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# EXPERIMENTAL INVESTIGATION ON FLY ASH BASED GEO POLYMER CONCRETE

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**ABSTRACT:**
Geopolymer concrete (GPC) represents a progressive alternative to conventional Portland cement concrete, employing industrial by-products such as fly ash, slag, or metakaolin as binders that are activated through alkaline solutions. This study aims to examine the impact of substituting natural coarse aggregate (NCA) with varying proportions of recycled coarse aggregate (RCA) on the characteristics of low calcium fly ash (FA)-based GPC, which is cured at elevated temperatures. The M25 grade of ordinary Portland cement (OPC) concrete was formulated in accordance with IS: 10262-2019, utilizing 100% NCA as the control sample. Due to the absence of standardized guidelines for GPC in existing literature, the same mix design was adapted for GPC by replacing OPC with 100% FA and adjusting the water-to-cement ratio to an alkalinity-to-binder ratio. All FA-based GPC mixtures were formulated by using a 12M sodium hydroxide (NaOH) solution with a sodium hydroxide to sodium silicate (NaOH: Na2SiO3) alkalinity ratio of 1:1.5. The mixtures were then cured at a temperature of 900°C for a duration of 48 hours. The study evaluated various properties, including workability, compressive strength, split tensile strength, flexural strength, water absorption, density, volume of voids, and rebound hammer value across all mixtures. Additionally, the correlation between compressive strength and other mechanical properties of GPC mixes was established and compared with the established relationships for traditional concrete. It was found that the proportion of natural aggregate replaced by RCA could potentially be increased to 50% in GPC under ambient curing conditions without adversely affecting the mechanical properties of the concrete.

**Keywords** Geopolymer concrete (GPC), fly ash, GGBS, Recycled aggregate concrete (RAC), Ambient temperature, Alkalinity ratio, Compressive strength, Molarity.

## INTODUCTION:

The most popular building material worldwide is concrete, and cement is one of the major ingredients of concrete. However, the Portland cement in its production results in enormous carbon emissions and resource depletion. Researchers and engineers have been looking for substitute binders that may reduce the environmental impact of concrete in recent years. According to the reports that are currently accessible, 5%–7% of $CO_2$ emissions that are embodied carbon from cement manufacturing are created by ordinary Portland cement (OPC) manufacturing industries. To reduce the harmful effects of $CO_2$ emissions on the environment, OPC replacements must be
developed. Fly ash (FA), ground granulated blast slag (GGBS) and silica fume (SF) have all been used frequently in the past to partially replace OPC, and it has been claimed that these alternatives have better durability and physical characteristics than OPC cement paste and also reducing the environment's negative effects from $CO_2$ emissions (Davidovits, 1993; Wang *et al.*, 2016; Kurda *et al.*, 2017a, 2017b).

Geopolymer concrete (GPC) has a rich history that dates back to the groundbreaking work of Joseph Davidovits in 1978. Davidovits introduced the term "geopolymer" to describe a family of mineral binders with a chemical composition similar to zeolites but possessing an amorphous microstructure. To address the environmental issues, the researchers examined FA-based GPC as a sustainable alternative to conventional concrete, using industrial by-products to improve structural performance (Davidovits, 1991; Meesala *et al.*, 2020) discussed the potential of geopolymer technology as a solution to reduce $CO_2$ emissions from the cement industry and increase FA utilization.

Past researchers found that the alkaline-activated geopolymer binder can effectively replace 100% OPC and has better mechanical and durability properties than conventional OPC paste (Hardjito *et al.*, 2004a, 2004b, 2004c; Fern´andez-Jim´enez and Palomo, 2005; Chindaprasirt *et al.*, 2007; Yunsheng *et al.*, 2008; Olivia and Nikraz, 2012). Several studies highlight the improved reactivity and mechanical properties of mechanically activated FA in geopolymers (Kumar *et al.*, 2007a, 2007b, Kumar *et al.*, 2007a; Verma *et al.*, 2022) concluded that M20 concrete mix revealed superior compressive strength in GPC compared to OPC.

Optimal results were achieved with 10 M of NaOH, curing temperature of 90°C for 24 h curing period and 1:1.5 alkaline solution ($NaOH:Na_2SiO_3$) ratio at 3, 7 and 28 days. Amar *et al.* (2023) found that the compressive strength of GPC was maximum at 12 M of NaOH. Najafi Kani and Allahverdi (2009) studied the effect of different temperatures on the compressive strength of geopolymer binders and found that at 85°C for 20 h, curing gave the better compressive strength. Fly ash-based GPC activated by alkali activation cured at 60°C for 24 h has yielded good mechanical properties (Julia *et al.*, 2015). This was reinforced by Singh and Murmu (2017) and Kubba *et al.* (2018).

It has been observed that when the curing temperature exceeds 60°C, lower strength values are achieved, attributed to the development of a non-homogeneous and porous geopolymer matrix. Nematollahi and Sanjayan (2014) have reported that there was a significant improvement in pore structure and strength of geopolymers when GGBS combined with FA in GPC compared to FA alone used in the GPC. The addition of GGBS to FA-based GPC helped in obtaining compressive strengths that were comparable to those of conventional concrete, as demonstrated by Nath and Sarker (2017). The formulation of the FA/GGBS mixture plays a crucial role in determining the compressive and flexural strengths of geopolymers. (Nath and Sarkar, 2014; Marjanovi´c *et al.*, 2015;

Das *et al.*, 2020) investigated the FA-based GPC at ambient conditions. Lime and SF were used as partial replacements for FA. Higher SF content increased slump and setting times, while
increased lime content reduced them. A combination of 7.5% lime and 2% SF replacement yielded the highest compressive strength, resulting in a densified microstructure.

Singh *et al.* (2023a, 2023b) reported that the GPC-MG15 concrete, which had a cement substitution ratio of FA: GGBS: SF – 35:50:15, demonstrated the highest compressive (52.15 MPa), flexural (5.81 MPa) and split tensile strengths (5.23 MPa). These values were 18%–34% and 7%–10% higher, respectively, than those of OPC concrete with natural aggregate and recycled aggregate. Singh *et al.* (2023a, 2023b) reported that the optimal conditions for attaining the high compressive strength in GPC were 12 M NaOH, 0.3–0.5 $Na_2SiO_3$ mass ratio and 2.0–
2.5 $Na_2SiO_3$/NaOH ratio. It was confirmed that the CSH, CASH and NASH product synthesis, yielding a peak compressive strength of 67.80 MPa when FA was replaced with 30% GGBS, 15% SF after 28 days (Singh *et al.*, 2023a, 2023b).

Increasing the percentages of GGBS and SF proportions in GPC reduced the loss in mass and degradation in compressive strength and hence improved the durability (Singh *et al.*, 2024). Enhanced microstructural and mineralogical properties, were observed by the formation of CSH, CASH and NASH gels. GPC mix with 35% FA, 50%: GGBS and

15%:SF yielded the highest strength and superior durability performance, offering a sustainable alternative to conventional OPC concrete with reduced reliance on natural aggregates (Singh *et al.*, 2024). The conventional method of curing geopolymer composites (GPC) at temperatures ranging from 40°C to 100°C may be substituted with curing at ambient temperatures. This alternative approach has the potential to improve mechanical properties, which is why this research emphasizes the activation of fly ash (FA) and its effects on geopolymer samples cured at ambient conditions.

In 2016, India generated nearly 15 billion tonnes of construction and demolition (C&D) waste, with less than 10% being effectively used. The improper disposal of these materials in landfills increases the carbon emissions and ecological challenges. However, using C&D waste as recycled aggregates in concrete, partially replacing natural aggregates, represents a sustainable engineering innovation (Benhelal *et al.*, 2013; Wang *et al.*, 2016; Colangelo and Cioffi, 2017; Jain *et al.*, 2019).

As a suitable recycled aggregate GPC, a geopolymer binder based on fly ash and GGBS has been suggested (Nuaklong *et al.*, 2016; Shaikh, 2016; Liu *et al.*, 2016). When using 100% recycled coarse aggregate (RCA), the compressive strength of RAC was reduced by a range of 17% to 30% (Rasheeduzzafar Khan, 1984; Xiao *et al.*, 2005; Xiao *et al.*, 2006; Poon *et al.*, 2007; Kou *et al.*, 2008; Kou *et al.*, 2008; Rao MC, 2010; Kou *et al.*, 2012). Additionally, the modulus of elasticity (MoE) was lowered by 15% to 45% (Frondistou- Yannas, 1977; Hansen and Boegh, 1986; Kheder and Al- Windawi, 2005; Poon *et al.*, 2006; Li, 2008; Limbachiya *et al.*, 2012; Elhakam *et al.*, 2012; Rao *et al.*, 2017,), split tensile strength decreases by 7% to 26%, (Prasad and Kumar, 2007; Yang *et al.*, 2008; Rao *et al.*, 2011; Elhakam *et al.*, 2012; Mas *et al.*, 2012) and flexural strength was reduced by 5% to 29% (Bairagi *et al.*, 1993; Prasad and Kumar, 2007; Yang *et al.*, 2008; Thomas *et al.*, 2022) found that the workability improved but increased water absorption and sorptivity with the addition of recycled aggregates in GPC. It was observe from the literature that the compressive strength of RAC with 100% RCA is approximately 60% (Bairagi *et al.*, 1993), 75% (Katz A, 2003), 95% (Kou and Poon, 2008) of that of concrete prepared with 100% natural aggregates. Several quality improvement techniques, namely, thermal treatment (Sui and Mueller, 2012; Al-Bayati *et al.*, 2016), mechanical treatment (Pape *et al.*, 2014; Babu *et al.*, 2014), chemical treatment (Tam *et al.*, 2007), pre-soaking in water, acid (Fathifazl *et al.*, 2009), etc., for RCA were suggested for better performance in RAC.

Li and Liu (2007) suggested improving the quality of RCA by coating it with pozzolanic materials. Incorporation of recycled aggregate in geopolymer binders and alkali-activated materials is an effective alternative techniques to improve the quality of RAC (Sata *et al.*, 2013; Mesgari *et al.*, 2020).

Tanuja and Chakradhara Rao (2023) reported that 50% RCA in GPC with a 60:40 proportion of coarse and fine aggregate based on particle packing density yielded a comparable results with OPC concrete with 100% NA. Further, it was concluded that to attain the maximum packing density, the Modified Toufar Model can be used.

Manjunatha and Kavitha (2023) attempted to increase the utilization of a higher percentage of RCA using 50% GGBS in self-compacting concrete (SCC). It was reported that 50% RCA gave the optimal mechanical properties of SCC. The study revealed that adding crumb rubber (CR) to normal concrete (NC) improved flexibility and durability. With CR ratios of 0%, 5%, 10% and 15%, combined with 7.5% micro-silica and magnetic water, the CR concrete sample exhibited the highest mechanical and durability properties (Nadi *et al.*, 2021; Kanagaraj *et al.*, 2023) developed GPC using manufactured sand (M-sand) and RCA under various curing conditions. It was reported that the natural coarse aggregate (NCA) can be replaced with RCA up to 40% in GPC, showing comparable compressive strength and enhancing sustainability.

**SIGNIFICANCE:**

Past studies show that the GPC is an alternative to OPC concrete. However, very few attempts have been made on all mechanical properties of GPC with RCAs. Further, previous studies highlighted that GPC needs high-temperature curing for better strength, so to overcome this further investigations need to be done for achieving its good strength at ambient temperature by using GGBS. Also, studies found that partial replacement (up to 30%) of natural aggregate by RCA does not show significant change in the strength and other properties of the conventional concrete. Also, different standards have suggested to replace the NCA with up to 30% RCA. However, very limited attempts have been made on the properties of GPC with a higher percentage of RCA. Therefore, this study aims to develop GPC by exploring the possibility of partial replacement of FA by GGBS as an alternative to high-temperature curing to provide better strength at room temperature by investigating the characteristics of GPC when different percentages of RCA are used.

## EXPERIMENTAL PROGRAMME:

The detailed experimental programme is shown in a schematic diagram (Figure 1.)

### Cement/fly ash/ ground granulated blast slag:

The fineness of OPC-53 grade and class-F fly ash obtained from the thermal power plant, Sipat, Bilaspur are conducted by dry sieve method using 90-micron sieve as per the guidelines of IS 4031 (Part 1):1996 (1996). The fineness of cement and FA obtained are 7.6% and 16.33%, respectively. The fineness of GGBS is found to be 6.36%. The compressive strength of OPC cement is found to be 53 MPa at 28 days. The chemical composition of FA and GGBS are presented in Tables 1 and 2, respectively.

### Aggregates:

According to Bureau of Indian Standards (BIS) requirements, the fine aggregate used in this experimental study was made from locally accessible river sand and confirms Grading Zone II (IS 383, 2016). The natural aggregate with a maximum size of 20 mm and confirming the (IS 383, 2016) grading specifications used in the mixtures. Waste from demolished buildings is first manually reduced into smaller pieces. To produce recycled aggregates, concrete fragments extracted from the rubble are then crushed using a laboratory jaw crusher until they reach the desired size, facilitating the reuse of materials.

According to BIS standards, tests were conducted on both natural and RCAs, and the results are shown in Table 3. Figures 2 and 3 demonstrate, respectively, the grading curves of natural fine aggregate and natural and RCAs, along with their BIS limitations.

Table 3 presents the results of the specific gravity, water absorption and bulk density of different aggregates. NCA demonstrates favourable properties with a high specific gravity, low water absorption and high bulk density, making it a preferred choice for concrete applications. In contrast, RCA exhibits slightly inferior characteristics.

The specific gravity and density of RCA is lower and water absorption is relatively higher than those of NCA. The water absorption and density of RCA, respectively, 2.25 times lower and 1.13 times higher than the natural aggregates. These may be due to the lower density and higher absorption of porous old mortar adhered to the recycled aggregate. However, both natural and recycled aggregates satisfy the limits specified by BIS (IS 383, 2016).

### Mix design and concrete mixes:

Based on the properties of OPC and aggregates, mix design is performed as per the guidelines of BIS (IS 10262:2019) for M25 grade concrete. The quantities of ingredients of M25 grade concrete mix per cubic meter of concrete are presented in Table 5.

Since no standard guidelines/procedures are available in the BIS codes for the mix design of GPC, the mix proportion of conventional concrete is adopted for GPC also.

In GPC, the cement is replaced with FA, GGBS and the alkaline solution is taken instead of water. The details of various mixes considered in this study are presented in Table 4. Table 6 presents the details of specimens, testing age and standards for various test methods adopted. Typical concrete samples are shown in Figure 4.

**PREPARATION OF ALKALINE SOLUTION:**

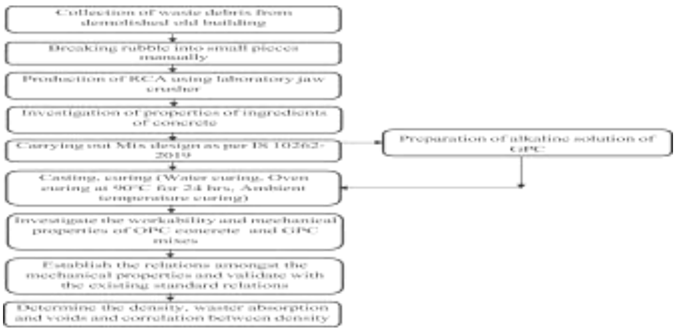
Preparation of alkaline solution containing 12 molar NaOH and ratio 1:1.5 ($NaOH/Na_2SiO_3$): In the preparation of the alkaline activator for GPC, sodium hydroxide (NaOH) pellets are combined with water to create a 12 M NaOH solution, using 480 grams of NaOH pellets per litre of water. Carefully dissolving the NaOH pellets in water while stirring until complete dissolution is achieved is a crucial step. Following this, the sodium silicate ($Na_2SiO_3$) solution is slowly added to the NaOH solution in a 1.5:1 ratio, with continuous stirring, to form the alkaline activator.

Past researchers recommended to prepare this solution 24 h prior to the concrete mixing and casting process, ensuring optimal geopolymerization (Hardjito *et al.*, 2002; Hardjito *et al.*, 2004a, 2004b, 2004c; Palomo *et al.*, 2004; Duxson *et al.*, 2007; Li and Liu, 2007; Panias *et al.*, 2007; Yip et al., 2008; Hou et al., 2009; Kong and Sanjayan, 2010; Bondar et al., 2011; Sanni and Khadiranaikar, 2013; Phoo-ngernkham et al., 2015). Hence, in the present study, the alkaline solution is prepared 24 h prior to mixing and casting of concrete.

**Curing of concrete mixes :**

OPC-based concrete samples are demoulded after 24 h of casting. Samples have been submerged into the water for 7 and 28 days. For GPC oven curing, samples are given 90°C for 48 h. After oven curing, the samples are demoulded when samples reach normal temperature and left at room temperature until the age of testing. Ambient curing of GPC concrete with 15% GGBS involves allowing freshly cast specimens to cure under ambient environmental conditions. Samples are demoulded after 24 h of casting and kept at room temperature till the age of testing.

**Figure 1 Schematic diagram of experimental programme:**




**Source:** Figure by Anchal Sondhiya

**Table 1 Chemical composition of fly ash**

| Components | Fly ash (in %) |
|---|---|
| $SiO_2$ | 52 |
| $Al_2O_3$ | 33.9 |
| $Fe_2O_3$ | 4 |
| CaO | 1.2 |
| $K_2O$ | 0.83 |
| $Na_2O$ | 0.27 |
| MgO | 0.81 |
| $SO_3$ | 0.28 |
| $SiO_2/Al_2O_3$ | 1.6 |

Source: Table by Anchal Sondhiya

**Table 2 Chemical composition of GGBS**

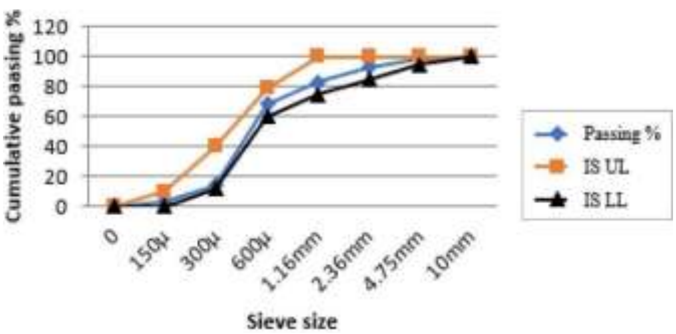
| Characteristics | Requirements as PER BS: 6699 | Test results |
|---|---|---|
| Particle size (cumulative %) | 45 Micron | 97.10 |
| Insoluble residue (%) | 1.5 (Max) | 0.49 |
| Magnesia content (%) | 14.0 (Max) | 7.73 |
| Sulphide sulphur (%) | 2.00 (Max) | 0.50 |
| Sulphite content (%) | 2.50 (Max) | 0.38 |
| Loss on ignition (%) | 3.00 (Max) | 0.26 |
| Manganese content (%) | 2.00 (Max) | 0.12 |
| Chloride content (%) | 0.10 (Max) | 0.009 |
| Glass content (%) | 67 (Min) | 91 |
| Moisture content (%) | 1.00 (Max) | 0.10 |
| Chemical moduli | 66.66 (Min) | 76.03 |
| CaO1MgO1SiO2 | >1.0 | 1.30 |
| (CaO1MgO)/SiO2 | <1.40 | 1.07 |
| CaO/SiO2 | | |

Source: Table by Anchal Sondhiya

**Table 3 Specific gravity, water absorptionbulk density of aggregate:**
**an**

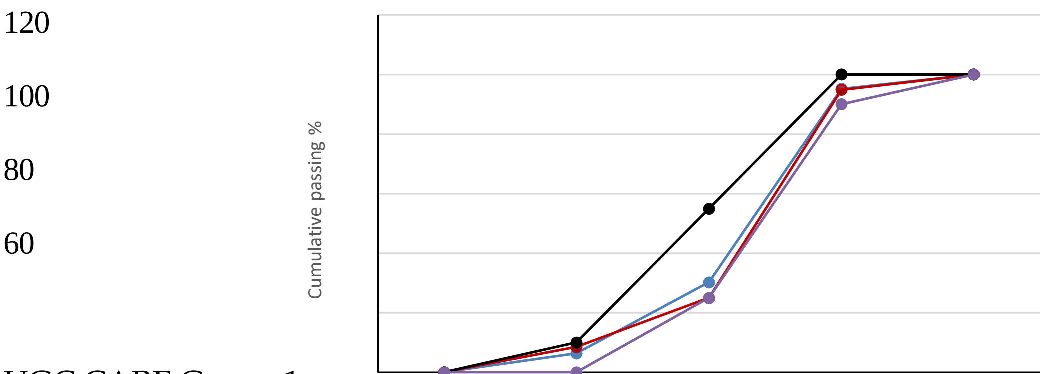
| Aggregate type | Specific gravity (IS 2386 Part 3:1963) | Water absorption (IS 2386 Part 3:1963) | Bulk density (IS 2386 Part 3:1963) |
|---|---|---|---|
| Natural coarse aggregate | 2.69 | 0.8% | 1,556 kg/$m^3$ |
| Recycled coarse aggregate | 2.46 | 1.8% | 1,376 kg/$m^3$ |

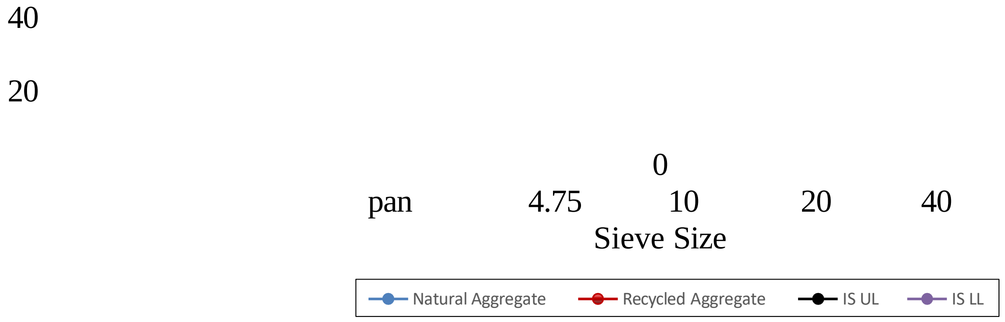
**Figure 2 Grading curve of natural fine aggregate:**




**Source:** Figure by Anchal Sondhiya

**Figure 3 Grading curve of coarse aggregates:**






**Source:** Figure by Anchal Sondhiya

**Table 4 Details of various mixes**

| Mix designation | OPC (%) | Fly ash (%) | GGBS (%) | Fine aggregate (%) | Natural coarse aggregate (%) | Recycled coarse aggregate (%) |
|---|---|---|---|---|---|---|
| OPC 2 NA100% | 100 | – | – | 100 | 100 | – |
| OPC 2 NA50%RCA50% | 100 | – | – | 100 | 50 | 50 |
| OPC 2 RCA100% | 100 | – | – | 100 | – | 100 |
| GPC 2 NA100% | – | 100 | – | 100 | 100 | – |
| GPC 2 NA50%RCA50% | – | 100 | – | 100 | 50 | 50 |
| GPC 2 RCA100% | – | 100 | – | 100 | – | 100 |
| GPC [FA85% 1 GGBS15%] 2 NA100% | – | 85 | 15 | 100 | 100 | – |
| GPC [FA85% 1 GGBS15%] 2 NA50%RCA50% | – | 85 | 15 | 100 | 50 | 50 |
| GPC [FA85% 1 GGBS15%] 2 RCA100% | – | 85 | 15 | 100 | – | 100 |

Source: Table by Anchal Sondhiya

**Table 5 Mix proportion of OPC concrete**

| Ingredients | Mass (kg) |
|---|---|
| Cement | 413 |
| Fine aggregate | 649.59 |
| Coarse aggregate | 1,124 |
| Water | 186 |
| W/C | 0.48 |

Source: Table by Anchal Sondhiya

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**Table 6 Details of property, age of test, size of specimens along with test method**

| Property | Age at test (days) | Size of Specimen | No. of specimens | Test method |
|---|---|---|---|---|
| Compressive strength | 7,28 | 100*100*100 mm cubes | 6 | (IS 516:1959) |
| Split tensile strength | 28 | Cylinders of 150 mm dia *300 mm height | 3 | (IS 5816:1999) |
| Modulus of elasticity | 28 | Cylinders of 150 mm dia *300 mm height | 3 | (IS 516:1959) |
| Flexural strength | 28 | 100*100*500 mm prisms | 3 | (IS 516:1959) |
| Rebound number | 28 | 100*100*100 mm cubes | 3 | (IS 13311 part 2:1992) |
| Density, water absorption, volume of voids | 28 | 100*100*100 mm cubes | 3 | (ASTM C642: 1997) |
| Source: Table by Anchal Sondhiya | | | | |

**RESULTS AND DISCUSSION :**

**Workability**

The workability (IS 1199: 2018) of all mixes is measured by performing slump cone test (Figure 5) and the results are presented in Figure 6.

Standard water curing: The results reveal that the inclusion of RCA consistently led to a significant reduction in slump values for OPC mixes, particularly with 100% RCA. It is found that the slump values of OPC mix with 100% NA is 30 mm, whereas with 50% RCA and 100% RCA are 25 mm and 20 mm, respectively. This demonstrated a negative effect on workability by the inclusion of recycled aggregate. This is probably due to that the RCA has 2.25 times higher water absorption than the natural aggregates. Similar results were reported in the literature.

Ben Nakhi and Alhumoud (2019) concluded that the workability of RAC gets reduced when compared to conventional concrete. This is probably due to the higher rate of water absorption of RCA. Oven curing (90°C for 48 h) and ambient curing: From Figure 6, it is observed that the RCA has a similar adverse impact on the workability of GPC mixes cured under oven curing conditions. A similar impact of observed in the case of GPC with recycled aggregate at ambient curing conditions (85% fly ash 1 15% GGBS). In the case of GPC at ambient curing, the slump values are 85 mm, 80 mm and 70 mm with 100% NA, 50% RCA and 100% RCA, respectively.

That is, 11% and 27% reduction in slump is observed with 50% RCA and 100% RCA, respectively, compared to the GPC with 100% NA. It may be concluded that there is a significant negative impact on workability with the inclusion of 100% RCA but 50% RCA inclusion does not show much impact. Hence, 50% RCA may be adopted in GPC at both ambient as well as oven curing conditions.

**Effect of fly ash (with and without ground granulated blast slag) vs ordinary Portland cement. Oven curing:**

From Figure 6, it is observed that the GPC mixes with and without recycled aggregate have shown significant improvement in the workability when compared to control concrete. The slump of GPC with 100% NCA, 50% RCA and 100% RCA are 90 mm, 80 mm and 65 mm, respectively, against those of 30 mm, 25 mm and 20 mm in control concrete.

**Ambient curing (85% fly ash 1 15% GGBS):**

Like the GPC mixes cured under oven, GPC mixes cured at ambient temperature also showed significant improvement in the workability when compared to OPC mixes under standard water curing conditions. It is found that GPC mixes cured under oven, GPC-NA100% exhibited a

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significant increase in slump values (average increase of approximately 183%). Similarly, GPC-NA50%RCA50% showed an increase of 166%, and with 100% RCA, the increase in a slump is 133% when compared to those of control concrete.

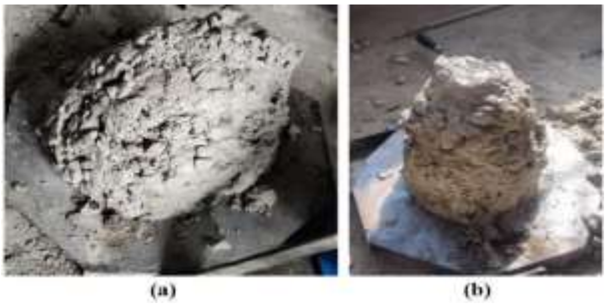
This suggests that GPC mixes can offer improved workability under ambient curing conditions compared to standard OPC, especially without the presence of RCA. It was reported in the literature that the workability of GPC is generally higher than conventional concrete (Singh *et al.*, 2019).

In a study by Nath and Sarker (2017), concrete made using FA and GGBS as the geopolymeric precursors was found to have a higher slump and flowability than conventional concrete made with Portland cement.

**Figure 4 Typical concrete samples**

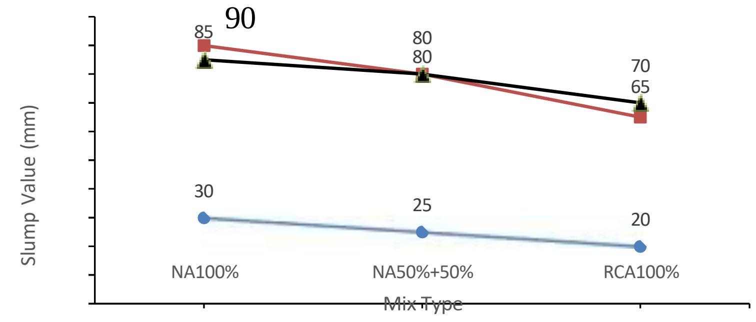
Source: Figure by Anchal Sondhiya

**Figure 5 Slump test of (a) GPC with FA and (b) GPC with FA 1 GGBS**




Source: Figure by Anchal Sondhiya

**Figure 6 Workability of concrete mixes:**




Source: Figure by Anchal Sondhiya

**COMPRESSIVE STRENGTH:**

Figure 7 shows the typical testing of compressive strength of concrete samples, and Figure 8 presents the compressive strength test results of both conventional and GPCs with different percentages of RCA. It is observed from Figure 8 that the OPC M25 concrete with water curing; notable trends emerge as the compressive strength increases with curing time. OPC-NA100% exhibits the highest compressive strength of 32.4 MPa at 28 days of curing.Introducing RCA, it is noticed that the compressive strength is marginally reduced. The compressive strength of OPC mixes with 50% RCA and 100% RCA are 31.9 MPa and 30.4 MPa, respectively, at 28 days of curing. That is, the compressive strength of OPC with 50% and 100% RCA reduced by 1.54% and 7.59%, respectively. The reduction in compressive strength of OPC concrete with RCA may be due to the lower strength of recycled aggregates by the porous nature than natural aggregate (Rao et al., 2011).

Further, the reduction may be due to the presence of old and new interfacial transition zones which had more volume of calcium hydroxide and voids (Xiao et al., 2013). It can be seen in Figure 8 that the GPC M25 concrete with oven curing GPC- NA100% exhibits the highest strength of 31.9 MPa at 28 days of curing. The compressive strength of GPC mixes with 50% RCA and 100% RCA are 31.6 MPa and 30.2 MPa, respectively, at 28 days. That is, the compressive strength of GPC with 50% and 100% RCA reduced by 0.94% and 5.33%, respectively, compared to GPC with 100% NA at oven curing. The incorporation of 50% RCA does not show any significant change in compressive strength.Singh et al. (2023a, 2023b) reported in the literature that the replacement of natural aggregate with recycled aggregate reduces the compressive strength of both OPC concrete and GPC. The reduction in compressive strength is more significant for higher percentages of recycled aggregate replacement. It is also observed from Figure 8 that the GPC M25 concrete with ambient curing (with 15% of GGBS) GPC-NA100% exhibits the highest compressive strength of 37.2 MPa at 28 days of curing. Incorporating RCA, it is found that the compressive strength is reduced.The compressive strength of GPC mixes with 50% RCA and 100% RCA are 36 MPa and 35.8 MPa, respectively, at 28 days of curing. That is, the compressive strength of GPC with 50% and 100% RCA reduced by 3.22% and 3.76%, respectively, lower than that of GPC with 100% NA under ambient condition. However, these values are more than the conventional concrete with 100% natural aggregate. Therefore, the negative effects of RCA are compensated when these are combined with FA and GGBS- based geopolymer technology in concrete cured under ambient curing condition.

The addition of GGBS in FA-based GPC may enhance the geopolymerisation process and form the gels of NASH and CASH, which yields the high compressive strength of GPC (Nath and Sarker, 2017). Hazard *et al.* (2016) reported that the inclusion of 40%–50% recycled concrete aggregate in place of natural aggregate in GPC had performed better than the conventional concrete. It was reported that the increase in strength is probably due to the presence of calcium in the old cement mortar adhered on the recycled aggregate which may lead to the C-S-H formation and also accelerate the process of geopolymerisation. The increase in compressive strength might be the result of the formation of CASH, NASH and CSH gels in GPC due to the interaction between alkali in NaOH solution and the presence of $SiO_2$, $Al_2O_3$ in GGBS (Pawluczuk *et al.*, 2021) The study by Rao and Kumar (2020) showed that FA 1 GGBS-based GPC cured at ambient temperature for 28 days had a compressive strength of 45 MPa, while FA-based GPC cured at oven temperature for 24 h had a compressive strength of 40 MPa.

These studies suggest that FA 1 GGBS-based GPC cured at ambient temperature is a promising alternative to OPC concrete, as it can achieve similar or even higher compressive strength without the need for ovencuring. This can lead to significant energy savings and reduced environmental impact.

Figure 8 shows that OPC M25 concrete’s compressive strength increases with curing time, with marginal reductions when introducing RCAs. GPC M25 concrete with oven curing or ambient curing exhibits similar trends, with limited strength reductions when incorporating RCA. It may be concluded from the above that 50% NCA may be replaced with RCA in GPC without compromising on compressive strength. Gopalakrishna and Dinakar (2023) concluded that the FA and GGBS-based GPC with RCA is a better choice than FA-based GPC for OPC concrete.

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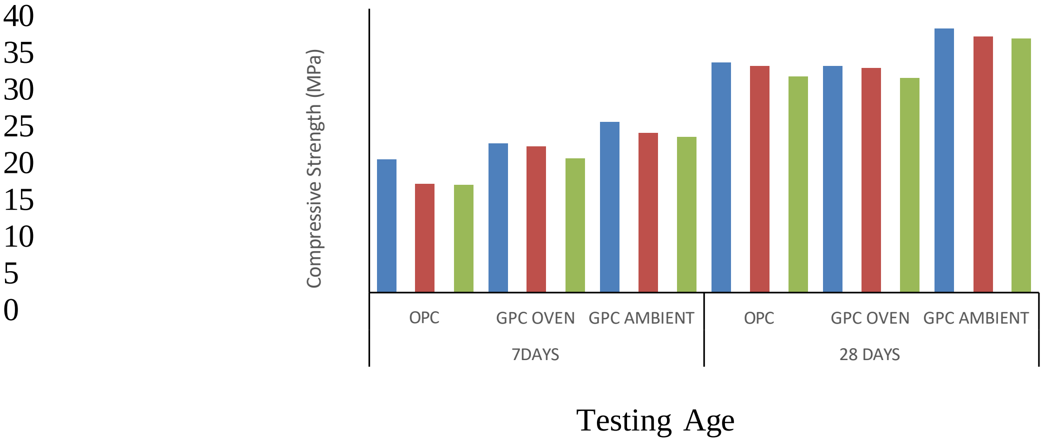
**Figure 7 Compressive strength testing of typical concrete samples**

Source: Figure by Anchal Sondhiy

**Figure 8 Compressive strength of concrete samples at 7 and 28 days**




**Source:** Figure by Anchal Sondhiya

**SPLIT TENSILE STRENGTH:**

The split tensile test set-up is shown in Figure 9, and the test results of both OPC concrete and GPC with different percentages of RCA are presented in Figure 10. It is noticed from Figure 10 that in the OPC M25 concrete with water curing; the split tensile strength of OPC-NA100% exhibits the highest strength of 3.3 MPa at 28 days.

Introducing RCA it is noticed that the split tensile strength is marginally reduced. The split strength of OPC mixes with 50% RCA and 100% RCA are 2.9 MPa and 2.4 MPa, respectively, at 28 days of curing. That is, the split tensile strength of OPC with 50% and 100% RCA reduced by 12.12% and 27.27%, respectively. The reduction in split tensile strength of OPC concrete with RCA may be due to the lower strength of recycled aggregates by the porous nature than natural aggregates. It can be seen in Figure 10 that the GPC M25 concrete with oven curing, GPC-NA100% exhibits the highest split tensile strength of 3.1 MPa at 28 days of curing.

The split tensile strength of GPC mixes with 50% RCA and 100% RCA are 2.8 MPa and 2.5 MPa, respectively, at 28 days. That is, the split tensile strength of GPC with 50% and 100% RCA reduced by 9.67% and 19.35%, respectively. It is also observed from Figure 10 that the GPC M25 concrete with ambient curing (with 15% of GGBS), GPC-NA100% exhibits the highest split tensile strength of 4.2 MPa at 28 days of curing. Incorporating RCA, it is noticed that the split tensile strength is reduced.

The split tensile strength of GPC (ambient curing) mixes with 50% RCA and 100% RCA are 4.1 MPa and

3.3 MPa, respectively, at 28 days, that is the split tensile strength of GPC with 50% and 100% RCA

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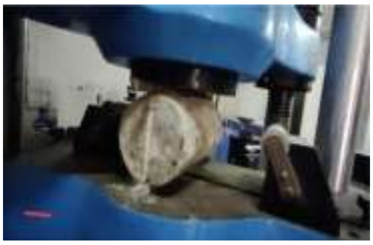
reduced by 2.44% and 21%, respectively.

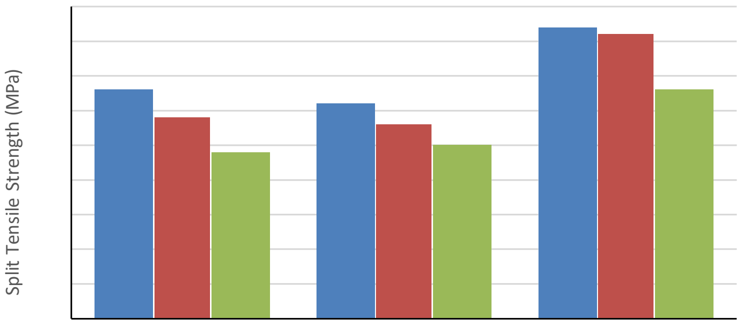
Tabhas et al. (2009) found that the split tensile strength of concrete decreased by 10%–25% when natural aggregate is replaced with recycled aggregate. The reduction in split tensile strength is attributed to a number of factors, including the lower specific gravity of recycled aggregate, the presence of impurities in recycled aggregate and the weaker bond between recycled aggregate and the cement matrix. Hu et al. (2019) concluded that due to inadequate bonding between RCA and the geopolymer matrix, the split tensile strength was reduced. It was noted that the incorporation of 30% GGBFS increased the tensile strength by 1.87 MPa for the mixtures containing 50% and 100% recycled aggregates, respectively. However, the reduction in split tensile strength is generally less significant for GPC concrete compared to OPC concrete. The addition of GGBS in GPC, which is cured under ambient temperature, the split tensile strength is significantly improved with both natural and recycled aggregates. The increase in split tensile strength of GPC at ambient curing with 100% NA, 50%RCA and 100% RCA are 27.27%, 24.24%
and 0%, respectively, when compared to the control concrete with 100% NA. This shows that without compromising on the split tensile strength, the higher percentage of RCA may be included in GPC cured under ambient condition.

**Figure 9 Test setup of split tensile strength**



Source: Figure by Anchal Sondhiya

**Figure 10 Split tensile strength of concrete**




4.5
4
3.5
3
2.5
2
1.5
1
0.5

OPC GPC OVEN GPC AMBIENT

Mix Designation

100%NA 100%RCA 50%NA + 50%RCA

**Source:** Figure by Anchal Sondhiya

**RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND SPLIT TENSILE STRENGTH :**

The relationship between the compressive strength (fck in MPa) and split tensile strength (fst in MPa) established by different standards ACI 363 R and CEB-FIP for NC and Xiao et al. for recycled aggregate concrete are expressed in equations (1)–(3), respectively:

fst = 0.49 fck (ACI Committee 318, 2005) for NC (1) fst =
0.301f 0.67 [Committee Euro — International du Beton×
(CEB — FIP), 1993]for NC (2)

fst = 0.24 * f 0.65 (Xiao et al., 2005)
for recycled aggregate concrete (3)

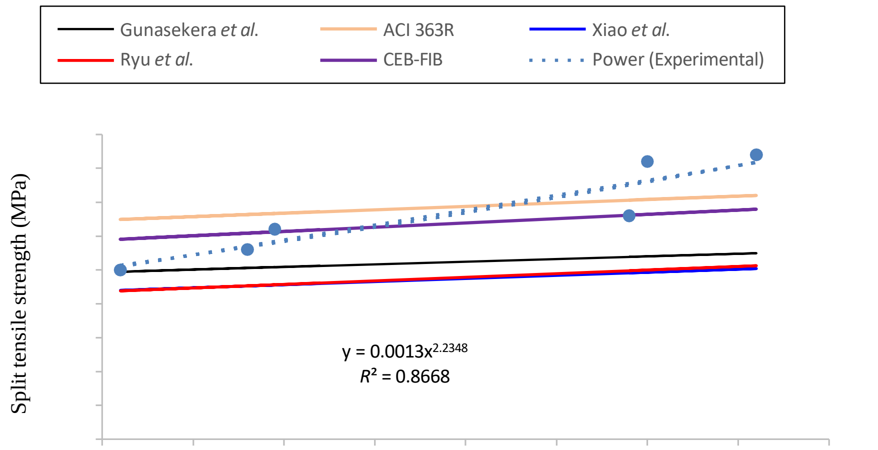
Ryu et al. (2013) suggested the models for low calcium FA- based GPC with natural aggregate at 9 M of NaOH, 50:50 $Na_2SiO_3$ mass ratio cured at 60°C for 24 h is presented in equation (4). The model suggested by Gunasekera *et al.* (2017) for four different fly ash-based GPC with natural aggregates for different split tensile strength ranges between 1.15 to 4.72 MPa at 28 days, 90 days and 365 days is shown in equation (5):

$$f_{st} = 0.17\ f^{0.75} \quad \text{(Ryu } et\ al.\text{, 2013) for GPC} \quad (4)$$

$$f_{st} = 0.45\ f_{ck} \quad \text{(Gunasekera et al., 2017) for GPC} \quad (5)$$

Figure 11 shows the variation of split tensile strength with respect to compressive strength as per the models suggested by equations (1)–(5).

**Figure 11 Relationship between compressive strength and split tensile strength**




4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30 31 32 33 34 35 36 37 38
Compressive strength (MPa)

**Source:** Figure by Anchal Sondhiya

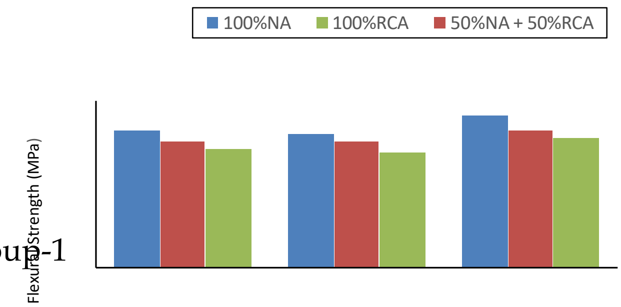
It is noticed from the figure that the models suggested by Ryu et al. (2013) and Gunasekera et al. (2017) for GPC and Xiao et al. (2005) for RAC underestimate the experimental results of GPC both cured under oven and ambient curing conditions.

$$f_{st} = 0.0013\ f_{ck}^{2.2348} \quad \text{(proposed equation) for GPC} \quad (6)$$

**Flexural strength :**

Figure 12 presents the flexural strength results of different concrete mixes. It is observed from Figure 12 that the OPC M25 concrete with water curing; the flexural strength of OPC-NA100% exhibits the highest strength as 3.7 MPa at 28 days of curing. It is noticed that the flexural strength is marginally reduced when RCA is included in concrete. The flexural strength of OPC mixes with 50% RCA and 100% RCA are 3.4 MPa and 3.2 MPa, respectively, at 28 days of curing. That is, the flexural strength of OPC with 50% and 100% RCA reduced by 8.18% and 13.51%, respectively. Chen *et al.* (2003) found that the reduction in flexural strength of OPC concrete with RCA may be due to the lower strength of recycled aggregates by the porous nature than natural aggregates.

**Figure 12 Flexural strength of concrete**




4.5
4

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3.5
3
2.5

**Source:** Figure by Anchal Sondhiya

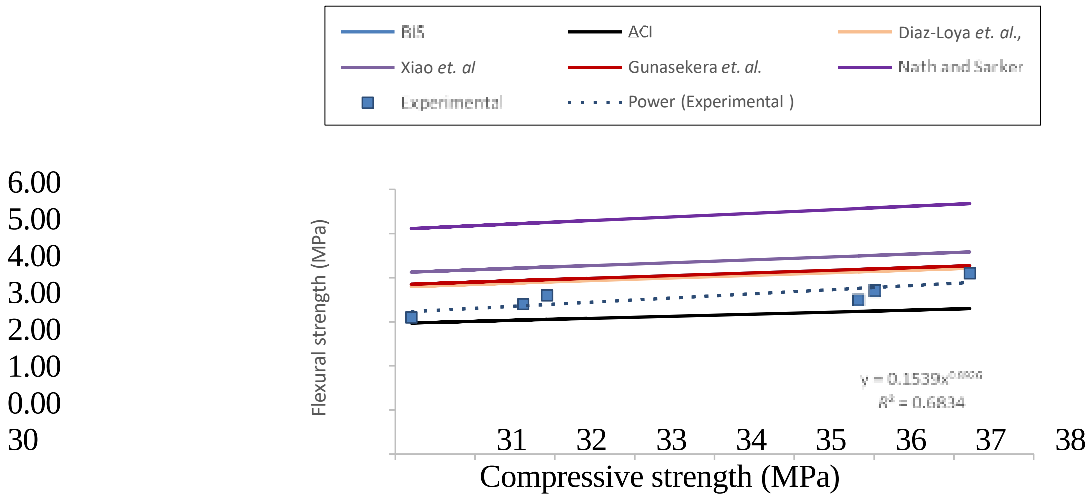
Further, it can be seen from Figure 12 that the GPC M25 concrete with oven curing, GPC-NA100% exhibits the flexural strength as 3.6 MPa at 28 days of curing. The flexural strength of GPC mixes with 50% RCA and 100% RCA are 3.4 MPa and 3.1 MPa, respectively, at 28 days. That is, the flexural strength of GPC with 50% and 100% RCA reduced by 5.5% and 13.88%, respectively. It is also observed from Figure 12 that the GPC M25 concrete with ambient curing (with 15% of GGBS), GPC- NA100% exhibits the highest flexural strength as 4.1 MPa at 28 days of curing. The incorporation of RCA, it is noticed that the flexural strength is reduced. The flexural strength of GPC (ambient curing) mixes with 50% RCA and 100% RCA are 3.7 MPa and 3.5 MPa, respectively, at 28 days. That is, the flexural strength of GPC with 50% and 100% RCA reduced by 9.75% and 14.63%, respectively. However, it is found that the GPC mixes under ambient curing conditions have shown significant improvement in flexural strength which are more than that of control concrete. Karthik *et al.* (2017) reported in the literature that 27.59% of flexural strength is improved in GPC with GGBS at ambient cured concrete for 28 days when compared to control concrete specimens.

**Relationship between compressive strength and flexural strength:**

The empirical relationship established between compressive strength (fck) and flexural strength (fb) by Bureau of IndianStandards (BIS) (2021), ACI Committee 318 (2005) for NC, Diaz-Loya et al. (2011) and Xiao et al. (2005) for recycled aggregate concrete and Gunasekera et al. (2017) and Nath and Sarker (2017) for GPC are expressed in equations (7)–(12):

$$fb = 0.7\sqrt{fck}$$ [Bureau of Indian Standards (BIS), 2021] for NC (7)

**Figure 13 Relationship between flexural strength and compressive strength**




**Source:** Figure by Anchal Sondhiya

For comparison, the experimental results are validated with the above equations and are presented in Figure
13. It is found that the equations (10) and (12) proposed by Xiao et al. (2005) for RAC and Nath and Sarker (2017) for GPC overestimate the experimental results of flexural strength of GPC cured under both oven curing and ambient curing. Whereas the ACI model closely estimates the GPC with 0%

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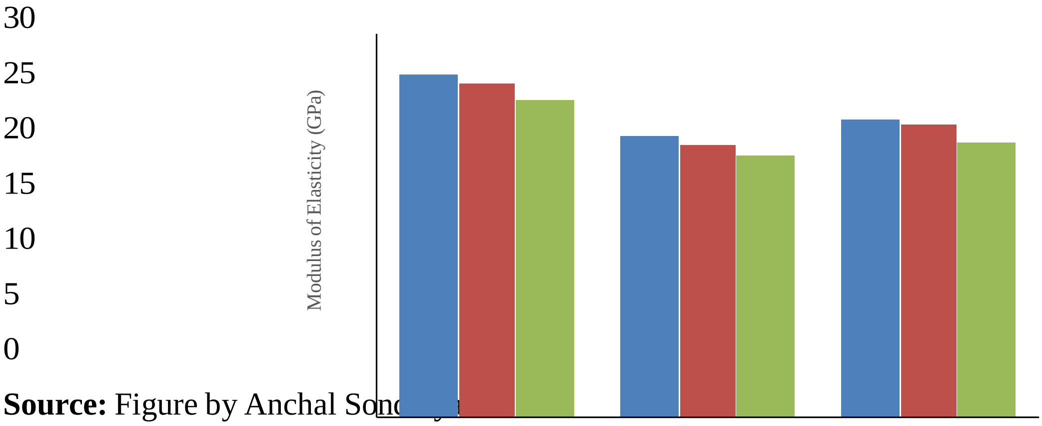
and 50% RCA values and underestimates the GPC with 100% RCA. Similarly, the models of BIS for NC and Gunasekera et al. (2017) for GPC closely estimate the experimental results of GPC with 100% RCA whereas overestimate the values of GPC with 0% and 50% RCA. Therefore, based on the experimental results, a regression model for relating the flexural strength and compressive strength of GPC is established with an R-values of 0.8267 and presented in Figure 13.

**Modulus of elasticity:**

Figure 14 shows the variation of static MoE of both control concrete and GPC with different percentages of RCA after 28 days of testing. It is observed that the OPC M25 concrete with water curing; the MoE of OPC-NA100% exhibits the highest MoE of 26.8 GPa at 28 days. After the inclusion of RCAs, it is noticed that the MoE is marginally reduced. The compressive strength of OPC mixes with 50% RCA and 100% RCA are 26.1 GPa and 24.8 Gpa, respectively, at 28 days of curing. That is, the MoE of OPC with 50% and 100% RCA reduced by 2.61% and 7.46%, respectively, compared to control concrete.

Park *et al.* (2015) reported that the reduction in MoE of OPC concrete with RCA may be due to the lower elastic modulus of recycled aggregates by the porous nature than natural aggregates and the presence of more micro-cracks in the RCA. It can also be seen from Figure 14 that the GPC M25 concrete with oven curing, GPC-NA100% exhibits the MoE of 22 GPa at 28 days. The MoE of GPC mixes with 50% RCA and 100% RCA are 21.3 GPa and 20.5 MPa, respectively, at 28 days. That is, the MoE of GPC with 50% and 100% RCA reduced by 3.18% and 6.8%, respectively. Further, it is found from Figure 14 that under ambient curing (85% FA and 15% GGBS), GPC-NA100% showed the MoE of 23.3 GPa at 28 days. Incorporating RCA, it is noticed that the MoE is reduced. The MoE of GPC mixes with 50% RCA and 100% RCA under ambient curing are 22.9 GPa and 21.5 GPa, respectively, at 28 days. That is, the MoE of GPC with 50% and 100% RCA are reduced by 1.71% and 7.7%, respectively.
Hardjito et al. (2004a, 2004b, 2004c) reported that GPC and OPC concrete mechanical properties, emphasizing that geopolymer mortars exhibit lower MoE due to their more porous microstructure. Unlike the compressive strength and split tensile strength, the MoE of GPC mixes cured under ambient curing with different percentages of RCA are lower than those of corresponding control concrete, but the reductions are not significant.

**Figure 14 Modulus of elasticity of concrete**

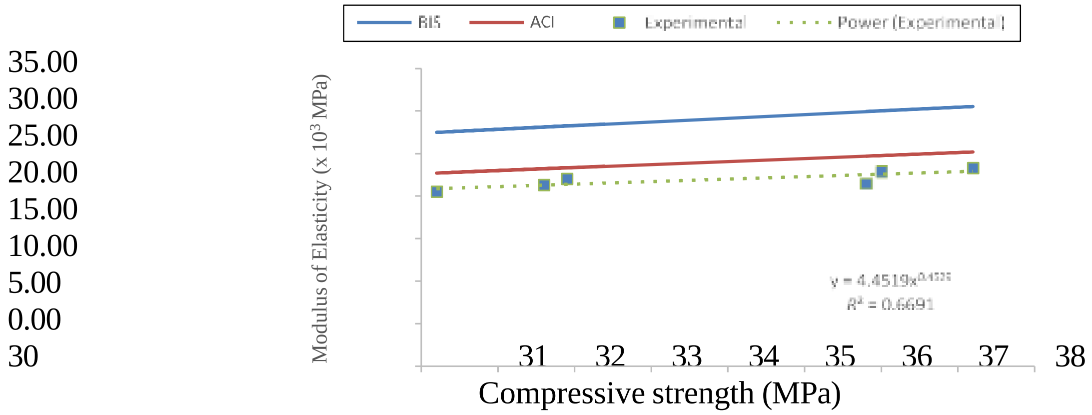



**Source:** Figure by Anchal Son

**Relationship between compressive strength and modulus of elasticity**

The relationship between compressive strength (fck) and modulus of elasticity (E) for concrete established by Bureau of Indian Standards (BIS) (2021) and ACI Committee 318(2005) for NC.

**Figure 15 Actual modulus of elasticity v/s analytical modulus of elasticity**




**Source:** Figure by Anchal Sondhiya

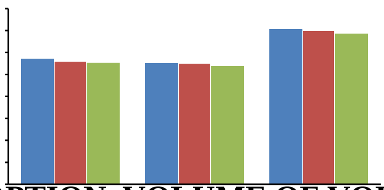
It is found that both ACI and BIS models overestimates the experimental results of MoE for GPC with different percentages of RCA cured under oven and ambient curing conditions. Hence, an equation is proposed based on the experimental results using the power regression analysis with an R-value equal to and is shown in Figure 15

**Rebound hammer:**

The rebound hammer test is a non-destructive test and is classified as a hardness test. It works based on the principle that the rebound of an elastic mass depends on the surface hardness against which the mass impinges and it gives only the surface zone properties. The rebound hammer test is conducted according to the guidelines given in BIS [IS: 13311–1992 (Part 2)].

Figure 16 presents the 28 days compressive strength results for three concrete compositions: 100% NA yielded the strengths of 28.6 MPa, 27.6 MPa and 35.3 MPa for OPC, GPC OVEN and GPC AMBIENT, respectively. A 50% NA and 50% RCA mixture achieved 27.9 MPa,27.4 MPa and 34.8 MPa strengths, while 100% RCA exhibited strengths of 27.6 MPa, 26.9 MPa and 34.3 MPa. The compressive strength of these concrete mixtures showed a minimal reduction (approximately 2%–3%) compared to 100% NA. The rebound hammer value of RAC was lower than the control concrete, due to the porous interfacial zone in the concrete generated by the presence of recycled aggregate, based on a study at the microscopic scale by Poon *et al.* (2004). The figure further reveal that the rebound values of GPC under ambient conditions exhibit the highest compared to other OPC and GPC mixes cured at elevated temperatures.These results are in tune with the compressive strength obtained at 28 days, as discussed in an earlier section.

**Figure 16 Rebound hammer test of concrete mixes**



**DENSITY, WATER ABSORPTION, VOLUME OF VOIDS:**

Durability is one of the important aspects in the concrete structures, especially when the structures are exposed to the sea environment. The pores in a concrete is the primary source for the permeation of fluids. This means that the density, water absorption and voids are directly related to the permeability. Permeability is one of the durability aspects. Hence, the density, water absorption and voids also indication of the durability indirectly. The test results of density, water absorption and volume of voids of all concrete mixes are presented in Table 7.

From Table 7, it is found that when using 100% OPC without any additives and with NCA, the density is 2,188 kg/m3 with 4.06% water absorption and 9.97% voids. However, when 100% RCA is introduced, the density slightly decreases to 2,049 kg/m3, while water absorption and voids increased to 8.8% and 15.63%, respectively. The reduction in density and increase in water absorption with the inclusion of 100% RCA is due to the fact that the RCAs had 2.25 times higher water absorption than natural aggregates.

Similar results were observed in the literature. It was reported that the reduction in density was due to the adherence of light and old mortar on the RCA (Rao et al., 2011). When 50% RCA is used, the density, water absorption and voids are observed to be 2,160 kg/m3, 5.10% and 10.85%, respectively. Therefore, the reduction in density and increase in water absorption and voids with the inclusion of 50% RCAs is not so significant when compared to the control concrete with 100% NCA. Rao et al. (2017) found in their research that the density decreased by 4.67%, and water absorption and volume of pores increased, respectively, by 12%, and 12.3% when 50% recycled coarse was used in recycled aggregate in OPC concrete.

Table 7 also presents the density, water absorption and void characteristics of GPC concrete subjected to oven curing at 90°C for 48 h and ambient curing. When using 100% FA in GPC with NCA, it is noticed that the density, water absorption and voids are, respectively, 2,180 kg/m3, 4.10% and 10.07%.

However, when 100% RCA is used, the density decreases to 2,040 kg/m3, accompanied by higher water absorption and voids, measuring at 9.11% and 15.98%, respectively. The properties of GPC under ambient curing condition, using a mixture consisting of 85% fly ash and 15% GGBS, the GPC-NA100% mixture exhibits a density of 2,253 kg/m3, remarkably low water absorption at 2.23% and voids measuring 5.9%.

When 100% RCA is introduced in GPC-RCA100%, the density decreases to 2,120 kg/m3, with 6.9% water absorption and 11.87% voids. It is found from the results that there is a significant improvement in the density and decrease in the water absorption and voids in case of GPC with 50%RCA at ambient temperature curing. Therefore, it may be concluded that the 50% RCA can be used without loss of properties of density and water absorption in GPC cured at ambient temperature.

**Table 7 Density, Water Absorption and Volume of Voids of Concrete Specimens at 28 days**

| Mix designation | Density (kg/m$^3$) | Water absorption (%) | Voids (%) |
|---|---|---|---|
| OPC 2 NA100% | 2188 | 4.06 | 9.97 |
| OPC 2 NA50%RCA50% | 2160 | 5.10 | 10.85 |
| OPC 2 RCA100% | 2049 | 8.80 | 15.63 |
| GPC 2 NA100% | 2180 | 4.10 | 10.07 |
| GPC 2 NA50%RCA50% | 2158 | 5.10 | 11.23 |
| GPC 2 RCA100% | 2040 | 9.11 | 15.98 |
| GPC [FA85% 1 GGBS15%] 2 NA100% | 2253 | 2.23 | 5.90 |
| GPC [FA85% 1 GGBS15%] 2 NA50%RCA50% | 2243 | 3.20 | 7.10 |
| GPC [FA85% 1 GGBS15%] 2 RCA100% | 2120 | 6.90 | 11.87 |

Source: Table by Anchal Sondhiya

## CONCLUSIONS:

In the present study, an attempt has been made to replace 100% cement with low calcium FA and GGBS in GPC with different percentages of RCA. Based on the experimental results discussed in the previous section, the following conclusions may be drawn: The workability of FA-based GPC has been observed to be superior to that of conventional OPC concrete due to the high lubricating effect of sphere-shaped FA particles in the fresh state of

GPC. In terms of compressive strength, ambient-cured GPC incorporating GGBS exhibits the highest strength, surpassing both OPC concrete and FA-based concrete subjected to oven curing at 90°C for 48 h.

The inclusion of RCA yields a substantial reduction in compressive strength, which may be due to the lower strength of recycled aggregates by the presence of the porous nature of old and new interfacial transition zones in RCA. These negative effects of RCA get compensated marginally when they were used in FA-based GPC. Further, when they were combined with 85% FA 1 15% GGBS in GPC cured under ambient curing condition, the compressive strength was significantly improved.

The compressive strength attained in GPC cured under ambient conditions with 50% RCA was 36 MPa which is more than the conventional concrete, i.e. OPC concrete with 100% NA. These improvements might be the results of the formation of C-S-H due to the presence of calcium in the old cement mortar adhered to RCA and the formation of CASH and NASH due to the interaction between alkali in NaOH solution and the presence of $SiO_2$, $Al_2O_3$ in GGBS. GPC (85% FA and 15% GGBS) cured at ambient temperature with 50% RCA exhibits similar behaviour with regard to the other mechanical properties, namely, split tensile strength, flexural strength and MoE.

The GPC with 85% FA and 15% GGBS cured under ambient conditions with 50% RCA has shown better performance in terms of density, water absorption and voids when compared to conventional concrete and GPC cured at elevated temperature.

The BIS suggested to replace 30% NA with recycled aggregate in concrete applications. From the investigation, the GPC composed of 85% FA and 15% GGBS with 12 M of NaOH and 1.5:1 alkalinity ratio and with 50% RCA cured under ambient conditions showed superior performance than the control concrete and GPC with 100% NA cured at temperature curing.

Hence, the GPC cured at ambient temperature with a higher percentage of RCA (50%) is a viable option to reduce the utilisation of cement and preserve the natural resources. This approach also contributes to energy conservation.

**LIMITATIONS & FUTURE SCOPE OF THE STUDY:**

- The scope of the present paper is limited to replace the FA by 15% GGBS. Further, only 50% and 100% RCA are used in place of natural aggregate. However, in future study, the replacement of FA by different amounts of GGBS (20%, 25%, 30% and 35%) may be tried to decide the optimum utilisation of GGBS so that the applications of GPC can be widely used in *cast-in-situ* applications, i.e. under ambient curing condition.

- Further, in the present study, the natural aggregate is replaced with only 50% and 100% RCA in GPC. However, further investigations may be carried out by considering different percentages between 50 and 100 with the optimum compositions of FA and GGBS to enhance the use of RCA in GPC applications.
- The present study is further limited to only the mechanical properties and a few other properties of GPC. For wider use of GPC under ambient curing conditions, the structural performance of GPC needs to be understood. Therefore, the structural performance of GPC subjected to different loadings under ambient curing with RCA will be investigated in future studies.

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