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T. Udhaya Kumar, M. Jayadurgalakshmi, Lenka Cepova, Sachin Salunkhe & Emad Abouel Nasr

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Mechanical and Microstructural Properties of Concrete Incorporating High-Strength Graphene Oxide-Based Geopolymer Aggregate

Udhaya Kumar T¹, Jayadurgalakshmi M², Lenka Cepova³, Sachin Salunkhe^{4*}, Emad Abouel Nasr⁵

¹Department of Civil Engineering, Vel Tech Rangarajan Dr. Sagunthala R & D Institute of Science and Technology, Tamil Nadu, Chennai, India

²Department of Civil Engineering, Veltech Multitech Dr. Rangarajan Dr. Sakunthala Engineering College, Avadi, Tamil Nadu, Chennai, India

³Department of Machining, Assembly and Engineering Metrology, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, 17. Listopadu 2172/15, 708 00 Ostrava, Czech Republic;

^{4a}Department of Biosciences, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, India

^{4b}Department of Mechanical Engineering, Gazi University Faculty of Engineering, Maltepe, Ankara, Turkey

⁵Department of Industrial Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

*Corresponding Author: sachinsalunkhe@gazi.edu.tr

ABSTRACT:

Artificial geopolymer aggregates (GPA) are environmentally friendly substitutes of natural aggregates. They assist in minimizing over-quarrying and reduce landfills. This paper was done to obtain high-strength graphene oxide-modified geopolymer aggregates (GO-GPA) in order to serve as coarse aggregates in concrete mixtures with water-to-binder ratios ($w/b = 0.45$). These aggregates obtained compressive strengths of paste more than 40 MPa. Examined and compared mechanical behavior of graphene oxide based geopolymer aggregate concrete (GPAC) and traditional natural aggregate concrete (NAC) on basis of mechanical behavior and failure properties. Intrinsic strength of GO-GPA was found to be lower than those of natural aggregates, but at w/b ratio of 0.45, GPAC improved compressive, splitting tensile and flexural strength by 8.0, 5.5 and 4.1 respectively. A failure mode analysis revealed that w/b ratios in which cracks in GPAC propagated were lower across aggregates and surrounding matrix, which is attributed to fact that material became bonded well. With rise in w/b ratio, crack propagation has mainly moved to aggregate-matrix interface. Conversely, mix proportions showed interfacial failure modes in NAC. Microstructural examination also verified formation of a denser and more cohesive interfacial transition zone (ITZ) in GPAC, especially at low w/b ratios. Results show that graphene oxide-enhanced geopolymer aggregates are potentially considered as a high-performance, sustainable alternative to conventional aggregates in construction of structural

concrete. They also show that there is better mechanical performance and failure mechanisms of GPAC.

Keywords: geopolymer aggregate, graphene oxide, mechanical performance, microstructural characterization

1. Introduction

One of common building materials in world is concrete. It is predominantly coarse and fine aggregates cement-bound [1,2]. Natural aggregates have become in demand because of high-paced urbanization and development of infrastructures. This has resulted in depletion of resources and adversely affecting environment [3]. To solve these problems researchers are concentrating on developing sustainable and environmentally friendly substitutes of natural aggregates. One of most important ones is possibility to convert industrial, agricultural, and construction wastes into effective materials to create concrete. This assists in enhancing circular economy and minimization of waste. Some aggregates are derived out of waste like recycled concrete aggregates [4], steel slag [5], and waste glass [6] which have been used successfully in concrete with good mechanical performance and durability. One of latest changes is conversion of powder-like waste materials into artificial aggregates, which is referred to as artificial aggregate technology [7,8]. In this region, cold-bonded geopolymer aggregates (GPA) have also been used because of their cement-free constituent, reduced energy demand and good mechanical and chemical properties including power to stabilize heavy metals [12]. Solid waste sources, such as fly ash, are generally used as GPA. They produce them by crushing hardened geopolymer pastes mechanically and pelletizing them by rotating discs [19]. GPA concrete, also known as geopolymer aggregate concrete (GAC) has less density, permeability and good performance in long-run; hence, concrete with GPA is particularly applicable in pavements and non-structural applications [13-17]. Also, on sophisticated cement systems like Engineered Cementitious Composites (ECC), GPA may be applied where its integration and characteristics of increasing ductile are of great advantage [24,25]. Concrete is a complicated composite comprising of an aggregate, cement binders, and an interfacial transition zone (ITZ) that contribute to its general mechanical response [26-28]. ITZ usually reaches a maximum of 30 μm away along aggregate surface and is extremely sensitive to such variables as aggregate properties and water-to-binder (w/b) ratio. It tends to be more porous than bulk matrix due to "wall effect" [29,30]. This microstructural distinction is regularly a feeble locality where cracks begin and propagate in customary natural aggregate concrete (NAC). Geopolymer aggregate concrete (GAC) on other hand displays different behavior during failure. Geopolymer cracks frequently traverse geopolymer aggregates, as in lightweight aggregate concrete. This is because geopolymer aggregates (GPA) are relatively weak and porous [28]. Besides, aggregate and matrix are chemically reactive and absorb high amounts of water, which modifies ITZ microstructure and alters primary failure modes in GAC [31].

In this regard, incorporation of graphene oxide (GO) to geopolymer aggregates (GPA) has been a viable approach to enhance performance of aggregates. Graphene oxide boasts of high specific surface area, high strength, and numerous oxygen-binding functional groups with potential to react with cement or geopolymer phases. These characteristics will improve microstructural stability and mechanical strength of GPA and concretes[32-34]. Mechanical characteristics and failure pattern of concretes produced with geopolymer aggregates modified with graphene oxide are not clear. In a bid to fill this knowledge gap in literature, present research will go through a methodical examination of mechanical and microstructure behavior of geopolymer aggregate concrete (GAC) containing graphene oxide. Significant mechanical characteristics, which include: splitting tensile strength, compressive strength and stress-strain response, will be explored. Results will offer more detailed information on interactions, between aggregate and matrix in GPA-based concretes and will aid in creating a scientific foundation on development and utilization of graphene oxide-enhanced geopolymer aggregates in sustainable construction.

2. Experimental programs

This research is based on development of graphene oxide-modified geopolymer aggregates (GPA) to be used as sustainable substitute of conventional coarse aggregates. The ground granulated blast furnace slag (GGBS), fly ash, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and graphene oxide (GO) are major raw materials. Materials have been selected due to their capacity to react, bind, and give environmental advantage. In order to prepare the geopolymer binder, fly ash and GGBS were mixed, and an alkaline solution comprising of NaOH and Na_2SiO_3 was used to activate mixture. Mechanical performance and durability was then enhanced by addition of graphene oxide. New geopolymer paste was poured into cube molds and allowed to cure after seven days and crushed to form synthetic aggregates of nominal size 20 mm. Testing on physical characteristics of resulting GPA was done as per standard tests. Experiments covered such tests as aggregate crushing value, impact value, water absorption, specific gravity and flakiness / elongation indices. This method resulted in a standard and repeatable procedure of creating high performance and environmentally friendly aggregates that could be used in structural concrete.

2.1 Raw materials

In this study raw material used to prepare concrete is Ordinary Portland Cement (OPC) 53 grade of cement that satisfies IS:12269-1987[35], Ground Granulated Blast Furnace Slag (GGBS) which was obtained in JSW Cement in Tamil Nadu, Class F fly ash that was obtained as per ASTM 383: 2016[36], manufactured sand (M-sand) as a fine aggregate that satisfies IS 383:2016[37] and graded natural

coarse aggregate with a maximum size of Also, graphene oxide (GO), an alkaline solution was added as well as water. Physical and chemical characteristics of materials were identified according to current standards of IS, and contributions to enhancement of concrete mix were thoroughly examined.

2.2 Geopolymer Aggregate

Preparation of geopolymer aggregate (GPA) provides a more environmentally friendly substitute to regular natural aggregates by reducing the use of fossil mineral raw materials. The precursor materials that were utilized in this study include fly ash, ground granulated blast furnace slag (GGBS) and graphene oxide (GO), which were activated with alkaline solution of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). Mix design ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ was 2.5 and liquid to slag ratio was 0.35. Table 1 illustrates the proportions of mix. GPA made four steps preparation, which included mixing, casting, crushing and curing. Figure 1 demonstrates a schematic of preparation process. To begin with, solid activators and precursor powders were intermixed dry that lasted about 5 minutes. Addition of water was then done in small portions and another 3 minutes of mixing was carried out to regulate setting time of GGBS-based geopolymer pastes. Homogenous mixtures were subsequently put into cube molds 150 x 150 x 150 mm, and allowed time to dry in room temperature at 24 hours before demolding. Compression of hardened blocks was performed with compressive loading machine at rate of 0.5 kN/s. Aggregates that were broken were sorted manually into 5-20 mm and those less than 5 mm. Fraction that was retained was heated at 105° C over 24 hours to minimize shrinkage and ensure an optimal dimension stability. Produced aggregates were left under room temperature to support geopolymerization process to proceed and increase durability and concrete application.

Table 1 Geopolymer aggregate Mix proportions (kg/m³)

S.No.	Raw materials	Values (kg/m ³)
1.	GGBS	1203
2.	Flyash	301
3.	Graphene oxide	79

4.	Sodium Hydroxide	150.3
5.	Sodium Silicate	402.9



Figure 1 Geopolymer Aggregate Preparation Mechanism

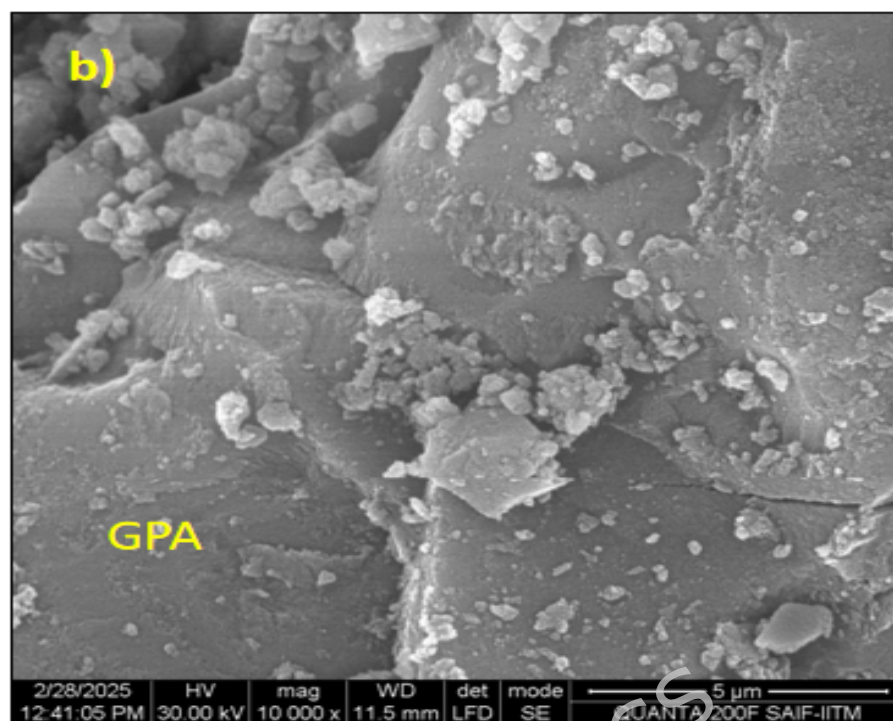


Figure 2 SEM image of Geopolymer aggregate



Figure 3 Micro FTIR colour mapping Expanded view

Microstructure of geopolymer aggregates (GPA) synthesized is shown in figure 2. Geopolymerization process is expected to give a rich and cohesive framework through which a robust mechanical interlocking and effective bonding with

neighboring cementitious matrix will be strengthened. Inherent surface roughness and angularity of particles of aggregates contribute to enhancement of interfacial transition zone (ITZ) that increases overall mechanical performance and efficiency of stress transfer of concrete[38-40]. Figure 3 gives Micro-FTIR colour mapping of sample, which gives a broader picture of surface chemistry and functional group distribution in GPA matrix.

2.3 Alkaline Solution

In this work, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were used as an alkaline activator to create geopolymer aggregates (GPA). Sodium-based activators were selected over potassium-based alternatives due to their superior cost efficiency and comparable reactivity. NaOH flakes were dissolved in distilled water to create NaOH solution, and target molarity was used to calculate necessary solid mass. In particular, 400 g of NaOH pellets (molecular weight = 40 g/mol) were dissolved in 1 L of water to create a 10 M NaOH solution. Water was main component in this solution, guaranteeing full dissolution and homogeneity of alkaline medium, whereas NaOH solids made up just a small percentage of overall mass.

2.4 Testing Methods

Mix proportioning for standard concrete and GPA concrete followed IS 10262:2019[41] guidelines for M25 grade. Different mix ratios detailed in Table 2 are prepared for this study by using various proportions of natural aggregate and GPA. These blends are referred to as Conventional, GPA25, GPA 50, GPA75 and GPA100. Granite aggregates make up 100% of coarse aggregate in standard mix. For GPA100 mix, entire mixture is created by GPA. In GPA25, GPA50, and GPA75 mixtures, proportions of GPA used are 25%, 50% and 75% respectively, with remainder in each mixture replaced by natural aggregate. Volumetric ratios provide basis for all mixing ratios, enabling evaluation of performance at different levels of GPA content. In both conventional concrete and GPA concrete casting, a balanced quantity of material was preserved concerning cement and water content at a water/cement ratio of 0.45. Characteristics of final product are determined by constituents in GPA mixes. Dilution of NaOH solution in analyzed mixture was estimated to range from 8 M to 16 M. To produce 1 liter of an 8 M NaOH

solution, 320 grams of NaOH pellets were calculated as 8×40 , where 40 represents molecular weight of NaOH, mixed in water. Additionally, 0.3, 0.35 and 0.4 were changed as activator solution's mass ratio to GGBS. A consistent compaction factor of 0.9 and a slump measurement of 90–120 mm were maintained throughout study. Based on preliminary trials and supporting evidence from previous studies[41- 42], an optimized sodium hydroxide (NaOH) molarity of 10 M and an activator solution-to-GGBS mass ratio of 0.35 were selected for the present investigation. A NaOH molarity of 10 M provides sufficient alkalinity to effectively dissolve aluminosilicate species from GGBS, thereby promoting efficient geopolymerization while avoiding the adverse effects associated with higher molarities, such as rapid setting, reduced workability, and marginal strength gains. Similarly, an activator solution-to-GGBS mass ratio of 0.35 was identified as optimal, as it ensures adequate availability of alkaline activator for the formation of geopolymeric binding phases without introducing excess liquid that could increase porosity[43]. This balanced proportion facilitates improved reaction kinetics, enhanced interfacial transition zone development, and stable mechanical performance. The adoption of these optimized parameters ensures consistency across mixtures and contributes to the reliable evaluation of the mechanical and durability properties of geopolymer aggregate concrete.

Table 2 provides an overview of materials required for preparing each mix of conventional and GPA concrete

Table 2 Concrete Mix Design Values (kg/m³)

S. No.	Concrete Type	Cement	Fine Aggregate	Coarse Aggregate		Water	W/C Ratio	Super plasticizer
				NA	GPA			
1.	Conventional	351	652	1201	-	158	0.45	1.93
2.	GPA 25	351	652	635	211	158	0.45	1.93
3.	GPA 50	351	652	423	423	158	0.45	1.93
4.	GPA 75	351	652	211	635	158	0.45	1.93
5.	GPA 100	351	652	-	846	158	0.45	1.93

* NA - Natural Aggregate

3. Results and Discussions

3.1 Compressive Strength of Concrete

Table 3 shows compressive strength of 7 and 28 days of mixtures with different proportions of GPA at. These values of compressive strength are graphically represented in figure 4. This graphical presentation explains effect of GPA replacement percentages with its 0 to 100 percent in 25 percent increments.

Table 3 Results of Compressive Strength Tests for Every Concrete Mix

S. No.	MIX ID	Compressive Strength (MPa)	
		7 days	28 days
1.	CONTROL	17	32.5
2.	GPA 25	17.5	33
3.	GPA 50	18.5	34.5
4.	GPA 75	18.9	35
5.	GPA100	19.2	37

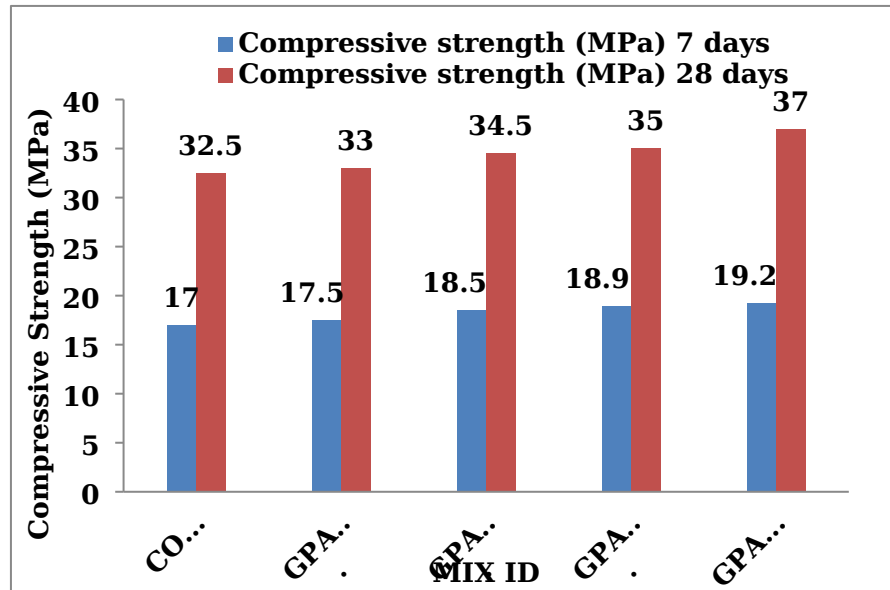


Figure 4 Compressive Strength of Concrete with Different GPA Replacement Levels

Compressive strength of aggregate is largely defined by surface properties of aggregate and this also influences adhesion of aggregates to cementitious matrix. Compressive strength progressively rose in present study as geopolymer aggregates (GPA) were substituted by natural coarse aggregates. Strength of M25 grade concrete increased by 1.5, 6.1, 7.7, and 13.8 at 25, 50, 75 and 100% GPA replacement respectively. This improvement is caused by several mechanisms which are interrelated. Coarse and rough surface of GPA provides increased mechanical interlocking with cement paste which reinforces bond. Specific surface area of GPA is rather high, which enhances paste-aggregate adhesion and also helps to achieve an effective decrease in local water-to-cement ratio without reducing workability. Additionally, pozzolanic action of GPA also enhances formation of additional binding phases that make cementitious matrix thick. Resulting improvement in interfacial transition zone (ITZ) further promotes enhanced compressive strength. These findings are not new and found better adhesion at ITZ in GPA-incorporated concrete due to positive surface morphology of aggregates[44-46]. Also, glassy phases that contain calcium in GPA can boost speed of development of strength. Combination of all these factors explains compressive strength increases slowly with increase in GPA substitution levels.

3.2 Split Tensile Strength of Concrete

Split tensile strength at 7 and 28 days of concrete mixes with different amounts of geopolymer aggregates (GPA) is shown in Table 4. Figure 5 provides a graphic representation of outcomes for GPA replacement levels of 0%, 25%, 50%, 75%, and 100%.

Table 4 Split Tensile Strength Test Results for Each Mix of Concrete

S.No.	MIX ID	Split Tensile Strength (MPa)	
		7 days	28 days
1.	CONTROL	1.6	2.5
2.	GPA 25	1.8	2.83
3.	GPA 50	2	3.05
4.	GPA 75	2.08	3.2
5.	GPA100	2.2	3.3

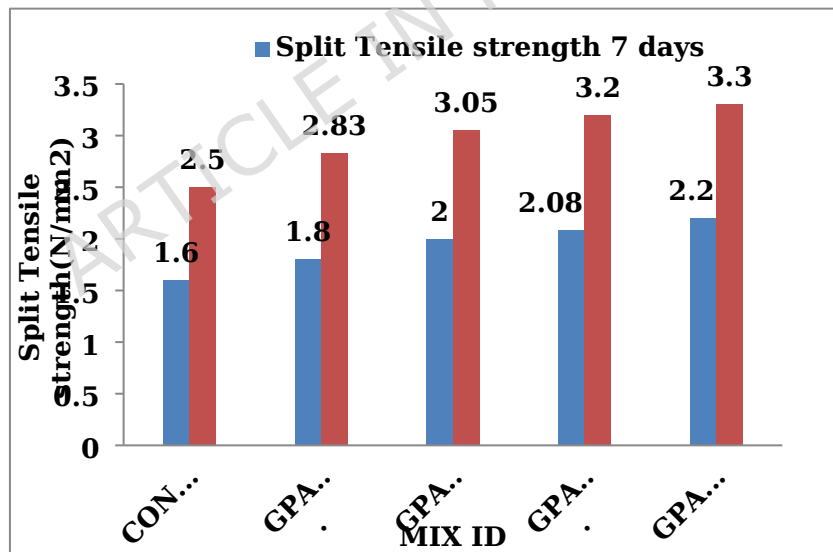


Figure 5 Illustrates split tensile strength of concrete with varying levels of geopolymer aggregate (GPA) replacement.

As percentage of geopolymer aggregate (GPA) replacement increased, splitting tensile strength gradually increased, as shown in Figure 5. Specifically, substitution of 25%, 50%, 75% and 100 % of natural aggregates improved strength by 13.2, 22.0, 28.0 and 32.0 percent respectively. In order

to separate influence of GPA substitution, cement paste was maintained constant across all concrete compositions in this experiment. Results clearly indicate that, most apparent augmentation of splitting tensile strength became possible when natural aggregates were substituted entirely with GPA. Other variables that have been synergistic towards this progress are other variables. GPA's porous and chemically reactive surface strengthens interfacial transition zone (ITZ) by fostering an excellent bond with cementitious matrix. Prolonged hydration is made possible by internal curing effect that water held in GPA holes provides, which reduces shrinkage-induced microcracking. Enhanced intrinsic toughness and structural integrity of GPA contribute to more uniform stress distribution within the composite matrix. These outcomes are in line and found that enhanced stress transmission and tensile performance are fostered by increased toughness and deformability of geopolymer aggregates[47-51]. When taken as a whole, these processes account for steady improvement in splitting tensile strength that is seen as GPA incorporation increases.

3.3 Relation between Compressive Strength and Split Tensile Strength

Figure 6 uses linear graphs to show split tensile strength as a function of compressive strength with regard to natural aggregate and GPA.

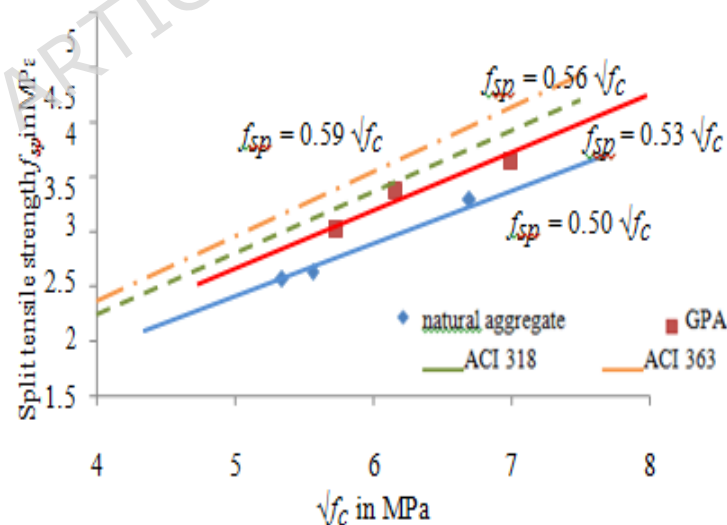


Figure 6 Split Tensile Strength as a Function of Compressive Strength

An empirical equation is generally adopted to relate split tensile strength (f_{sp}). It is presented as below:

$$f_{sp} = k \sqrt{f_c} \quad (1)$$

where k is a coefficient that depends on size of specimen, humidity condition, and shape and surface roughness of aggregate.

Vide American Concrete Institute's code 318:1999, following is the relationship between concrete's tensile and compressive strengths:

$$f_{sp} = 0.56 \sqrt{f_c} \quad (2)$$

ACI also provides an equation that indicates relationship of tensile strength to compressive strength of structural concrete, with value of compressive strength being between 21 MPa and 83 MPa, as follows:

$$f_{sp} = 0.59 \sqrt{f_c} \quad (3)$$

Equations (4.5) and (4.6), which express split tensile strength as a function of compressive strength, were developed using statistical regression analysis of experimental test results.

$$f_{sp} = 0.50 \sqrt{f_c} \text{ for natural aggregate} \quad (5)$$

$$f_{sp} = 0.53 \sqrt{f_c} \text{ for GPA} \quad (6)$$

Regression equations are provided along with corresponding regression coefficient for lines of best fit for both GPA concrete types. Regression coefficient for GAC was 0.91, and regression coefficient for natural aggregate was 0.98. Figure 4.5 illustrates specimen types exhibit an increasing trend in tensile strength as a function of higher compressive strength. For GPA and natural aggregate, split tensile strength to compressive strength ratio is in line with ACI Standard[52]. Even though specimen sizes and humidity conditions for both types of concrete were similar, improved surface roughness and intrinsic shape of GPA have improved in split tensile strength considerably.

3.4 Flexural Strength of Concrete

Figure 7 shows Figure 7 presents the flexural strength results of M25 grade concrete incorporating geopolymer aggregate (GPA) at replacement levels of 0%, 25%, 50%, 75%, and 100%, while Table 5 summarizes the corresponding values at 7 and 28 days. The results demonstrate a consistent enhancement in flexural strength with increasing GPA content. At 28 days, concrete mixtures with 25%, 50%, 75%, and 100% GPA replacement exhibited

flexural strength improvements of 3.0%, 6.1%, 9.2%, and 15.3%, respectively, compared to the control mix.

The observed improvement in flexural performance can be primarily attributed to the angular geometry and rough surface texture of geopolymer aggregates, which promote stronger mechanical interlocking with the cementitious matrix. Similar observations were reported and demonstrated that geopolymer aggregate concrete beams exhibited superior bond strength and enhanced flexural behaviour due to improved interfacial transition zone (ITZ) characteristics[53-57]. The enhanced ITZ reduces stress concentration at the aggregate-paste interface and effectively delays crack initiation and propagation under bending loads.

Table 5 Flexural Strength Test Results for Each Mix of Concrete

S. No.	MIX ID	Flexural Strength (MPa)	
		7 days	28 days
1.	CONTROL	6	6.5
2.	GPA 25	6.3	6.7
3.	GPA 50	6.45	6.9
4.	GPA 75	6.7	7.1
5.	GPA100	7	7.5

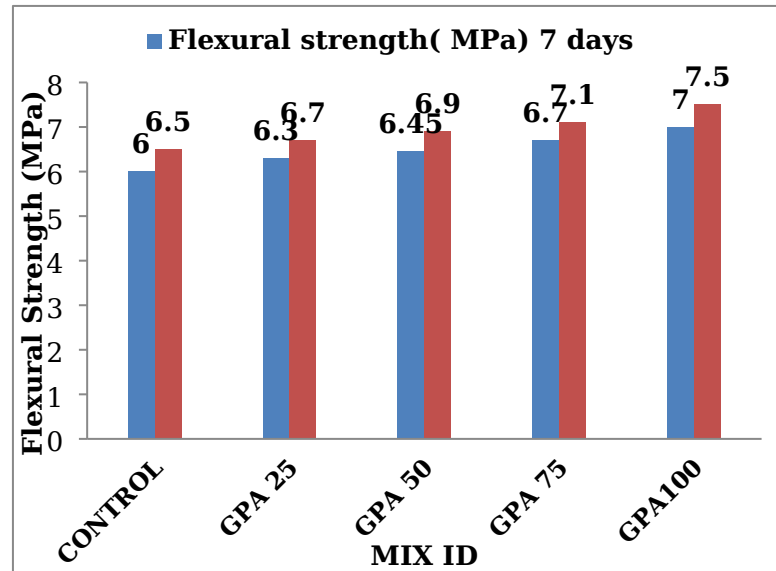


Figure 7 Flexural Strength of Concrete with Various Levels of Replacement by GPA

Furthermore, the progressive increase in flexural strength with higher GPA replacement levels aligns with the findings and noted that geopolymer aggregates facilitate more efficient stress transfer across the matrix-aggregate interface[58-61]. The inherently higher stiffness and strength of GPA compared to conventional natural aggregates contribute to improved load-carrying capacity and reduced microcracking under flexural stresses. Complete replacement of natural coarse aggregates with GPA resulted in a more homogeneous internal structure, minimizing localized weak zones and enabling uniform stress distribution throughout the matrix.

Additionally, the improved packing density achieved with GPA incorporation enhances matrix compactness, which further contributes to increased resistance against flexural deformation. The combined effects of superior aggregate morphology, strengthened ITZ, and improved stress distribution explain the maximum flexural strength observed in concrete with 100% GPA replacement. These findings corroborate earlier research and confirm the suitability of geopolymer aggregates as a sustainable alternative to natural aggregates in structural concrete applications.

3.5 Static Modulus of Elasticity of Concrete

The static modulus of elasticity values of M25 grade concrete incorporating geopolymer aggregate (GPA) at replacement levels of 0%, 25%, 50%, 75%, and 100% are presented in Table 6. The results indicate that concrete mixtures containing GPA consistently exhibit a higher modulus of elasticity compared to the control mix prepared with conventional natural aggregates at the same water-cement ratio. Since aggregates constitute the major volumetric fraction of concrete, their mechanical characteristics play a dominant role in governing the overall stiffness of the composite material.

The enhanced modulus of elasticity observed in GPA concrete can be attributed to the superior stiffness and rigidity of geopolymer aggregates, which contribute to improved resistance against elastic deformation. Similar trends were reported and observed an increase in the dynamic modulus of elasticity in geopolymer lightweight aggregate concrete and attributed this improvement to the intrinsic stiffness of geopolymer aggregates and their stronger interaction with the surrounding binder matrix[62-65]. The improved aggregate-paste interfacial transition zone (ITZ) in GPA concrete facilitates efficient stress transfer under load, thereby enhancing the elastic response of the composite.

Table 6: Concrete Static Elasticity Modulus at Different Replacement Levels by GPA

S. No.	MIX ID	Modulus of Elasticity (N/mm²)
1.	CONTROL	28504
2.	GPA 25	29154
3.	GPA 50	29580
4.	GPA 75	30207
5.	GPA100	30822

Moreover, the internal curing capability of geopolymer aggregates plays a crucial role in mitigating microcrack formation by maintaining moisture availability within the matrix during hydration and geopolymerization. This reduction in microcracking contributes to a more continuous and homogeneous microstructure, which further enhances stiffness. The combined effects of

improved aggregate stiffness, strengthened ITZ, and reduced internal damage explain the progressive improvement in the modulus of elasticity with increasing GPA replacement levels.

Importantly, all GPA replacement ratios satisfied the modulus of elasticity requirements prescribed by IS 456:2000[66], confirming the structural suitability of GPA concrete. The findings demonstrate that the incorporation of geopolymer aggregates not only preserves but also enhances the elastic performance of concrete, supporting its application in structural elements where long-term stiffness, reduced deformation, and improved durability are critical.

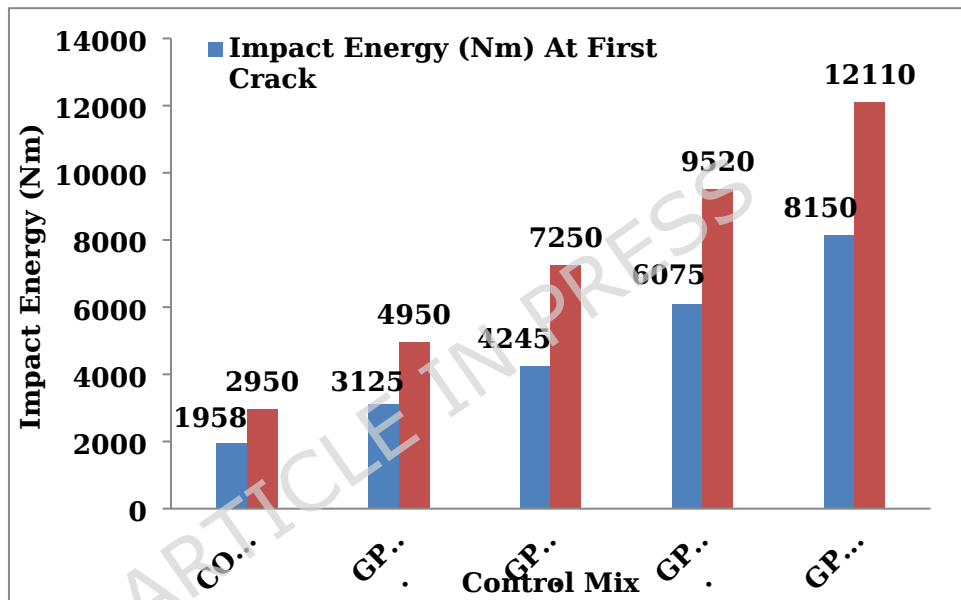
3.6 Impact Resistance Test

The impact resistance values of concrete incorporating geopolymer aggregates (GPA) at replacement levels of 0%, 25%, 50%, 75%, and 100% are summarized in Table 7, while the corresponding energy absorption at first crack and ultimate failure is illustrated in Figure 8. The results indicate a consistent increase in impact resistance with higher GPA content, with GPA-based concretes exhibiting substantially greater impact resistance than conventional concrete of the same grade prepared with natural aggregates. Quantitatively, the impact resistance of GPA concrete improved by 48%, 39%, 28%, and 20% for GPA25, GPA50, GPA75, and GPA100 mixes, respectively, yielding an average enhancement of approximately 34%.

The enhanced impact performance of GPA concrete can be attributed primarily to the angular shape and rough surface texture of geopolymer aggregates, which improve mechanical interlocking with the cementitious matrix and increase resistance to crack initiation under dynamic loading. These findings are in agreement with the observations reported and demonstrated that improvements in impact resistance of geopolymer concrete are strongly associated with enhanced crack-bridging mechanisms, improved energy dissipation, and stronger aggregate-matrix bonding[67-69]. Although their study focused on the incorporation of steel fibers, the underlying mechanism of improved stress transfer and delayed crack propagation is similarly observed in GPA concrete due to its favorable morphological characteristics.

Table 7 Impact Resistance of Various Mixes of Concrete

S. No.	MIX ID	Impact Energy (Nm)	
		At First Crack	At Failure
1.	CONTROL	1958	2950
2.	GPA 25	3125	4950
3.	GPA 50	4245	7250
4.	GPA 75	6075	9520
5.	GPA100	8150	12110

**Figure 8 Impact Resistance of Various Mixes of Concrete**

Furthermore, the linear relationship between compressive strength and impact resistance, as illustrated in Figure 9, confirms that higher-strength GPA concretes possess a greater capacity to absorb impact energy before failure. The strong correlation observed for GPA100 indicates that the superior intrinsic strength and stiffness of geopolymer aggregates play a decisive role in enhancing resistance to repeated impact loading. This behavior aligns with the conclusions are reported a direct relationship between compressive strength enhancement and increased impact energy absorption in geopolymer concrete systems[70-73].

Overall, the improved impact resistance of GPA concrete arises from the combined effects of aggregate angularity, strengthened interfacial transition

zone, and higher compressive strength, validating the suitability of geopolymer aggregates for applications subjected to dynamic and impact loading conditions.

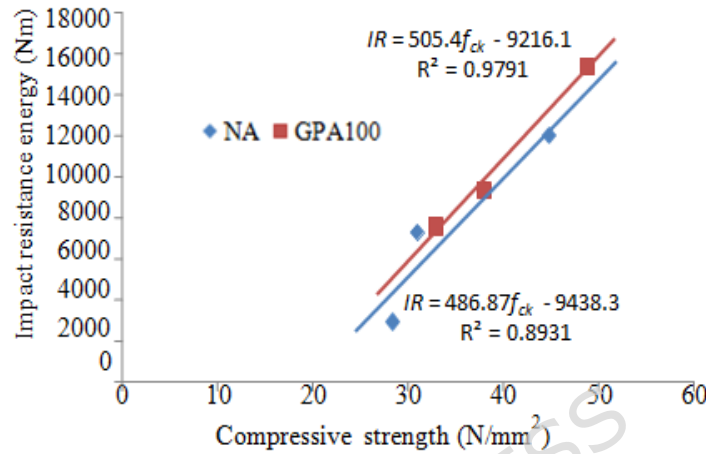


Figure 9 Relation between Compressive Strength and Impact Resistance

3.7 Pull out Test

The bond behavior between reinforcing steel and the surrounding cementitious matrix governs the efficiency of load transfer in reinforced concrete structures. The bond strength results obtained at slip levels of 0.025 mm and 0.25 mm are presented in Table 8. The results clearly indicate a progressive improvement in bond strength with increasing geopolymer aggregate (GPA) replacement. Concrete with 100% GPA replacement exhibited bond strengths of 4.21 MPa at 0.025 mm slip and 5.91 MPa at 0.25 mm slip, surpassing those of conventional concrete prepared with natural aggregates. Correspondingly, the pull-out force required to extract the reinforcing bar increased with GPA content, reaching a maximum value of 44 kN for the GPA100 mix.

The enhancement in bond performance can be attributed to the dense and angular nature of geopolymer aggregates, which promotes superior mechanical interlocking and improved adhesion at the steel-concrete interface. These findings are consistent with the experimental observations reported and demonstrated that geopolymer concrete exhibits improved bond behavior compared to conventional concrete due to a refined interfacial transition zone

and enhanced confinement around the reinforcement, as evidenced through pull-out tests under varying curing conditions[74-77]. The improved microstructural integrity of GPA concrete facilitates efficient stress transfer from steel to the surrounding matrix, thereby increasing resistance to slip and pull-out failure.

Table 8 Pull Out Test of Various Mixes of Concrete

S. No.	Description	CONTROL	GPA25	GPA50	GPA75	GPA100
1.	Rebar diameter in (mm)	12				
2.	Rebar type	HYSD Bars				
3.	Bond strength at 0.025 mm slip (MPa)	3.28	4.1	4.12	4.18	4.21
4.	Bond Strength at 0.25 mm slip (MPa)	4.82	5.52	5.61	5.65	5.91
5.	Design Bond Stress for M25 grade as per IS 456 : 2000 (MPa)	3.14				
6.	Force required to pull out rod (kN)	37	41	42	41.5	44

Moreover, the higher density and stiffness of GPA contribute to reduced local cracking and improved confinement of the reinforcement under load, which further enhances bond strength. The strong correlation between increased GPA content and higher pull-out force suggests that GPA concrete provides a more uniform stress distribution around the reinforcing bar, minimizing stress concentration and premature bond failure. Importantly, all GPA mixes exceeded the design bond stress requirements specified in IS 456:2000 for M25 grade concrete, confirming their structural adequacy.

Overall, the results demonstrate that geopolymer aggregate incorporation not only satisfies but significantly enhances bond performance, ensuring reliable load transfer and improved structural safety. The comparable influence of GPA and natural aggregates on strength characteristics, coupled with the observed improvements in bonding efficiency, highlights the potential of GPA concrete as a viable and superior alternative for reinforced concrete applications where bond reliability is critical.

3.8 Micro Structural Characteristics

The microstructural characteristics of geopolymer aggregate (GPA) concrete were examined using scanning electron microscopy (SEM) and compared with those of conventional concrete, with emphasis on the morphology of the cementitious matrix and the aggregate-paste interfacial transition zone (ITZ) after 28 days of curing. The observations are interpreted qualitatively to establish links between microstructural features and the measured mechanical performance.

Figure 10 presents the SEM micrograph of conventional concrete, illustrating the typical morphology of a hydrated cement matrix. The microstructure consists of hydration products such as calcium silicate hydrate (C-S-H) gel, along with crystalline phases including portlandite [$\text{Ca}(\text{OH})_2$] and calcite [CaCO_3]. The C-S-H gel appears to be locally concentrated around partially hydrated cement particles, forming a heterogeneous framework with visible capillary pores and microcracks. These discontinuities at the paste matrix and aggregate-paste interface are characteristic of conventional concrete and may act as potential pathways for long-term deterioration.

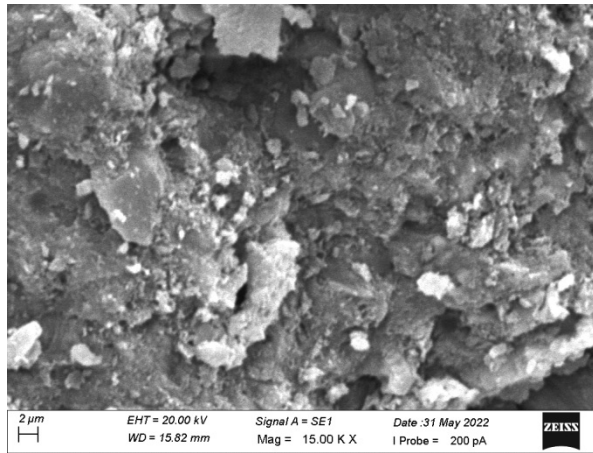
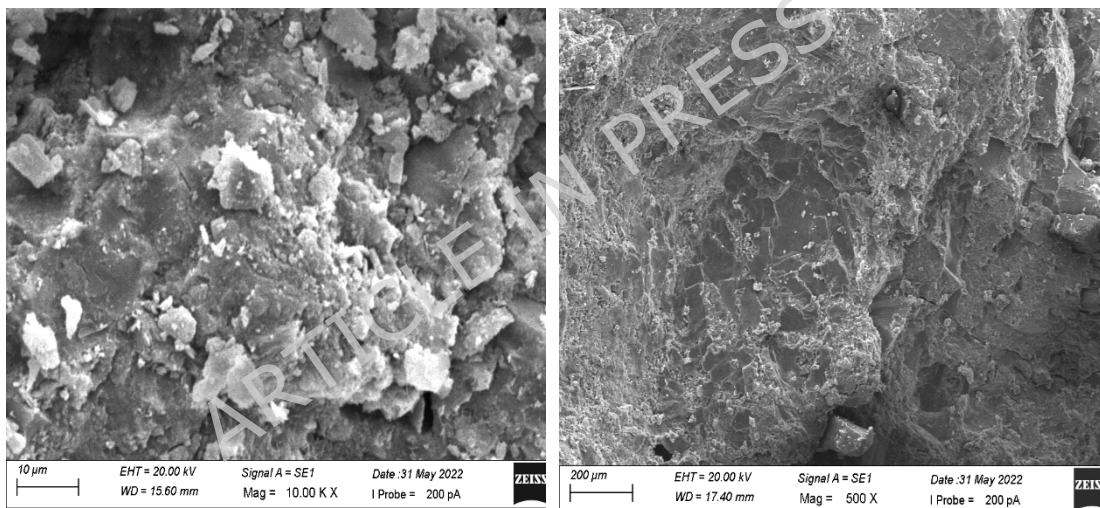


Figure 10. SEM Micrograph of Conventional Concrete Mix



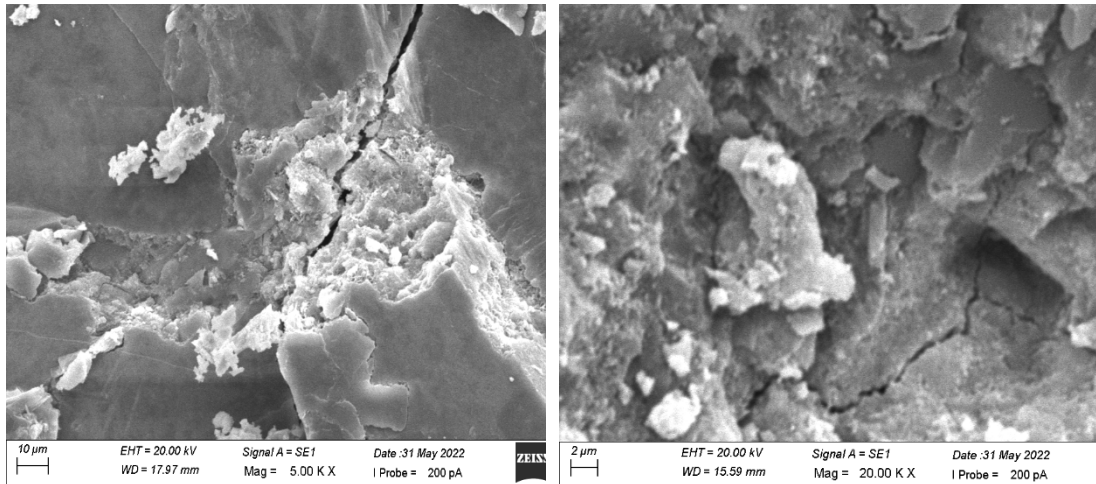


Figure 11. SEM Micrograph of GPA100 Concrete Mix

In contrast, the SEM micrograph of the GPA100 concrete mix (Figure 11), in which natural coarse aggregates were fully replaced by geopolymer aggregates, reveals a comparatively more compact and homogeneous microstructure. The cementitious matrix exhibits a more uniform distribution of hydration products, with fewer visible pores and microcracks at the aggregate-paste interface. This improved microstructural continuity is attributed to the physical characteristics and reactive surface nature of geopolymer aggregates, which are produced from alkali-activated GGBS and can contribute additional calcium- and silica-rich phases that participate in secondary reactions within the cementitious system. These reactions are expected to promote the formation of additional binding phases; however, it is emphasized that such interpretations are based on morphological evidence rather than quantitative phase identification.

The ITZ in GPA concrete appears denser and more continuous compared to that of conventional concrete, suggesting improved interfacial bonding between the geopolymer aggregates and the surrounding paste. This observation is further supported by the reduced presence of interfacial voids and microfractures. The absorption capacity of GPA may have contributed to local internal curing effects by temporarily absorbing free water during early hydration stages, thereby reducing the effective local water-to-binder ratio at the interface. As hydration progressed, the gradual release of absorbed moisture likely facilitated

continued formation of hydration products, contributing to partial filling of interfacial pores and healing of microcracks.

Although the hydration characteristics of GPA100 concrete generally resemble those of conventional cement-based systems, differences in the distribution and morphology of reaction products were observed. These microstructural features qualitatively correlate with the enhanced compressive and flexural strength recorded for GPA concrete. The improved ITZ integrity and reduced microstructural discontinuities are consistent with previous studies, which emphasize the critical role of ITZ quality in governing the mechanical performance of concrete [78-83].

Overall, the SEM analysis confirms that modifications in aggregate type significantly influence the microstructural development of concrete. While the present observations provide valuable qualitative insight into the role of geopolymer aggregates, future studies incorporating quantitative techniques such as SEM-EDS mapping, porosity measurements, and phase analysis are recommended to further substantiate these findings.

3. Conclusions

This study evaluated the feasibility of replacing natural aggregates with geopolymer aggregates (GPA) in concrete, incorporating graphene oxide (GO) as a performance modifier. Increasing GPA content led to a reduction in workability due to the angularity and rough surface texture of GPA; however, the target slump was maintained through appropriate mix design adjustments. GPA incorporation resulted in consistent improvements in mechanical properties compared to natural aggregate concrete (NAC). At 100% GPA replacement, compressive strength increased by approximately 1.5-14%, split tensile strength by 13-32%, and flexural strength by an average of 15.3%, with the highest performance observed in the GPA100 mix. The static modulus of elasticity and impact resistance also improved by up to 11% and 36%, respectively. Microstructural analysis confirmed the formation of a dense and continuous aggregate-matrix interfacial transition zone (ITZ) in GPA concrete, characterized by enhanced microhardness and the absence of interfacial discontinuities, indicating superior bonding and efficient stress transfer. The observed enhancements are attributed to the synergistic interaction

between geopolymer aggregate formation and GO incorporation, which together improve aggregate morphology, interfacial characteristics, and crack resistance.

Overall, GO-modified geopolymer aggregates demonstrate strong potential as a sustainable and high-performance alternative to natural aggregates in structural concrete applications. For future research, it is recommended to include GO-free GPA control mixtures to quantitatively isolate the individual contribution of graphene oxide. Further studies should also investigate long-term durability, shrinkage behavior, and large-scale structural performance to support broader field implementation.

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Data Availability: Data Will Be Made Available Upon Request. Contact The Corresponding Author If Someone Wants to Request the Data from This Study.

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