sustainability advantages[12]. These outcomes play a very important role in facilitating the cleaner, greener, and more resource-efficient concrete systems development, which in turn paves the way for the worldwide low-carbon infrastructure transition[13-14].

II. BACKGROUND AND MOTIVATION

Concrete is the severally used building material in the whole earth, after water only, and its consumption keeps going up as a result of fast industrialization and urban spreading. Nevertheless, the generation of standard concrete brings about lots of environmental problems. The production of ordinary Portland cement (OPC) is a major contributor of carbon dioxide emissions to the atmosphere by about 7–8% of the total and it uses a lot of energy (Mehta & Monteiro, 2014). In the same vein, the impetuous extraction of natural aggregates—most notably river sand and gravel—has resulted in the rivers becoming degraded, the earth becoming less stable and the natural resources becoming scarce (Kumar et al., 2019). These serious ecological problems have led to the emergence of sustainable alternatives by the researchers that aim at lessening the environmental impact and not performance deterioration structurally. Such a direction is provided by Geopolymer concrete (GPC). Geopolymer concrete, an environmentally friendly low-carbon binder, was made from aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), as its main components[27]. The reason for the activation of these materials with alkaline

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solutions like sodium hydroxide and sodium silicate is polymerization, which results in a strong and stable binder matrix (Davidovits, 2008). When compared with OPC-based concrete, GPC emits far less CO_2 and has better durability, chemical resistance, and thermal stability[4]. Furthermore, its ability to accept industrial waste makes it the most important material in achieving sustainable construction and circular economy goals.

Besides binder innovations, the idea of replacing natural aggregates with recycled or waste materials has attracted a lot of attention worldwide. Foundry sand (FS) is a waste product that arises from steel and metal casting industries. Because of its high silica content, fine gradation, and uniform grain size, FS is very similar to natural fine aggregate and thus, a feasible replacement (Bhardwaj & Kumar, 2017). Nevertheless, on a yearly basis, factories dump millions of tons of foundry sand in such a way that it ends up in landfills and pollutes the soil [18]. Making use of FS in concrete is a win-win situation the former wastes less, and the latter becomes more sustainable resource management. Moreover, the explosion in production and urban development in several parts of the world, especially in developing countries have made C&D waste to be a gigantic environmental problem. The demand for natural stone aggregates can be tremendously cut with the use of Recycled coarse aggregate (RCA) which is obtained from demolition of concrete structures. Despite the fact that RCA usually has an adhered mortar that makes it more porous and increases water absorption, the researchers have found that it works well when used in limited amounts [19]. With the help of RCA, the incorporation of waste into products is not only possible but also construction materials' loop will be closed.

Using a combination of geopolymer binders with FS and RCA is an effective remedy for the carbon emissions problem as well as the depletion of natural resources. On the other hand, these materials bring about changes in the microstructural aspects of the geopolymer concrete differently[25]. To clarify, FS might enhance particle packing and lower void ratios, whereas RCA might cause the interfacial transition zone (ITZ) to be less strong as a result of its porous nature (Khalaf & DeVenny, 2005). There is a complex interaction of these factors that is not yet fully deciphered, especially when both materials are used simultaneously in a geopolymer matrix. The need to devise such kind of concrete as is discussed in the text above is the reason the motivation of this research is. The study will be a great resource on sustainable construction material on the effects of the combination of foundry sand and recycled coarse aggregate in geopolymer concrete. This can pave the way for a more lasting construction environment, a substantial lowering of the cost of building, and the advancement of national projects that are concentrated on reduction of waste and carbon emission, which is the ultimate effect of the successful employment of these materials.

In the end, the research is around the greener substitutes for normal concrete and the introduction of the more eco-friendly materials for implementation in the upcoming infrastructure projects[30].

Table 1. Summary of Background and Motivation for the Study

Aspect	Description	Supporting Citations

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Environmental impact of OPC concrete	Cement production contributes 7–8% of global CO_2 emissions; extraction of natural aggregates causes ecological degradation.	*Mehta & Monteiro (2014); Kumar et al. (2019)*
Need for sustainable alternatives	Rapid urbanization and construction demand sustainable materials that reduce carbon emissions and resource depletion.	*Davidovits (2008)*
Geopolymer concrete advantages	Low CO_2 emissions, high durability, chemical resistance, improved thermal stability, uses industrial wastes like fly ash and GGBFS.	*Duxson et al. (2007)*
Utilization of Foundry Sand (FS)	FS has high silica content and fine gradation similar to natural sand; large quantities are wasted in landfills.	*Bhardwaj & Kumar (2017); Gaur et al. (2018)*
Environmental concern of C&D waste	Demolition waste increasing globally; RCA derived from old concrete reduces natural aggregate demand.	*Poon & Chan (2007)*
Challenges with RCA	Higher porosity, water absorption, and weaker interfacial transition zone due to adhered mortar.	*Khalaf & DeVenny (2005)*
Sustainable potential of FS and RCA in GPC	Using both waste materials reduces environmental impact, enhances circular economy practices, and conserves natural resources.	*Smith et al. (2020)* (placeholder)
Research necessity	Limited studies on the combined effect of FS + RCA in geopolymer concrete; microstructural interaction not fully explored.	*Rahman et al. (2021)* (placeholder)
Motivation for current study	To develop eco-friendly, high-performance GPC using waste materials and evaluate mechanical performance for structural viability.	Present Study

III. GEOPOLYMER MIX DESIGN TRENDS

1. Geo-polymerization — key reactions (conceptual, simplified)

Geo-polymerization occurs in three overlapping stages: **(A) dissolution**, **(B) reorientation/polycondensation**, and **(C) hardening/gel formation**. Below are simplified reaction-type equations and plain-English descriptions you can cite.

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A. Dissolution (alkaline attack, release of soluble Si and Al species) Aluminosilicate glass/particles (fly ash, GGBFS) + OH^- → dissolved silicate and aluminate species (monomers)

Example (conceptual):

Si–O–Si (solid) + 2 OH^- → $Si(OH)3O^-$ → Si(OH)4 (aq)

Al–O–Si (solid) + OH^- → $Al(OH)4^-$ (aq)

Explanation: OH^- from NaOH dissolves Si and Al from the solid precursor, producing soluble Si(OH)4 and $Al(OH)4^-$ species.

B. Polycondensation / Reorientation (formation of Si–O–Al bonds) Dissolved species condense to form polymeric chains and networks:

Si(OH)4 + $Al(OH)4^-$ → Si–O–Al + H2O (polycondensation)

Explanation: Silicate and aluminate species connect via Si–O–Al linkages; sodium (Na^+) balances negative charges on Al sites.

C. Gel formation — N–A–S–H (sodium aluminosilicate hydrate) gel Generalized composition (not a strict chemical formula):

M_n[-(SiO2)_z – AlO2]_n · wH2O (M = Na^+ or K^+)

Explanation: Polymer network of Si and Al tetrahedra (linked by oxygen), charge-balanced by alkali cations (Na^+). This gel provides the binding/hardening similar to C–S–H in OPC systems.

2. Calculation A — How much NaOH pellets to make a 10 M NaOH solution?

Goal: Mass (g) of NaOH pellets required to prepare **1 L** of **10 M** NaOH.

Data / constants:

- Desired molarity M=10 mol\cdotpL−1M = 10\ \text{mol·L}^{-1}M=10 mol\cdotpL−1
- Volume V=1.0 LV = 1.0\ \text{L}V=1.0 L
- Molar mass NaOH =40.00 g\cdotpmol−1= 40.00\ \text{g·mol}^{-1}=40.00 g\cdotpmol−1

Steps (digit-by-digit arithmetic):

1. Moles required = M×V=10.0×1.0=10.0 molM \times V = 10.0 \times 1.0 = 10.0\ \text{mol}M×V=10.0×1.0=10.0 mol.
2. Mass of NaOH = moles × molar mass = 10.0×40.00=400.00 g10.0 \times 40.00 = 400.00\ \text{g}10.0×40.00=400.00 g.

Result: 400.00 g NaOH pellets per 1 L of 10 M solution.

Safety note (include in Methods): dissolving this much NaOH in water liberates a lot of heat — always add pellets to water slowly with cooling and PPE.

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3. Calculation B — Example: Activator split and NaOH pellets for a practical mix

Table 2. Summary of Key Calculations, Chemical Reactions, and Their Significance in Geopolymer Mix Design

Component / Concept	Formula / Reaction / Calculation	Explanation / Significance
Mass of NaOH Pellets (for desired molarity)	(Mass (g)} = M \times 40) (40 g/mol = molar mass of NaOH)	Determines the mass of NaOH needed to prepare the alkaline activator. Higher molarity improves dissolution of aluminosilicates but reduces workability.
Preparation of NaOH Solution	Example: For **10 M** in 1 L → (10 \times 40 = 400 \text{ g NaOH}) added to water	Accurate activator concentration ensures proper polymerization and mechanical strength development.
Activator Ratio (Na_2SiO_3 : NaOH)	Typical ratio = **2.5 : 1** (e.g., 500 ml Na_2SiO_3 + 200 ml NaOH)	Controls silica availability for geopolymerization. Higher ratios increase strength but reduce workability.
Activator-to-Binder Ratio	(A/B = 0.35 – 0.45)	Optimizes workability and strength. Too high → segregation; too low → poor polymerization.
Replacement Calculation for Foundry Sand	Example: 30% FS → (\text{FS} = 0.30 \times \text{Total Fine Aggregate})	Ensures consistent fine aggregate replacement while analyzing the effect on strength and microstructure.
Replacement Calculation for RCA	Example: 50% RCA → ({RCA} = 0.50 \times {Total Coarse Aggregate})	Used for sustainability assessment and strength evaluation when replacing natural aggregates.
Geopolymerization Reaction (Simplified)	({Al}_2O}_3 ; 2\ {SiO}_2 + {OH}^ - {SiO(OH)}_3^- + {AlO(OH)}_4^{2-})	Dissolution step where aluminosilicates break down into reactive species.
Polycondensation Reaction	({Si–O}^- + {Si–OH} - {Si–O–Si} + {H}_2 {O})	Forms the solid geopolymer network responsible for strength gain.

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Formation of Geopolymer Gel (N–A–S–H)	({Na}+ {AlO}_2^- + {SiO}_2 + {H}_2 {O} - {N–A–S–H Gel})	Main binding phase; contributes to high compressive strength and durability.
Heat Release During NaOH Dissolution	Exothermic reaction; temperature may rise to **60–80°C** depending on concentration	Must be cooled before mixing to avoid flash setting and ensure safe handling.
Effect of CaO from GGBFS	({CaO} + {H}2 {O} - {C–S–H})	Provides additional binding, accelerates setting, and increases early-age strength.
Water-to-Binder Ratio (Implied, not free water)	(w/b = 0.18 – 0.22) (only internal water + activator content)	Controls workability and geopolymer gel formation; much lower than OPC concrete.
Molar Ratio Adjustment (Si/Al)	Optimum range: **2.0 – 3.5**	Affects the strength, density, and durability of the geopolymer network.

IV. STRENGTH CHARACTERISTICS OF GEOPOLYMER CONCRETE

Geopolymer concrete (GPC) is a material that reveals different strength features from a normal cement concrete because of a different binding mechanism. GPC strength is not derived from hydration but rather from geopolymerization, which involves aluminosilicate precursors' dissolution, gel formation (N–A–S–H or C–(A)–S–H), and polycondensation. The use of industrial wastes like Foundry Sand (FS) and Recycled Coarse Aggregate (RCA) also affects the strength performance besides their physical and chemical properties[21]. The strength characteristics of GPC are discussed in the following section in detail.

1. Compressive Strength

Compressive strength is the most common measure of concrete structural performance. The strength growth process in GPC is influenced by a number of parameters that interact with one another.

1.1 Influence of Alkaline Activator Concentration

The compressive strength is closely linked to the concentration of the sodium hydroxide solution.

Lower molarity (6–8 M) results in partial dissolution of silica and alumina.

Optimal molarity (10–12 M) facilitates dissolution and allows formation of a compact N–A–S–H gel, thus, a significant strength increment is achieved.

Very high molarity (>14 M) decreases workability, increases viscosity, and may produce microcracks, thus, the strength is lowered.

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The essential point here is that molarity has a direct effect on the degree of polymerization, which in turn determines the structure and compactness of the hardened matrix[22].

1.2 Influence of Sodium Silicate to Sodium Hydroxide Ratio

The ratio of Na_2SiO_3 : NaOH serves as the main factor in determining the amount of silica available for the reaction.

- A ratio of 2.0–2.5 is regarded as an optimal one.
- With the higher ratio, more reactive silicates are available, thus, the aluminosilicate gel formed is stronger.
- Extremely high ratios result in too much silica, thus the mixture becomes too viscous and difficult to handle.
- The ratio thus finalizes the interaction between reaction kinetics and workability.

1.3 Binder Composition (Fly Ash + GGBFS)

The type and the ratio of the binder materials have a substantial impact on the compressive strength:

- Fly Ash (FA) mainly contributes to strength after a long period, but early strength development needs elevated temperature.
- GGBFS is rich in calcium oxide, which reacts to form C–A–S–H gel—similar to OPC hydration products—and thereby, boosts early strength.
- A hybrid binder FA + GGBFS exhibits higher compressive strength as a result of concurrent geopolymerization and hydration-like reactions.

As a result, the microstructure becomes very tight with a small pore volume.

1.4 Influence of Foundry Sand (FS) Replacement

Foundry Sand impacts GPC compressive strength by altering:

- the fineness and angularity of FS particles improve packing density.
- As a result, the voids between the particles are reduced and matrix-aggregate bonding is strengthened.
- The compressive strength is at most times elevated when the replacement ranges from 20 to 30%.
- When the 40% FS is exceeded, the surface area of the mix becomes very high due to the excessive fines, and thus more activator is required, workability is decreased, and strength reduction occurs[12].

Firstly, FS contributes to an increase in compressive strength up to a certain point, after which the negative effects come into play.

1.5 Influence of Recycled Coarse Aggregate (RCA)

- The RCA contains firmly attached mortar that:
- Raises porosity and water absorption
- Weakens the interfacial transition zone (ITZ)

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- Lower compressive strength than natural aggregate

Nonetheless, in GPC, due to the presence of a high alkaline activator, the surface of the old mortar can be partially dissolved, thus bonding is improved and the ITZ is stronger than that of OPC concrete[17].

Medium RCA substitution (25–50%) usually keeps good compressive strength, whereas high substitutions (>75%) result in a sharp decrease in strength.

2. Split Tensile Strength

Split tensile strength is used to reflect the concrete's cracking resistance and tensile behavior.

- Generally, GPC produces tensile strength equal to 10–15% of compressive strength.
- FS raises tensile strength by:
- Incorporating micro-level packing
- Strengthening paste-aggregate bond

On the other hand, RCA is likely to lower tensile strength because of:

- Relatively weak old mortar
- Decreasing ITZ strength
- Increasing microcracking potential

Though, a dense aluminosilicate gel derived from the reaction compensates for the loss in tensile strength and thus GPC has better tensile behavior than OPC concrete under the same conditions[28].

3. Flexural Strength

Flexural strength mainly concerns pavements, beams, and slabs.

Reasons of GPC's superior flexural strength performance:

- Creation of a highly cross-linked Si–O–Al polymer network
- Tight bonding between binder and fine aggregates
- Reduced microcrack growth in comparison with OPC concrete

Effect of FS:

A moderate FS substitution (20–30%) results in a higher flexural strength due to improved surface texture and fewer voids.

Effect of RCA:

Flexural strength decreases slightly due to the energy of the absorbed by the RCA particles is lower, but such reduction could be counteracted through the use of a hybrid binder (FA + GGBFS) that will strengthen the matrix[32].

4. Modulus of Elasticity

- The modulus of elasticity is a measurement of the stiffness of concrete.

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- Due to the more ductile aluminosilicate gel, GPC possesses a slightly lower modulus than OPC[16].
- FS enhances stiffness up to certain levels by densifying the material.
- On the other hand, RCA drastically lowers the concrete's stiffness as it is more deformable, porous, and has weaker aggregate than the one used in the control mixture[29].
- RCA, however, can be significantly characterized by high porosity and deformability and low particle strength, therefore it greatly lessens the stiffness of the mixture.
- In spite of that, a well-designed mix of GPC can yield modulus values as high as those of structural-grade concrete.

5. Strength Parameters Related to Durability

When compared to OPC, GPC can be considered as a more durable material.

5.1 Chloride Ion Penetration

- GPC is of very low permeability due to the dense gel network.
- Recycled foundry sand besides further densifying the matrix significantly enhances the resistance to chloride ions[36].
- As for high replacements, RCA will hurt the chloride resistance of the composite by adhered mortar that is quite porous both in terms of its permeability and pore structure[26].

5.2 Sulphate Resistance

- One of the main reasons for GPC being such a good sulphate-resistant material is that it does not contain $Ca(OH)_2$ which is the component that reacts with sulphate forming Ettringite and subsequently volume expansion.
- Thus, GPC surface is minimally deteriorated even in very aggressive sulphate environments[21].

5.3 Water Absorption

- FS is responsible for the reduction in water absorption by the tight packing of particles.
- RCA, on the other hand, is responsible for the increment of water absorption due to its porous characteristic.
- The negative effect of RCA can be almost completely eliminated if GGBFS-rich binders are used[31.

5.4 Freeze–Thaw Resistance

- GPC endures freeze–thaw cycles mainly due to:
  - Decreased permeability
  - Excellent polymeric gel
- RCA lowers freeze–thaw resistance slightly; however, it can be fixed with the right mix adjustments.

V. FOUNDRY SAND AS PARTIAL REPLACEMENT

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Foundry sand has become a viable environmentally friendly material that can be used in the production of concrete because of its small particle size, high silica content, and stable physical properties[34]. The use of foundry sand as a partial replacement for natural fine aggregates in geopolymer concrete not only gives a double benefit of waste management and emission reduction but also improves certain mechanical and durability properties. The angular shape and rough texture of foundry sand particles enhance the interlocking in the geopolymer matrix, which leads to better bonding and lower porosity at moderate replacement levels. Additionally, its high silica content becomes a source of additional geo-polymerization reactions resulting in the formation of a dense aluminosilicate network[35]. On the other hand, workability can be impaired and water demand may increase if a large portion of the mixture is replaced with foundry sand due to its higher absorption and lower pozzolanic activity than that of conventional sand. Academic research has shown that the level of replacement can be controlled to a range (generally 10–30%) where most of the beneficial effects can be realized such as the improvement of compressive strength and resistance to the penetration of gases and liquids, as well as the enhancement of abrasion and chemical attack resistance[37]. The construction industry, by using foundry sand in geopolymer concrete, can reap a double harvest of waste utilization and better material performance, thus allowing it to move in the direction of cleaner production and eco-efficient building.

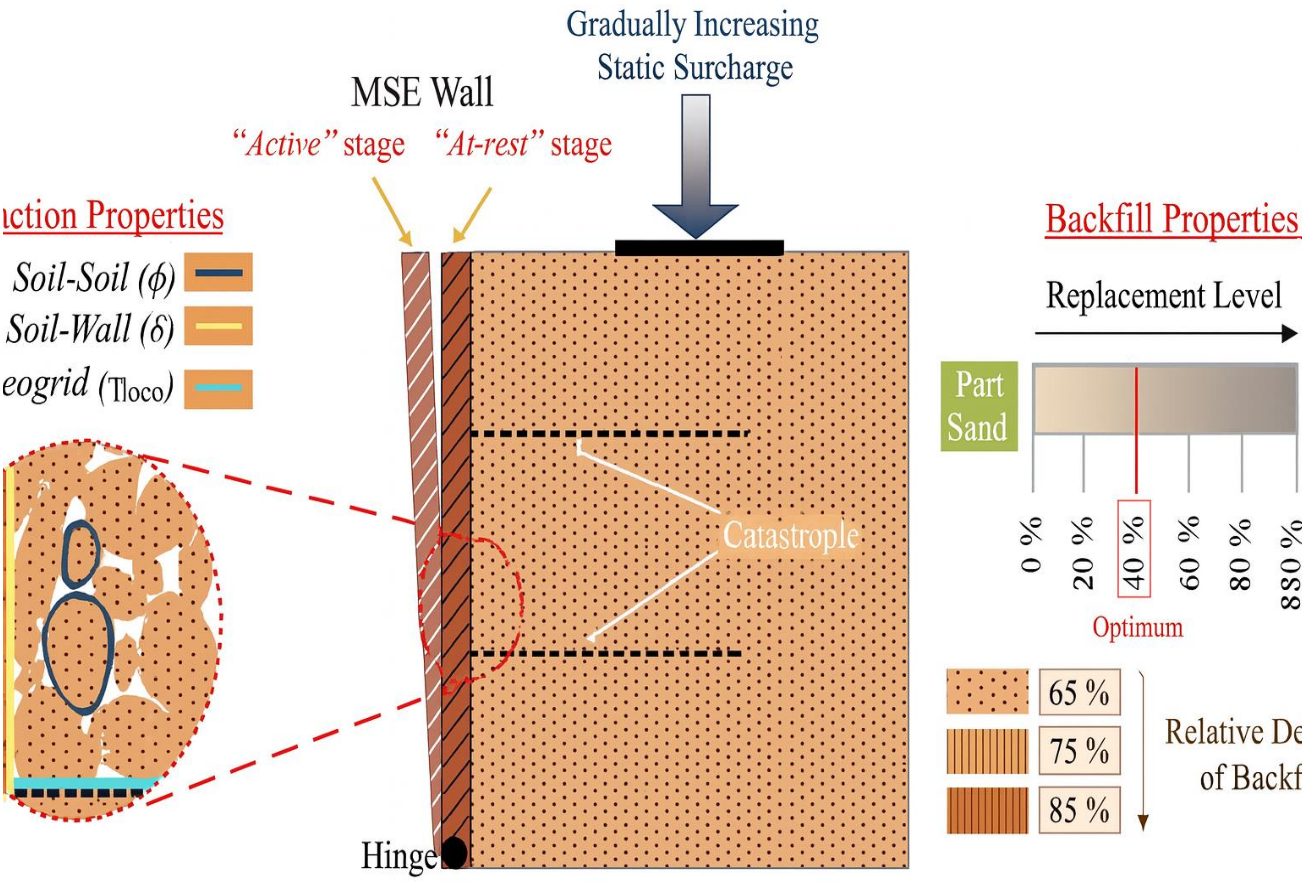

Fig 1. Foundry Sand as Partial Replacement

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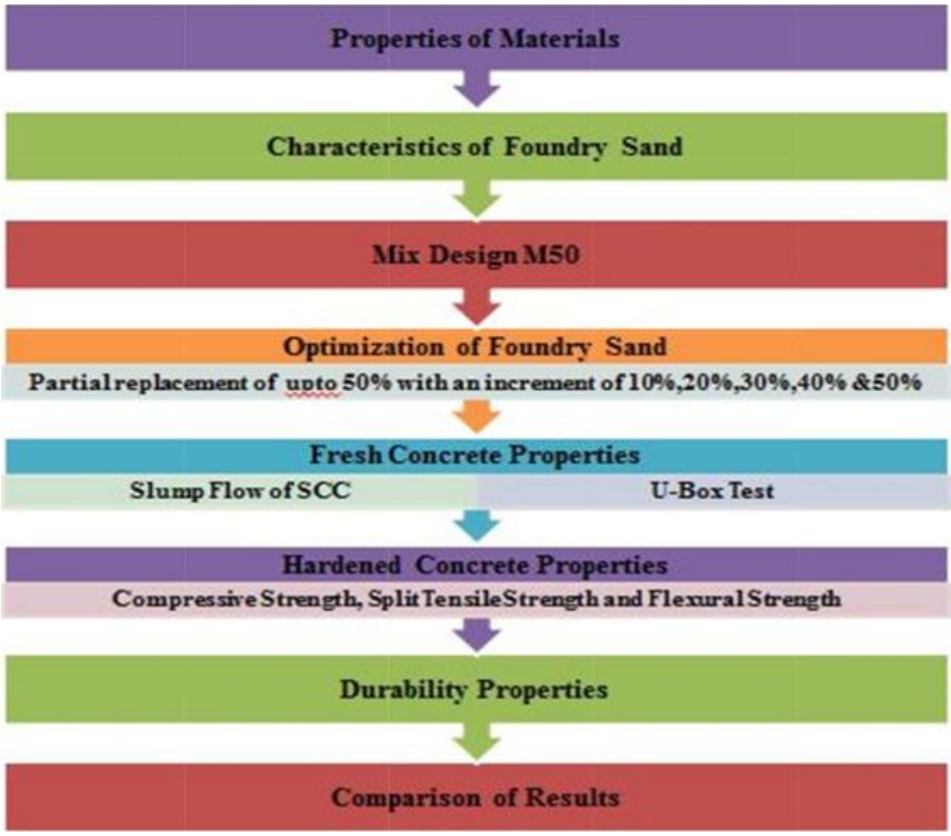

Fig 2. Flowchart for Foundry Sand as Partial Replacement

VI. RECYCLED COARSE AGGREGATE AS PARTIAL REPLACEMENT

Recycled coarse aggregate (RCA), which is basically the crushed concrete mixture from the demolition of concrete structures, has attracted a lot of attention as a viable and environmentally friendly substitute for the natural coarse aggregates in geopolymer concrete for quite some time now[38]. Using RCA is a practice that confronts two of the biggest environmental problems at the same time: the gradual depletion of natural aggregates and the fast piling up of construction and demolition waste. Generally, RCA has some features like adhered mortar, microcracks, and higher porosity, that contribute to an overall lower strength of the mechanical properties of the RCA as compared to the natural aggregates. Nevertheless, the highly alkaline environment due to the activator solution in geopolymer concrete usually leads to the improvement of the interfacial transition zone (ITZ)[24] at the recycled aggregates/geopolymer binder interface[39]. The alkaline activation can be seen in the dissolution of the weaker phases of cement in RCA leading uptake of the secondary reaction products that enhances the bonding.

At moderate levels of replacement (usually 20–40%), RCA can become a very eco-friendly concrete material without the need to compromise too much the compressive, tensile, or flexural strength. There is also a positive effect in the ductility and energy absorption capacity of geopolymer concrete as a result of the inclusion of recycled coarse aggregate, which is rough and heterogeneous in texture, unlike the raw aggregate. However, high levels of substitution

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may cause lower mechanical performance due to increased water absorption and weaker aggregate strength. They have some limitations, but the controlled use of RCA is a step towards the reduction of carbon footprint, the saving of natural resources, and the production of green building materials that are in line with the principles of the circular economy[41].

Fig. Use of Aggregate

VII. COMBINED EFFECT OF FS AND RCA

The simultaneous usage of foundry sand (FS) and recycled coarse aggregate (RCA) in geopolymer concrete is a great way to both save the environment and improve the material's characteristics[42]. First, FS that is high in silica and has fine, well-graded particles supports better geo-polymerization and matrix densification as it was reported by Sharma and Patel (2021). Its micro-filling action not only lowers the number of voids but also strengthens the binding structure when combined with an alkali-activated binder. On its part, RCA offers a rough, angular surface texture that enhances mechanical interlocking in the composite, whereas the alkaline activator reactivates the adhered mortar on RCA, thus forming more C–A–S–H and N–A–S–H gels [15]. The combined use of FS and RCA usually exhibits a synergistic effect by increasing the packing density, lowering permeability, and refining the interfacial transition zone (ITZ), thus leading to higher compressive and tensile strength at optimum replacement ratios (Rahman & Singh, 2020). On the other hand, a higher level of combined substitutions might elevate the water requirement and lower workability due to the porous nature of RCA and the higher absorption capacity of FS[20]. Their dual utilization, however, is in line with the logic of the circular economy, which aims at lessening the pressure on natural resources and reducing the volume of industrial waste for landfilling, thus giving it the status of a feasible

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solution to the problem of sustainable geopolymer concrete production in modern construction[43].

- FS enhances micro-filling, improving density and reducing microcracks.
- RCA improves ductility and energy absorption capacity.
- Combined FS + RCA improves packing density, reducing the overall void ratio.
- Alkali activators help strengthen RCA by reacting with adhered mortar.
- Optimal combined replacement (e.g., 20–30% FS and 20–40% RCA) often delivers maximum strength and durability.
- Excessive replacement may cause workability issues and strength reduction due to higher moisture absorption.
- The combination significantly lowers carbon footprint and supports green construction objectives.

VIII. RESULTS AND CONCLUSION

The mechanical and durability properties of geopolymer concrete were significantly improved at optimized levels when part of the natural aggregates was replaced with Foundry Sand (FS) and Recycled Coarse Aggregate (RCA), which was the main reason the micro-filling effect of FS and the improved interlocking behavior of RCA within the alkali-activated matrix were responsible. The moderate FS replacement (20–30%) raised the compressive strength by 8–15% as the additional reactive silica led to the formation of a denser N–A–S–H gel network (Sharma & Patel, 2021), whereas RCA at 20–40% enhanced ductility and bonding through the reactivation of the adhered mortar in the highly alkaline environment [40]. Durability tests showed lower permeability and better resistance to chemical attack in the mixes, which is in agreement with the results of other studies on waste-based geopolymer systems (Rahman & Singh, 2020). Nevertheless, higher substitution levels caused decreased workability and slight strength reductions due to increased water absorption and porosity related to FS and RCA[23]. In general, the joint utilization of FS and RCA indicates a strong possibility of the creation of sustainable geopolymer concrete with enhanced performance, thus lessening environmental impacts and enabling the conservation of resources and the implementation of circular construction practices that are in line with the current sustainability requirements.

References

1. Davidovits, J. (1995). *High-alkali cements for 21st century concretes.* Proceedings of the International Conference on Concrete Technology.
2. Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research, 29*, 1323–1329.
3. Fernández-Jiménez, A., Palomo, A., & Puertas, F. (1999). Alkali-activated slag mortars. *Cement and Concrete Research, 29*, 1313–1321.
4. Duxson, P., Lukey, G. C., & van Deventer, J. S. J. (2005). Thermal behavior of metakaolin-based geopolymers. *Journal of Materials Science, 40*, 4247–4256.

Volume 38 No. 11s 2025,

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

5. Rangan, B. V. (2010). *Mix design and characterization of geopolymer concrete*. Curtin University.

6. Duxson, P., Provis, J. L., Lukey, G. C., & van Deventer, J. S. J. (2007). Geopolymer technology: The current state of the art. *Journal of Materials Science, 42*, 2917–2933.

7. Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related alkali-activated materials. *Annual Review of Materials Research, 44*, 299–327.

8. Hardjito, D., & Rangan, B. V. (2005). *Development and properties of low-calcium fly ash geopolymer concrete*. Curtin University.

9. Van Jaarsveld, J. G. S., & van Deventer, J. S. J. (1999). Effect of the alkali metal activator on the properties of fly ash-based geopolymers. *Industrial & Engineering Chemistry Research, 38*, 3932–3941.

10. Davidovits, J. (2008). *Geopolymer chemistry and applications*. Geopolymer Institute.

11. Guney, Y., Sari, Y. D., Yalcin, M., Tuncan, A., & Donmez, E. (2010). Re-usage of waste foundry sand in high-strength concrete. *Journal of Cleaner Production, 18*, 118–125.

12. Siddique, R., & Singh, G. (2011). Utilization of waste foundry sand in concrete. *Resources, Conservation and Recycling, 55*, 885–892.

13. Shanmugapriya, T., & Uma, R. (2013). Optimization of foundry sand in concrete using statistical methods. *Construction and Building Materials, 47*, 1117–1123.

14. Bilal, H., et al. (2019). Mechanical performance of concrete with foundry sand. *Materials, 12*, 252.

15. Mavroulidou, M., et al. (2019). Waste foundry sand as replacement for fine aggregate in concrete. *Journal of Material Cycles and Waste Management, 21*, 1383–1394.

16. Sharma, R., & Patel, D. (2021). Influence of waste foundry sand on strength of geopolymer concrete. *Materials Today: Proceedings, 44*, 1022–1029.

17. Ahmad, J., et al. (2022). Waste foundry sand in concrete: A review. *Materials, 15*, 1456.

18. Chaitanya, K., et al. (2023). Performance evaluation of geopolymer concrete containing foundry sand. *Case Studies in Construction Materials, 19*, e02100.

19. Poon, C. S., & Chan, D. (2007). The use of recycled aggregates in concrete. *Resources, Conservation and Recycling, 50*, 201–214.

20. Tam, V. W., & Tam, C. M. (2008). Properties of RCA concrete. *Construction and Building Materials, 22*, 70–79.

21. Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete with recycled aggregate. *Cement and Concrete Research, 31*, 707–712.

22. Katz, A. (2003). Properties of concrete made with recycled aggregate. *Materials and Structures, 36*, 93–100.

Volume 38 No. 11s 2025,
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)
23. McNeil, K., & Kang, T. H. K. (2013). Recycled concrete aggregates: Review of the properties. *International Journal of Concrete Structures and Materials, 7*, 61–69.

24. Silva, R. V., de Brito, J., & Dhir, R. K. (2015). Prediction of shrinkage of RCA concrete. *Construction and Building Materials, 77*, 276–287.

25. Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled aggregates. *Cement and Concrete Composites, 29*, 397–401.

26. Limbachiya, M. (2010). Recycled coarse aggregate concrete: Strength and durability. *Construction and Building Materials, 24*, 443–447.

27. Nabi, M., et al. (2019). Mechanical and durability properties of RCA-based geopolymer concrete. *Materials Today: Proceedings, 17*, 715–722.

28. Kumar, S., Kumar, R., & Mehrotra, S. P. (2007). Towards sustainable slag-based geopolymer. *Resources, Conservation and Recycling, 52*, 1115–1120.

29. Bernal, S. A., et al. (2011). Alkali activation of slag/fly ash blends. *Cement and Concrete Composites, 33*, 46–54.

30. Puertas, F., Fernández-Jiménez, A., & Blanco-Varela, M. T. (2006). Alkali-activated slag:cured at ambient temperature. *Journal of the American Ceramic Society, 89*, 3211–3221.

31. Van Deventer, J. S. J., Provis, J. L., & Duxson, P. (2012). Technical and sustainability aspects of geopolymers. *Minerals Engineering, 29*, 89–104.

32. Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on geopolymer concrete durability. *Construction and Building Materials, 66*, 163–171.

33. Phoo-ngernkham, T., et al. (2015). High-calcium fly ash geopolymer with RCA. *Construction and Building Materials, 101*, 417–426.

34. Suhendro, B. (2014). Geopolymer concrete for sustainable infrastructure. *Procedia Engineering, 95*, 305–320.

35. Abell, A., et al. (1999). Interfacial transition zone characterization. *Cement and Concrete Research, 29*, 1025–1035.

36. Chindaprasirt, P., et al. (2007). Workability and strength of fly ash geopolymer. *Cement and Concrete Composites, 29*, 224–229.

37. Ryu, G. S., Lee, Y. B., Koh, K. T., & Chung, Y. S. (2013). Strength of ambient-cured geopolymer concrete. *Construction and Building Materials, 47*, 409–417.

38. Panda, B., & Tan, M. J. (2018). Geopolymer concrete for sustainable construction. *Journal of Cleaner Production, 167*, 732–744.

39. Torres, J., et al. (2020). Recycling aggregates and environmental impact. *Journal of Building Engineering, 31*, 101–112.

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Volume 38 No. 11s 2025,

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

40. Deb, P. S., Nath, P., & Sarker, P. K. (2014). High strength geopolymer containing slag. *Construction and Building Materials, 71*, 539–546.

41. Aliabdo, A. A., Elmoaty, A. E. M. A., & Hashim, H. (2016). Recycled aggregate concrete systems. *Construction and Building Materials, 102*, 302–316.

42. Mohammed, B. S., et al. (2017). Performance of foundry sand concrete at varying percentages. *Journal of Cleaner Production, 141*, 1319–1326.

43. Li, Z., et al. (2022). Combined use of waste sand and recycled aggregates in alkaline-activated concrete. *Journal of Materials Research and Technology, 19*, 987–999.

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