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Transforming waste into sustainable building materials: Properties and environmental impacts of geopolymer concrete with recycled concrete aggregates

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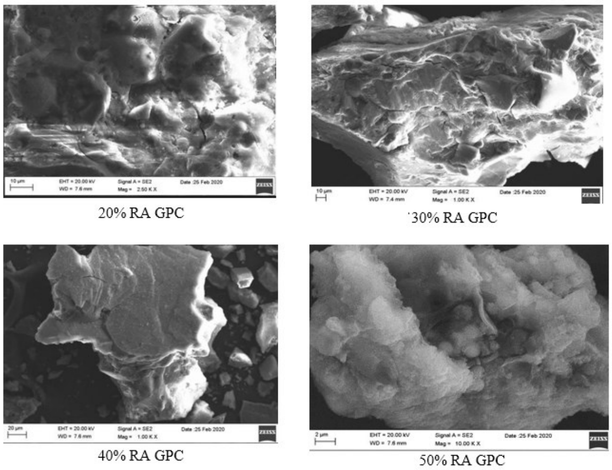
Graphical abstract



Abstract

Industrial by-products such as cementitious materials or aggregates have the potential to mitigate the adverse environmental effects associated with traditional cement manufacture. Geopolymer Concrete (GPC) is more eco-friendly than conventional concrete because it does not require cement. GPC with Recycled concrete aggregates (RCA), Ground granulated blast furnace slag (GGBS), and Fly Ash (FA) reduce raw material use and create sustainable infrastructure. GPC compounds increase workability, slump value above standard concrete, and reduce the amount of water usage. This study examines GPC mechanical properties, durability, and environmental properties with different RCA content. The M30 concrete mix design is established by trial and error utilizing a 0.45 water/binder ratio. GPC with 0%, 10%, 20%, 30%, 40%, and 50% recycled coarse aggregate replaced natural aggregate(NA) by mass. GPC with 50% GGBS provides an early strength of 96% of normal compressive strength on day seven. The compressive, split tension, and flexural strengths exhibit significant improvement with up to a 40% substitution of NA with RA. These results highlight GPC's potential as a sustainable alternative in the construction sector.

Keywords: Geopolymer concrete, sustainability, flexural strength, recycled aggregates, GGBS

1. Introduction

The manufacturing process of Ordinary Portland cement (OPC) leads to the emission of a substantial quantity of carbon dioxide (CO_2) into the atmosphere, hence causing detrimental impacts on both human well-being and the natural environment. The process of cement manufacture necessitates substantial quantities of raw materials, notably limestone, which emits CO_2 into the atmosphere, hence intensifying the phenomenon of global warming.

Concrete is the preferred construction material due to its superior performance, longer life, and cheap maintenance cost. Every year, smaller structures are demolished in order to make way for larger, newer structures. These demolished materials (the vast majority of which are usually concrete) are frequently dumped on land and are never recycled, this approach has an impact on land fertility. Scientists and engineers all around the world are looking for sustainable and reusable construction materials as the tsunami of sustainability sweeps through the construction industry. Recycled aggregate is one such substance.

Concrete waste recycling provides an environmentally preferable alternative to more conventional disposal practices (Gulmez 2021). Crushing up old concrete into aggregates, which may then be utilized in place of natural aggregates in new concrete mixtures. Using recycled aggregates minimizes the need for new raw materials and the energy required to collect and process them (Anwari *et al.* 2023). In turn, this results in reduced carbon dioxide being released into the atmosphere. Sand and gravel are essential for ecosystems and many different businesses and recycling concrete waste helps to protect these resources (Nagaraju *et al*. 2023).

Geopolymer concrete (GPC) is a novel and environmentally sustainable construction material, serving as a viable substitute for conventional Portland cement concrete. The utilization of geopolymer materials mitigates the need for Portland cement, hence addressing the issue of elevated CO_2 emissions. Daidovits used the term “geopolymer” in 1978 to describe substances that exhibit the properties of chains, networks, or inorganic molecules. Fly ash and ground granulated blast furnace slag (GGBS) are just two examples of the waste materials that go into making geopolymer cement concrete. Both thermal power plants and steel mills produce waste: fly ash from power plants and ground granulated blast furnace slag from mills. GPC is made from processed fly ash and GGBS is utilized in construction projects. Since less Portland cement is needed, fewer greenhouse gasses are released when this concrete is used. Alkaline activating solutions polymerize natural materials (Imtiaz *et al.* 2020) or industrial byproducts (like fly ash or slag) into molecular chains and networks to create a hardened binder, which is the main component of geopolymers. It is also referred to as alkali-activated cement or inorganic polymer cement. Uses are identical to those of cement concrete. However, widespread usage of this material has not yet occurred in a number of contexts. Precast bridge decks, water tanks, and retaining walls have all been built with this concrete.

A large number of study initiatives have been conducted to investigate the advancement of alternative binders that exhibit diminished environmental harm and minimized negative consequences. Recycled concrete aggregate (RCA) refers to the waste generated from the demolition of roads, concrete constructions, and buildings, which is then collected and repurposed. The utilization of building and demolition processes has become increasingly prevalent in the production of recycled concrete aggregate (Kamal, 2023). This trend has been driven by its ability to address challenges associated with mass storage, mitigate environmental pollution, decrease construction expenses, and preserve finite natural resources (Malkawi *et al.* 2016).

Although RCA has been the subject of numerous research examining its mechanical and durability properties, natural aggregates still outperform it in terms of strength and durability. They are frequently used in smaller quantities in the manufacturing of modern concrete because of their decreased strength and durability. A foundation material with lesser strength, a landfill, and other traits are additional pertinent qualities of recycled concrete aggregate. When making cement concrete, RCA is effectively used to replace a smaller proportion of natural aggregate without sacrificing strength. Portland cement concrete is frequently used in construction because it lasts longer. Based on the generation of carbon dioxide, the high utilization of PCC, which is made from a variety of raw materials, is posing environmental challenges (Shakor *et al.* 2023).

The cementitious binder has been substituted with various supplementary materials such as fly ash (FA), silica fume, meta-kaolin, slag, and burnt clay. Extensive research and investigations have been conducted on geopolymeric materials derived from recycled sources (Zhang *et al.* 2022). The utilization of fly ash (FA) and alkali in the production of ordinary Portland cement (OPC) results in the creation of concrete that exhibits reduced energy consumption and enhanced environmental sustainability.

The building sector has recently decreased its use of cement as a result of these issues. The emphasis has changed to waste materials and replacement binders as a result of this research. One alternative method that addresses the aforementioned issues is geopolymer technology (Jain *et al.* 2022). Lower expenses are ensured with a progressive solution using the GPC. Due to its lower energy consumption and pollution output, GPC is environmentally friendly (Kumar *et al.* 2022). Construction material for the GPC is made from hazardous industrial waste. Fly ash, blast furnace slag, clay materials, and rice husk ash are other components used to manufacture GPC. The FA-based geopolymer binder is more economical and emission-efficient when it uses recycled materials (Xiaonan *et al.* 2023; Lee *et al.* 2017). This study proposes a hybrid approach for investigating the properties of GPC using recycled concrete particles. The primary objectives of the suggested method are to calculate the optimal strength of GPC using recycled concrete aggregate and to examine how important parameters interact with prediction results. n contrast to the strength attained by other researchers utilizing materials such as ground granulated blast furnace slag, recycled concrete aggregate, and less calcium FA, A unique GPC formulated by Kumar and Mishra. (2022), The strength of is 85 MPa, which is relatively high. The emphasis also uses the obtained coarse aggregate (CA) from the demolished wastes. Making concrete that could be used in an area of aridity where water was scarce was another goal. Consequently, the creation of both solid and liquid binders was carried out. An ultra-high-performance geo-polymer concrete (UHPGPC) made using micro-silica made of polypropylene fiber (PF) and steel fiber (SF) and GBFS (Kumar *et al.* 2022). The impacts of recycled material powder at pumice-based geo-polymer paste have been developed (Nasaeng *et al.* 2022). Two waste products, RC ground and calcined oyster shell (CS), were used to exchange pumice powder (PM) in the range of 0 to 50% by weight. As alkali-activators (AA), sodium hydroxides (NaOH) in 10 M concentrated solutions and sodium silicate (Na_2SiO_3) solutions in 1.00 were used. Every combination used a liquid-to-binder (L/B) ratio of 0.60. SEM, energy-dispersive X-ray spectroscopy, X-ray diffraction, a mesoporous inorganic polymer, and Fourier-Transform infrared were used to examine the microstructure and compressive strength of geo-polymer paste. The effects of recycled concrete aggregates used as CA in concrete with equal substrate stiffness and sustainable AA (Damrongwiriyanupap *et al.* 2022). Commercial silica-fume (SF) was used as a precursor for the production of high-calcium fly ash (HFA) and AAHFA concrete (AAHFAC). The answer for the L/B ratio of sodium silicate (SS) and sodium hydroxide (SH) is 0.50, while the solution for the AA is 1. Zhang *et al.*(2021) have presented an investigational study of dynamic and static compressive aspects of ambient cured fiber-reinforced GPC (FRGPC) including mono-polypropylene (PP) or hybrid steel-polypropylene fibers and mono-steel. To test the dynamic compressive during various strain rates of 130.5 s to 1, the Split Hopkinson Pressure Bar (SHPB) was utilized.

The main objective of this study is to create a substitute for cement with the goal of minimizing CO_2 emissions. This involves the amalgamation and repurposing of industrial by-products like GGBS and FA, along with the recycling of building and demolition waste as a substitute for natural aggregates. Additionally, the aim is to examine the mechanical properties and workability of GPC using various optimal ratios of recycled aggregates and aims to fulfill the demand for sustainable building materials. This novel technique combines and converts industrial wastes such as GGBS and FA, while intelligently repurposing construction and demolition waste as an environmentally friendly substitute for natural aggregates.

2. Materials and methods

2.1. Materials for GPC

The primary source of coarse aggregate in this study is derived from crushed concrete wastes obtained from the demolition of civil constructions, while the reference or control group utilizes natural coarse aggregate sourced from granite. The small industry offers FA and GGBS as its products. According to the diagram presented in Figure 1, the constituents utilized in the production of GPRAC consist of sodium hydroxide, sodium silicate, fly ash, recycled aggregate (RA), and deionized water. The crushed waste concrete is utilized in this work.

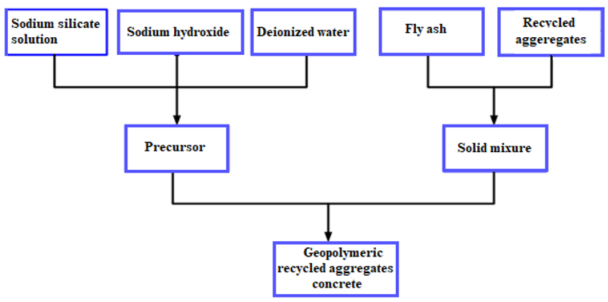


Figure 1. Formation of geo-polymeric recycled aggregates concrete

2.2. Configuration of the proposed Geo-polymer concrete

Geopolymer Concrete's strength helps integrate varied elements. This condition involves the specimen's age, coarse aggregate (CA), water, and cement concentration. In contrast, "output" refers to optimal compressive strength. The water binder ratio (W/B) gives geopolymeric recycled aggregates concrete (GRAC) fresh and hardened alkali characteristics. GPC is made by replacing Portland cement with recycled coarse aggregates. An alkaline solution starts the reaction, not FA, OPC, or GGBS-based geopolymers. The fine and coarse particles of steel slag are used to make aggregate. The suggested GPC is shown in Figure 2. The GGBS and fly ash characteristics were listed in Table 1.

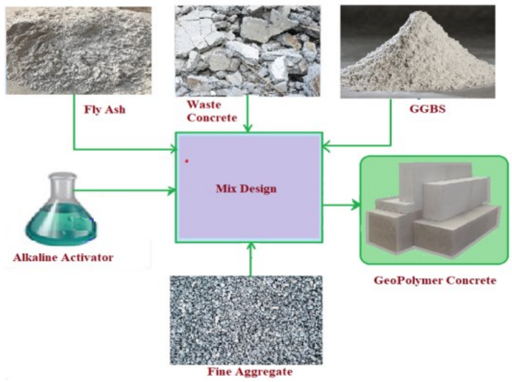


Figure 2. Structure of proposed GPC

3. Effect of fresh and hardened properties of GPC

3.1. Workability

The novel formulation of geopolymer composites exhibits higher cohesive and viscous characteristics, with a less significant increase with GGBS concentration. The recycled aggregates lose workability as more water is absorbed during mixing. To solve these issues, pre-soaked aggregates are used in dry, surface-saturated environments. Concrete workability is the rate at which freshly mixed concrete may be consolidated, mixed, set, and finished with the least amount of homogeneity loss.

3.2. Bleeding, segregation and setting time

Bleeding concrete is defined as concrete that is physically moving water toward the top surface. Bleeding is a form of segregation where water in the concrete mixture is forced upward by the cement and settled particles. Segregation happens when the components of a concrete mix aggregate, cement and water separate both before and after curing. A considerable amount of water will also surface as a result of the separation. The settling time is lengthened by increasing the amount of recycled material. The hardening characteristics of concrete, such as density, tensile strength, and compressive strength, are impacted when recycled materials are substituted for ordinary aggregates.

3.3. Resistance to surface abrasion and compressive strength

The compressive strength test is an essential method employed in the evaluation of concrete, as it yields valuable insights into the material's qualities. The phenomenon of wear resulting from friction and rubbing can be mitigated through the implementation of surface abrasion resistance. The distribution of weight loss following specific abrasion cycles is frequently observed. The concrete interfacial bond is inherently connected to the compressive strength and aggregate matrix.

3.4. Strength of splitting-tensile, flexural, and toughness

Flexural strength is the measure of the tensile strength of concrete slabs and beams. Additionally, it determines the amount of stress that could cause a flexural failure in an unreinforced concrete beam, slab, or other structure. Flexural strength and splitting tensile are decreased as RA content rises Due to excessive deformation brought on by the increased amount of recycled aggregate, the toughness of GGBS falls with the same loading as the recycled aggregate content increases.

Table 1. GGBS, FA and OPC properties

Items	GGBS	FA	O PC
Specific surface area (m^2/kg)	400	600	–
Density (g/c）	2.81	2.33	–
Fineness (80 µm)	–	–	1.1
SiO_2	35.51	51.48	21-24
Al_2O_3	13.61	24.35	4-6
CaO	35.06	9.7	61-67
Fe_2O_3	0.61	5.49	5-6
SO_3	0.30	2.134	2.12
MgO	9.58	1.2	0.9
Loss of Ignition	3	2.34	1.7

4. Experimental study on strength and workability of geopolymer concrete

This section details the experimental investigations conducted on test specimens, the concrete were broken into pieces and crushed to specific size aggregates using jaw crusher. The aggregates are categorized by size as coarse and fine aggregate The properties of the recycled coarse aggregate was found similar to that of natural coarse aggregate. The crushing method (mechanical or manual) of concrete to produce coarse aggregate for the production of new concrete is one of the factors that affect the strength of the concrete. The density of crushed concrete aggregate is smaller than natural aggregate density. Water absorption of recycled aggregate is greater than of natural aggregate. Presence of contaminants in recycled aggregate decline strength of concrete produced with this aggregate, thereby recycled aggregates are treated before it is used. It is treated by washing with water and air drying. Drying shrinkage of concrete made from recycled aggregate is usually greater than concrete made using natural aggregate. Figure 3(a-d) depicts the complete recycling process of waste concrete aggregates. The concrete mix design for the M30 grade is developed through trial and error using a water/binder ratio of 0.45. In place of natural aggregate (by mass), concrete was employed with 0%, 10%, 20%, 30%, 40%, and 50% recycled coarse aggregate. Workability as well as mechanical parameters such as compressive strength, split tensile strength, and flexural strength were investigated. Each trial was carried out in accordance with Indian standards.

4.1. Scanning electron microscope analysis of GPRAC

The generation of images in scanning electron microscopes (SEMs) involves the scanning of a material using a concentrated electron beam. The detection of signals is facilitated by the interaction between the atoms and electrons of the sample, thereby yielding valuable insights about the topography and composition of the surface. Figure 4 (a-f) presents the different degrees of RA GPC percentages, whereas SEM exhibits resolution capabilities above 1 nm.

Figure 3 a. Breaking of concrete

Figure 3 b. Jaw crusher

Figure3 c. Washing and drying RCA

Figure 3 d. Recycled aggregate

Figure 3. Recycled coarse aggregate

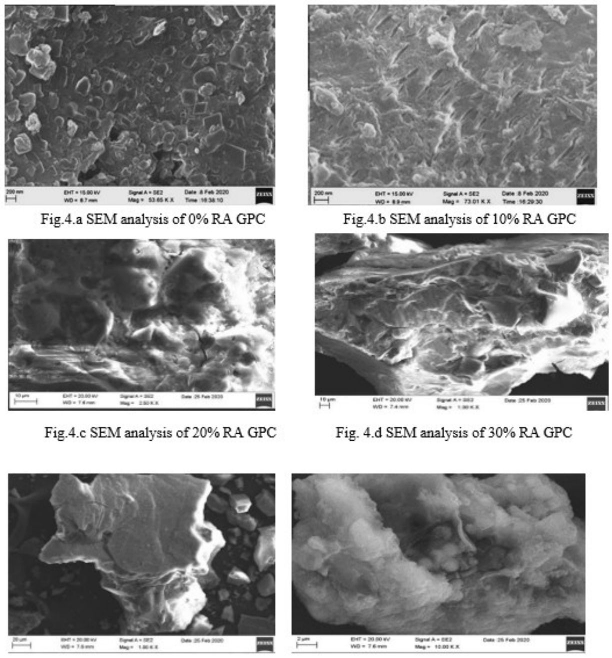


Fig.4.a SEM analysis of 0% RA GPC

Fig.4.b SEM analysis of 10% RA GPC

Fig.4.c SEM analysis of 20% RA GPC

Fig. 4.d SEM analysis of 30% RA GPC

4.e SEM analysis of 40% RA GPC

Fig.4.f SEM analysis of 50% RA GPC

Figure 4. SEM analysis of GPRAC

4.2. Slump cone test

The concrete slump cone test is an empirical method for determining whether freshly mixed concrete is workable. It closely monitors that batch of concrete's consistency. And used to determine the consistency of freshly made concrete.

The test's popularity stems from how easy it is to utilize the equipment and methodology. The purpose of the slump test is to assess the effects of plasticizers and the homogeneity of different batches of similar concrete in the field. As per IS 1199:1955 standard, the examination was carried out. The slump cone with the necessary proportions is selected. Non-absorbent grease is added to the interior of the cone, which is subsequently affixed to a uniform metallic plate. A 16 mm diameter tamping rod is used to tamp each of the four layers of evenly mixed concrete mix 25 times. Using a trowel, strike the top layer off-level. The slump cone is then gradually lifted, as shown in Figure. 5, and the concrete is then given time to settle. A slump is the space between the top of the concrete and the height of the mold. The procedure is repeated for every concrete mixture, and the results are recorded.

Figure 5. Slump cone test setup

Figure 6. Testing of concrete cube for compression

5. Mechanical properties of GPRAC

5.1. Cube compressive strength

Concrete cubes of 150 x 150 x 150 mm were made for cube compression testing. In compliance with IS: 516-1959 requirements, the cube specimens were assessed utilizing a compression testing apparatus capable of testing up to 3000 kN, as shown in Figure. 6. Three cubes from each mix were examined after 7th and 28th days of ambient curing, and the average compressive strength was determined.

5.2. Cylinder split tensile strength

This procedure measures the tensile strength of cylinder-shaped samples indirectly. After a curing time of 28 days, cylinder specimens were split tested for tensile strength using a 3000 KN compression testing instrument (Figure. 7a), as specified by IS: 5816 - 1999. To ensure that the applied force was distributed equally throughout the specimen and to reduce the quantity of severe compressive stresses close to the point of application of load, metal strips were placed between the specimen and the machine's loading plates. The force was gradually increased before readings were collected. The following formula was used to get the split tensile strength and the failure pattern shown in Figure 7b.

$$f_t = 2P / \pi DL \tag{1}$$

f_t = split tensile strength in N/mm^2

P = maximum load in N applied

D = measured diameter in mm, and

L = measured length in mm.

Figure 7a. Testing of Cylinder for tension

Figure 7b. Failure pattern

5.3. Flexural strength test

The ability of a material to withstand deformation when stressed is described by its flexural strength, also known as the rupture modulus. Flexural strength is a measure of the maximum stress that may be applied to a material before it breaks. Because it is weak in tension, concrete will crack under strain before it breaks under compression. Flexural strength is defined as the maximum tensile stress that a specimen can withstand before breaking. On the 28th day of curing, the specimens' flexural strength was tested in accordance with IS 516:1959. The 500x100x100 mm specimens are supported by two steel rollers spaced 400 mm apart on the bed of the testing machine as shown in Figure.8.

Figure 8. Flexural strength test setup

The load must be applied by two identical rollers set on one-third of the span. The load must be distributed evenly across the rollers and applied axially without causing torsional strains in the specimen. The specimen is loaded at a rate of 180 kg/min until it fails. The maximum load at which the specimen fails is recorded, as well as the distance of the crack from the nearest support. The formula is used to calculate flexural strength.

$$F = PL / bd^2 \quad if\ a > 13.3\ cm \tag{2}$$

$$F = 3Pa / bd^2 \quad if\ a < 13.3\ cm \tag{3}$$

Where,

F = flexural strength in N/mm^2,

P = Peak load specimen fails in N

L = length of the specimen in mm

b = breadth of the specimen in mm

6. Result and discussion

6.1. Workability test

The workability of concrete is a crucial factor that influences its strength, durability, and the aesthetic quality of the final surface. The workability of concrete is determined by its ability to be easily placed and compacted without causing bleeding or segregation. The concrete slump test is a practical examination used to assess the workability of recently mixed concrete (Kumar and Mishra, 2022). Table 2 displays the mechanical parameters of GPC with varying combinations of RA.

Table 2. Mechanical properties of various GPC composites

Properties	Percentage of RA (%)					
	0	10	20	30	40	50
Slump (mm)	210	220	225	230	238	245
Average 7th day Compressive Strength (N/mm^2)	28.77	35.01	35.19	40.85	41.06	42.32
Average 28th day Compressive Strength (N/mm^2)	36.54	41.04	42.65	43.47	56.06	51.77
Average 28th day Split Tensile Strength (N/mm^2)	2.46	1.909	2.17	2.38	2.64	2.31
Average 28th day flexural Strength (N/mm^2)	2.57	3.382	3.51	3.585	5.191	3.13

6.2. Slump cone test

The GPC with a 100% natural aggregate (NA) content showed a 210 mm slump measurement throughout the testing. Then, with replacement levels of 10%, 20%, 30%, 40%, and 50%, respectively, the slump values increased by 4.76%, 7.14%, 9.52%, 13.33%, and 16.66%. The data clearly indicates that there was a minor rise in the incidence of GPRAC collapse with an increase in the percentage of NA substitution with RA (Damrongwiriyanupap *et al.* 2022). Figure. 9 presents a graphical depiction of the findings.

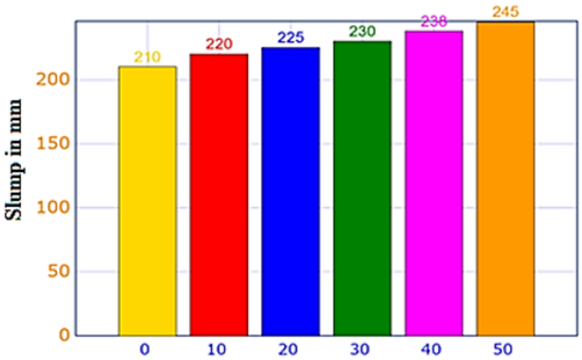


Figure 9. Slump cone test results

Slump value may increase with RA concentration because of the aqueous layer that surrounds the RA. It's possible that the slump was aggravated by the presence of a water film covering the recycled aggregates (RA) before all of the water was absorbed, as the water was used to wash the RA before mixing.

6.3. Compressive strength test results

Compressive strength data for a cube is measured on the 7th and 28th days of life. Six different permutations, each using three cubes, were examined. The compressive strength of GPRAC was found to improve with increasing RA substitution percentage in the experiments (Damrongwiriyanupap *et al.* 2022). The average compressive strength on day 7 and day 28 is depicted in Figure 10.

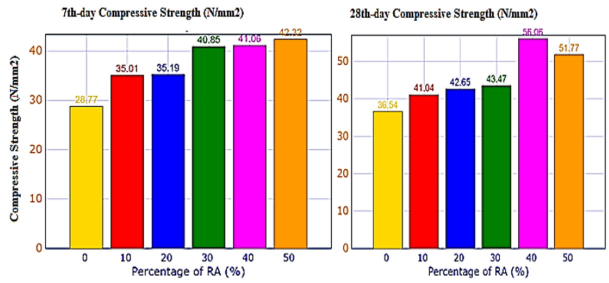


Figure 10. Average compressive strength on the 7th and 28th day

GPC's compressive strength at 28 days was 36.54N/mm^2 with 0% recycled aggregate. GPC increased concurrently with replacement rates of 10%, 20%, 30%, 40%, and 50%, increasing by 12.31%, 16.72%, 18.96%, 53.42%, and 41.68%. Strength increased from 53.42 to 41.68 percent, or between 40 and 50% of replacement. The mortar's adherence to the RA surface was the cause of the Weak Interfacial Transition Zones (Kumar *et al.* 2022; Zhang *et al.* 2023). This suggests that the best option is to replace 40% of the aggregate with recycled material. Concrete strengthens with time, regardless of the replacement %. All of the GPC displayed strong early strength since GGBS replaced 50% of the cement composition. For replacement levels of 0, 10, 20, 30, and 50%, respectively, the gain in strength from the seventh to the eighth day was calculated to be 27%, 17.2%, 21.19%, 6.4%, 36.5%, and 22.3%.

6.4. Split tensile strength results

On the 28th day, the split tensile strength results for all GPC composites are determined. Three-cylinder examples were made for each combination. After casting, the specimen was allowed to cure naturally for 28 days (Kumar and Mishra, 2022). As demonstrated in Figure. 11, the split tensile strength of GPRAC improved with an increase in the quantity of RA replacement up to 40%, then decreased by 50%. For GPC-NA, the split- tensile strength on the 28th day was 2.46(N/mm^2). For GPC with RA, it decreased by 22.4%, 11.8%, 3.25%, and 6.09% for 10%, 20%, 30%, and 50% of replacement, respectively, with 40% of replacement increasing by 7.4%, indicating that it is an optimum percentage of replacement.

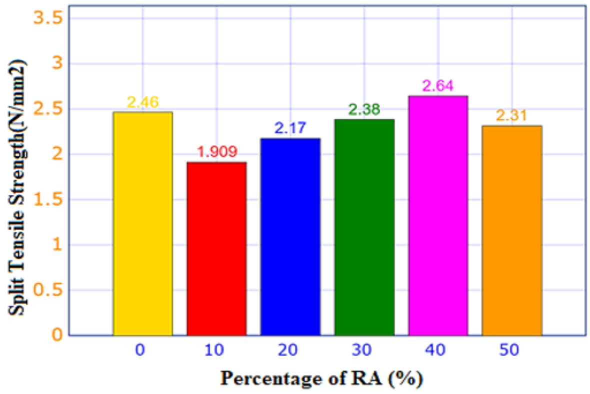


Figure 11. 28th day Avg. Split Tensile Strength

6.5. Flexural strength test results

The flexural strength of all GPC composites is assessed on the 28th day. Three prisms with dimensions of 100mm x 100mm x 500mm are made for each blend. Following a period of 28 days of ambient curing, the specimens underwent evaluation utilizing a two-point loading technique. The observed trend in flexural strength values exhibited a close resemblance to those of compressive strength. Based on the findings of the experiment, it was observed that there was an improvement in the flexural strength of GPC with an increase in the proportion of recycled aggregate (RA) replacement (Kamal, 2023). Flexural strength for GPC-NA was 2.57N/mm^2 on the 28th day. For 10%, 20%, 30%, and 50% replacement, GPC increased by 31.6%, 36.6%, 39.5%, and 21.8%, respectively. When compared to GPC-NA, it increased twice for 40% replacement. The results are graphically depicted in Figure 12.

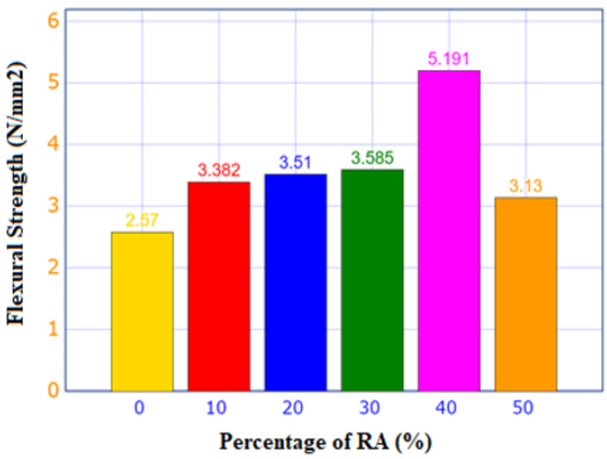


Figure 12. 28th day Average flexural strength results

Conclusion

Based on the experimental investigations carried out the following conclusions are arrived:

- Because GGBS and FA function as lubricants and promote the workability of the concrete, GPRAC has a slightly higher slump value than traditional concrete.
- The utilization of saturated surface dried aggregates significantly mitigates the requirement for excessive water quantities. Consequently, the substitution of natural aggregate with recycled aggregates led to a marginal enhancement in workability.
- The duration of the geopolymer binder's handling time was limited to a maximum of 15 minutes, which proved to be sufficient for the adequate mixing and preparation of concrete.
- The high early strength of all GPC samples was observed due to the replacement of 50% of the cement component with GGBS.
- At the seventh day, about 96% of the compressive strength was attained without adding RA instead of NA. Further replacement of NA with RA was linked to an increase in early strength.
- The compressive, split tension, and flexural strength exhibit an increase when the substitution of natural aggregates (NA) with recycled aggregates (RA) increases up to a maximum of 40%. Therefore, it may be concluded that a replacement percentage of 40% is the most favorable option.
- The observation of decreased strength can be attributed to the production of weak interfacial transition zones, which becomes greater as the replacement of RA increases.
- The microstructure of the geopolymer composites with varying percentages of substitution of RA remained mostly unchanged.
- In terms of its mechanical properties and workability, the utilization of GPRAC with a binder consisting of GGBS/flyash in a 1:1 ratio, together with a water-binder ratio of 0.45, presents a more suitable alternative when compared to traditional concrete.
- The use of geopolymer concrete instead of traditional Portland cement concrete would result in an 80% reduction in carbon dioxide emissions related with concrete production.

Appendix

CO_2- Carbon dioxide

Na_2SiO_3- Sodium silicate

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