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Investigation On High-Strength Geopolymer Concrete with UFGGBS and Recycled Coarse Aggregate

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ABSTRACT
The objective of the present study is to investigate high-strength recycled coarse aggregate-based geopolymer concrete (HRGC) using recycled coarse aggregate and ultra-fine ground granulated blast furnace slag (UFGGBS). The current investigation is split into two phases. In Phase 1, geopolymer recycled coarse aggregate grades (GRM), GRM70, and GRM80 are developed with partial replacement of GGBS with UFGGBS. The optimization of UFGGBS is done through workability and compressive strength (CS) for both grades at 7 and 28 days. In Phase 2, the Tensile strength and Flexural strength are compared with limiting values of conventional concrete as per the IS 456:2000 guidelines. The results showed that, as the amount of UFGGBS content increased, the workability of both grades of concrete declined with an increase in CS. At 7 days, GRM 70 and GRM 80 have achieved a CS of 82–86%. Target strength for 28 days was attained at 100% replacement of UFGGBS for both grades.

Keywords- Fly ash, ultrafine ground granulated blast furnace slag, recycled coarse aggregate, geopolymer concrete.

INTRODUCTION

Steel and concrete are among the most extensively utilized building materials throughout the world. Nonetheless, the production of Portland cement releases a significant amount of greenhouse gases (GHS) and CO_2. About, One ton of Ordinary Portland cement contributes to around about one ton of CO_2 and other GHGs [1]. United States Department of Energy officials noted that by 2015, CO_2 emissions could be 50% higher than they were in 1997. If current emissions levels are maintained, global mean temperature (GMT) will rise by 5.8 degrees Celsius above current levels [2].

There have been numerous attempts to make concrete more sustainable and turn it into an environmentally friendly construction material. Several academic, business, and governmental efforts are actively working to increase the sustainability of built environments on a global scale. These initiatives center on the creation and acquisition of green building materials, low-energy design, waste resources, and energy-efficient building techniques [3].

One of the numerous initiatives that can be taken to overcome issues that influence sustainability and can achieve green concrete with the usage of supplemental cementitious materials (SCMs). This usage of various cementitious materials or admixtures can reduce the amount of cement used, which is beneficial from an environmental point of view [4]. Numerous articles have been written about lowering CO_2 emissions. On the contrary, the global availability of FA and GGBS creates a chance to put it to use the coal and steel byproducts [5]. Other factors, along with energy requirements, water consumption, and the generation of Construction and Demolition (C&D)

waste, contribute to an overall perception that Portland cement concrete isn't sustainable and compatible with the needs of long-term development.

A step toward greening the concrete industry for long-term development was taken, paving the way for the use from the coal and steel industries. Compared to ordinary Portland cement (OPC) paste, Geopolymer concrete (GPC) paste produces superior physical and durability qualities when Ground Granulated Blast Furnace Slag (GGBS) and low calcium Fly ash (FA) are used. It is advised to completely replace OPC with these materials in consideration with the mechanical characteristics of blended concretes and the cost effectiveness of such materials [6]. Because of this, green concrete is a good substitute for using all of the FA and GGBS for sustainability. The only practical way to lower CO_2 emissions while making full use of FA and GGBS is through GPC [7]. Joseph Davidovits , used a chemical procedure known as polymerization to produce an alkaline activator [8]. A. Palomo, found that the kind of activator in polymerization process is crucial. Reactions occur at a quicker pace when the alkaline activator contains solvable silicate, either sodium or potassium [9].

Water content significantly affects the polymerization process of GPC, where decrease in water content of FA-based GPC leads to decrease in its compressive strength [10]. GPC is developed when the activator binds silica and alumina-rich source materials like FA and GGBS. A cement-free concrete alternative that recycles waste by-products into useful building components [11]. The FA and GGBS-based GPC mix design yields promising density, workability, and compressive strength results for various grades M20-M60. Which assures compliance with IS 456: 2000 [12] criteria with minimal variation in flexural and splitting tensile strength, and showed promising mix design methods [13], [14].

The compressive strength of GPC improves as the molarity of sodium hydroxide solution increases [15]. Alccofine is an ultrafine processed GGBS i.e., UFGGBS is a mineral admixture used in OPC to increase the fresh and toughened properties of special concrete mixes [16], [17]. Alccofine can be added to GPC to improve its early strength and workability. It has been shown that adding Alccofine to GPC results in higher-strength concrete when cured in an oven. Alccofine can also significantly improve the compressive strength and workability of GPC at both ambient and elevated temperatures [18]. UFGGBS and RCA are both sustainable materials that can be used to improve the performance of GPC. The use of these materials can help to reduce the environmental impact and enhance workability, strength, and durability, which can reduce water absorption, and permeability of GPC [19], [20].

In India, C&D on the other hand generates approximately 150 million tons of waste per year, with only one percent of that waste being utilized (Centre for Science and Environment). However, worldwide progress in the substitution of various recycled materials for aggregate has made significant progress, reducing the need for natural coarse aggregate (NCA) in conventional concrete [21] [20]. Similar research has been started in the GPC field by incorporating partial replacement and complete replacement of recycled coarse aggregate (RCA) in determining the mechanical and durability properties of recycled coarse aggregate-based GPC [19], [20], [21]. However, recycled coarse aggregate had detrimental impacts on the characteristics of GPC that were comparable to those of portland cement concrete [21]. Compared with OPC, GPC replacing RCA with NCA is more sustainable [15].

It was observed that very little research on the development of high strength recycled coarse aggregate geopolymer concrete (HRGC) as GRM 70 and GRM 80 with RCA and UFGGBS materials. It was further noticed that the development of GRM70 and GRM80 grade GPC at low molarity such as 8M of NaOH concentration at ambient curing was found to be scarce in the literature. Furthermore, the comparison between GRM70 and GRM 80 grade GPC with standard concrete limiting values as per IS 456:2000 guidelines, is found to be very few in the literature [16], [22], [23].

Therefore in the current investigation, HRGC (i.e., GRM 70 and GRM 80 grades) was developed by maintaining RCA to NCA of 25:75 and FA to GGBS ratios of 54:46 for GRM70 and 51:49 for GRM80 grades GPC. There were two phases in present work. In Phase 1 the optimization is accomplished by replacing GGBS with UFGGBS in 25% increments, i.e., 0%, 25%, 50%, and 100% for grades GRM70 and GRM80. The highest strength GRM 70 and GRM 80 grade strength was achieved by optimizing UFGGBS through slump cone test and compressive strength tests at 7 and 28 days of ambient curing. In Phase 2, the optimised mix is used to develop the flexural strength and splitting tensile strength of HRGC, which are in comparison to standard concrete limiting values accordance with IS 456.2000 specification[12].

II. MATERIALS

A. Alkaline Binder

In this research, the alkaline binders such as FA, GGBS, and UFGGBS have been used to create HRGC as per IS 3812:2013 [24] SEM images are presented in fig. 1. The FA has been obtained from Telangana, India's NTPC Ramagundam. The FA is often more rounded than the particles of cement and lime. The diameter spans from 150µm to less than 1µm [10]. The specific gravity of FA is 2.2. The GGBS & UFGGBS are steel by-products that can be purchased from a nearby vendor in India. GGBS and UFGGBS have specific gravities of about 2.70. The composition of the chemicals for GGBS and FA is shown in Table 1.

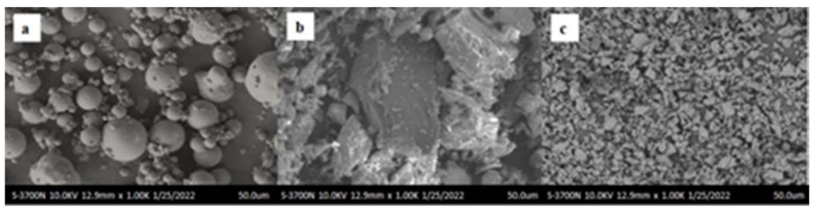

Fig 1. SEM images of (a) Fly ash, (b) GGBS, and (c) UFGGBS

B. Aggregates

Three different aggregate types have been used during this study to create HRGC, in accordance with IS 383:2016 [25].

- **Fine Aggregates**

As a fine aggregate, natively found natural sand that passed through a 4.75mm screen was used in the development of GPC in accordance with IS 383:2016 [25]. The fineness modulus and specific gravity of fine aggregates are 3.56 and 2.64, respectively, and it is verified to be zone II. The fine aggregate's particle size distribution is presented in fig 2. The fine aggregate physical properties are shown in Table 2.

- **Natural Coarse Aggregates**

GRM70 and GRM80 grades were developed using locally available NCA with a maximum size range of 10 to 20mm. Table 2 shows the properties of NCA according to IS 383:2016 [25]. The grading of 10mm and 20mm coarse aggregated is presented in fig. 2. fig. 3(a-b) shows the appearance of 10mm and 20mm aggregates.

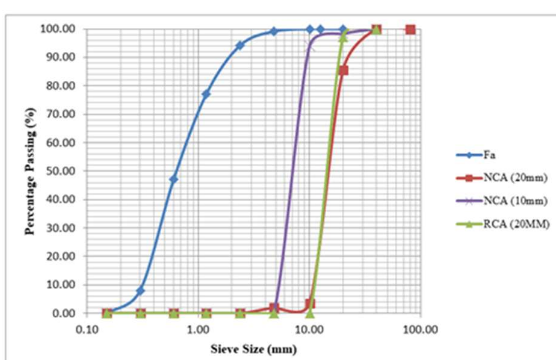

Figure 2: Particle size distribution of Fine aggregate (Fa), natural coarse aggregate (NCA), and recycled coarse aggregate (RCA).

- ## Recycled Coarse Aggregates

The RCA for this investigation was attaained from concrete specimens that had undergone testing in the concrete laboratory. The recycled aggregate processing equipment is used to recycle the coarse aggregates and crushed concrete specimens. The RCA processing unit consisted of a crusher to extract coarse aggregates from concrete specimens and a segregator for different sizes of coarse aggregate of which RCA of size 20mm was obtained, presented in fig 3(c). RCA's grading is shown in fig 2. Table 2 presents the physical characteristics of RCA. The image of RCA's is shown fig 3(c).

Figure 3: (a) 10mm NCA, (b) 20mm NCA, and (c) 20mm RCA.

C. Alkaline Liquid

NaOH and Na_2SiO_3 are the alkaline solutions utilized in these studies. NaOH pellets and Na_2SiO_3 were purchased from local sources. The solution was made by dissolving the NaOH particles in distilled water and multiplying the molecular weight of NaOH by the needed molar (8X40=320gms) per liter of solution. As per the literature [26], Before casting, the alkaline liquid was made 24 hours in advance. Table 3 shows the chemical analysis of sodium silicate composition.

Table 1: Chemical Composition of FA, GGBS and UFGGBS

Elements	FA	GGBS	UF GGBS
SiO_2	50.39	34.81	35.45
Al_2O_3	31.47	17.92	21.68
Fe2O3	4.16	0.66	1.29
CaO	4.43	37.63	32.76
MgO	-	7.80	8.47
P	0.47	-	-
TiO_2	1.76	-	-
Mn	0.66	0.21	0.15
Na_2O	1.23	-	-
K_2O	3.09	-	-
SO_4	2.34	0.20	0.20
LOI	-	0.77	-

Table 2: Properties of NCA and RCA

S. No	Description	NCA		RCA
		10mm	20mm	20mm
1	Specific gravity	2.71	2.76	2.635
2	Bulking density (kN/m^3)	1645	1514	1353
3	Fineness (Sieving method)	7.33	7.21	7.4

4	Water absorption	1.6%	1.9%	2.7%

Table 3: Chemical Properties of Sodium Silicate Solution

S. No	Composition	Na_2SiO_3
1	Na_2O	10.42
2	SiO_2	18.92
3	SiO_2:Na_2O	1.04
4	Suspended solids	0.75
5	PH	10.2
6	Total solids	41.03
7	Baume	52
8	Specific Gravity	1.96

Table 4: Mix Proportions of GRM70-25%HRGC in kg/m^3

Mixes	MIX-1	MIX-2	MIX-3	MIX-4	MIX-5
FA	259.2	259.2	259.2	259.2	259.2
GGBS	220.8	165.6	110.4	55.2	0
UF GGBS	0	55.2	110.4	165.6	220.8
Fine aggregate	769.5	769.5	769.5	769.5	769.5
NCA 20mm	142.6	142.6	142.6	142.6	142.6
NCA 10mm	570.6	570.6	570.6	570.6	570.6
RCA 20mm	237.7	237.7	237.7	237.7	237.7
NaOH	17.9	17.9	17.9	17.9	17.9
water	50.6	50.6	50.6	50.6	50.6
Na_2SiO_3	171.4	171.4	171.4	171.4	171.4
Super-plasticizer	1.9	1.9	1.9	1.9	1.9

Table 5: Mix Proportions of GRM80-25%HRGC in kg/m^3

Mixes	MIX-A	MIX-B	MIX-C	MIX-D	MIX-E
FA	244.8	244.8	244.8	244.8	244.8
GGBS	235.2	176.4	117.6	58.8	0
UF GGBS	0	58.8	117.6	176.4	235.2
Fine aggregate	771.9	771.9	771.9	771.9	771.9
NCA 20mm	143.1	143.1	143.1	143.1	143.1
NCA 10mm	572.39	572.39	572.39	572.39	572.39
RCA 20mm	238.5	238.5	238.5	238.5	238.5
NaOH	17.97	17.97	17.97	17.97	17.97
Water	50.6	50.6	50.6	50.6	50.6
Na_2SiO_3	171.4	171.4	171.4	171.4	171.4

Super-plasticizer	1.9	1.9	1.9	1.9	1.9

D. Mix proportions

Based on the previous literature, the mix proportions for the GRM70 and GRM80 grades were derived [15]. The alkaline activator had a molarity of 8 M, with a Na_2SiO_3 to NaOH ratio of 2.5, and the amount of alkaline activator to binder (FA and GGBS) ratio remained constant at 0.5 across all HRGC grades. GRM20, GRM30, GRM40, GRM50, and GRM60 grades are created with GGBS to FA alkaline binder ratios of (9.5:90.5, 21:79, 28:72, 38.5:61.5, and 43.5:56.5), with a constant 25%RCA replaced by NCA. Furthermore, GRM70 and GRM80 were achieved in two Phases, initially, phase-I involved optimization by substuting GGBS with UFGGBS in 25% increments (0%, 25%, 50%, 75% and 100%) for GRM70 and GRM80 grades. The heighest strength for GRM70 and GRM80 were achieved by optimizing UFGGBS through tests for slump cone and compressive strength at 7 and 28 days under ambient curing conditions. Subsequently, in Phase 2, the optimized mix was utilized to enhance the flexural strength and splitting tensile strength of HRGC, Comparing with the specified valued of IS 456-2000 for standard concrete. A poly-carboxylate-based superplasticizer with the brand name BASF-B233 was used to achieve workability, according to IS 9103:1999 [27], with an additional 4% use of extra water to develop GRM70 and GRM80 grade HRGC. The mix proportions for the GRM 70 and GRM 80 grades are given in Table 4 and Table 5. The abbreviations used for the present work is shown in Table 6.

E. Preparation of specimens

Weigh batching was used to prepare the concrete. In a pan mixer, fine, natural, and recycled coarse aggregates were dry mixed for 2 to 3 minutes. The binders FA and GGBS were then added to the pan and stirred for 3 to 4 minutes more. The prepared alkaline liquid was then poured to the dry mixture. All of the ingredients were blended for 4 to 5 minutes until they became homogenous. Before casting, the material was tested for workability. Specimens were cast for GRM70 and GRM80 grades and they were demoulded after 24 hours. Immediately after demoulding the specimens such as cubes, cylinders, and prism are kept in ambient curing for the 28 days as shown in fig 5.

III. EXPERIMENTAL INVESTIGATION

A. Test on Workability of HRGC

A Slump test is carried out as per IS 1199:1959 specifications [28]. HRGC developed to investigate the workability of fresh characteristics of different grades of concrete (i.e., GRM70 and GRM80) with an 8M NaOH concentration. The slump cone specimen has dimensions of 100mm in diameter at the cone top, 200mm in diameter at the bottom, and 300mm in height. fig 4(a-b). Shows the slump cone test for 100% replacement of UFGGBS for GRM70 and GRM80 grades GPC.

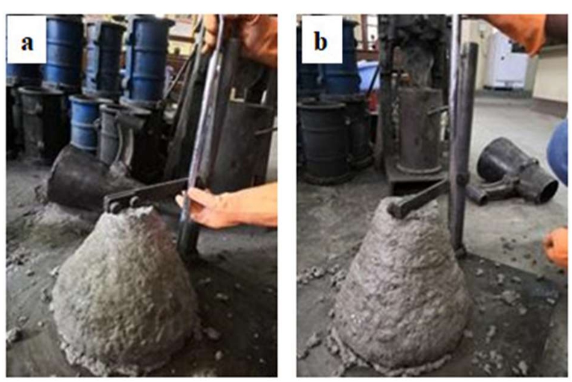

Figure 4: (a) GRM70 Slump, (b) GRM80 Slump

B. Harden properties of HRGC

- **Compressive strength**

HRGC's compressive strength F_{ck} and splitting tensile strength F_t were measured using universal testing equipment with a capacity of 2000 kN. According to IS 516:2004 requirements [29], the loading rate applied to the specimens was 140kg/cm^2/min. As shown in fig 5(a), a cube specimen of 150x150x150 mm was made and tested after 7 and 28 days of ambient curing. For a reliable compressive strength study, an average of three samples were taken and compared with the standard concrete's limitation value, as stated in equation 1.
Limiting value of Target strength.

$$(F_{ck}^{1}) = f_{ck} + 1.65 * \sigma \quad (1)$$

Whereas, F_{ck}= Achieved Compressive strength, F_{ck}^{1} = Limiting Target strength, f_{ck}= Standard compressive strength, σ = Standard deviation.

- **Splitting tensile strength**

According to IS 5816:1999 [30] requirements, Cylinder specimens of 150 mm in diameter and 300 mm in height underwent split tensile strength F_t^1 testing following 28 days of ambient curing, as seen in fig 5(b). Equation 2 compares the resulting split tensile strength findings to the split tensile strength limit value for conventional concrete.

Split tensile strength's limit

$$F_t^1 = 0.398\sqrt{f_{ck}} \quad (2)$$

- **Flexural strength**

On prism specimens, two-point loading was used, and the loading rate was kept constant at 180kg/min until the prism failed. The flexural strength (Fy) of HRGC was measured after 28 days of ambient curing as per IS 516:2004 [29] requirements, as shown in fig 5(c). The prism measures 500mm in length, 100mm in height, and 100mm in width. The average of three samples is calculated and compared to the conventional concrete's limitation value of flexural strength, as stated in Equation 3.

Limiting value of Flexural strengt

$$F_v^1 = 0.7\sqrt{f_{ck}}$$
(3)

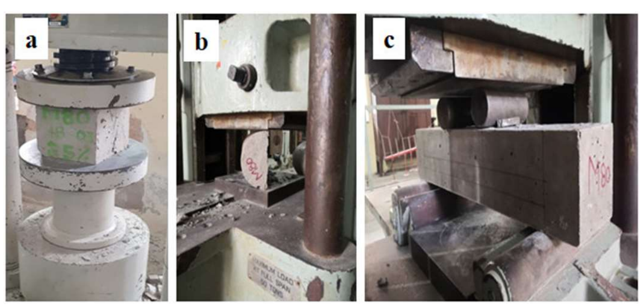

Figure 5: (a) Compressive strength, (b) Splitting tensile strength, (c) Flexural strength.

IV. RESULTS AND DISCUSSION

A. Workability of HRGC

Fig 6 shows the workability of the HRGC for GRM70. It was discovered that the slump value for GRM70 grade HRGC decreased as the amount of UFGGBS material increases [29]. Slump values of GRM70 grade for Mix-1, Mix-2, Mix-3, Mix-4 and Mix-5 are 102mm, 89mm, 73mm, 64mm and 53mm, respectively. fig 6 shows the workability of HRGC for GRM80. It was found that when the content of UFGGBS increased, the slump value of GRM80 grade HRGC considerably decreased [23]. Slump values of GRM80 grade for Mix-A, Mix-B, Mix-C, Mix-D and Mix-E are 90mm, 79mm, 63mm, 56mm and 49mm, respectively. had the highest slump of 102mm with 0% replacement of UFGGBS, Mix -2 had value of slump 89mm with 25% addition of UFGGBS, Mix-3 had a value of slump 73mm with 50% addition of UFGGBS, Mix-4 shown a slump 64 for 75% replacement of UFGGBS and Mix-5 had a slump of 53mm with 100% replacement of UFGGBS, respectively.

The HRGC's slump was improved by using a super plasticizer based on polycarboxylate [31][32]. There could be a correlation between the rise in UFGGBS content and the decline in slump value. The GGBS has additional CaO, which when combines with extra water in newly mixed concrete to accelerate the geopolymerisation process [33].

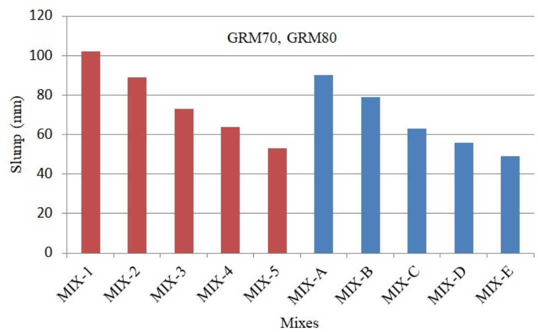

Figure 6: Workability of GRM70, GRM80

B. Mechanical Properties of HRGC

- ### Compressive Strength

Fig7 shows the compressive strength (F_{ck}) of HRGC grades GRM70 & GRM80 for 7 days and 28 days. It was noticed in both GRM70 and GRM80 grades that, with the increase of UFGGBS (i.e., 0%, 25%, 50%, 75%, and 100%), the F_{ck} is gradually increasing. The highest strength (i.e., GRM70 and GRM80) is achieved by replacing GGBS with 100% UFGGBS. For GRM70 mixes the amount of F_{ck} obtained at 7 days of ambient curing for Mix-1, Mix-2, Mix-3, Mix-4, and Mix-5 is 59MPa, 61MPa, 63MPa, 67MPa, and 70MPa, respectively. whereas, the noticed F_{ck} for Mix-A, Mix-B, Mix-C, Mix-D, and Mix-E of GRM80 mixes is 59 MPa, 65 MPa, 70 MPa, 76 MPa, and 84 MPa, respectively, after 7 days of ambient curing. According to IS 456:2000, the F_{ck} gained after 7 days of HRGC was between 80% and 85%, and this is greater in comparison to F_{ck} gained from ordinary concrete, which was 65% [12]. The same behaviour was observed in previous researchers, B.B. Jindal, noticed that increasing UFGGBS content improves the compressive strength properties for developing GPC [34]. Saloni observed that the characteristics of fresh and hardened GPC were improved by addition of UFGGBS in the GPC [20].

At 28days of ambient curing, the amount of increase in F_{ck} for GRM70 mixes such as Mix-2, Mix-3, Mix-4, and Mix-5 when compared to without UFGGBS mix i.e., Mix-1 is 2.77%, 4.16%, 8.33%, and 12.5%, respectively. At 28days of ambient curing for GRM80 mixes, i.e., Mix-B, Mix-C, Mix-D, and Mix-E, while comparing with Mix-A, the amount of increase in F_{ck} is 6.75%, 13.51%, 18.91%, and 25.67%, respectively. The highest F_{ck} achieved for each grade is 81MPa for GRM70 and 93MPa for GRM80. The optimised mixes for GRM70 and GRM80 grades at Mix-5 and Mix-E. According to Saloni, Fresh characteristics demonstrated better workability, density, and less air voids [20]. The weak inter-transition zone of the recycled coarse aggregate has an impact on the GPC's; however, the addition of UFGGBS creates calcium silicate hydrate gel, which strengthens the RCA and enhances bonding between them. Further studies like flexural strength and splitting tensile strength for GRM70 and GRM80 grades are investigated at Mix-5 and Mix-E, respectively.

The F_{ck} of GRM70 and GRM80 mixes exhibit a linear correlation, with fig 7 displaying the limiting value of the F^1_{ck} after 28 days of ambient curing. The coefficient of the R^2 value was found to be approximately equal to one in fig 7, indicating a positive correlation.

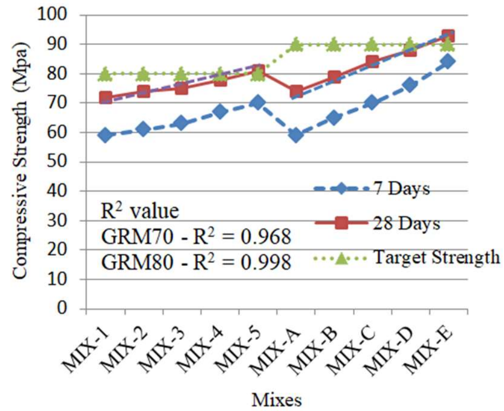

Figure 7: GRM70, GRM80 mix 7 and 28 days compressive strength compared to ordinary concrete target strength.

- ## Splitting Tensile Strength

For grades, Mix-5 and Mix-E, the splitting tensile strength (F_t) is as shown in fig 8. The F_t study involving multiple grades of specimens was conducted to analyze how they behavior for HRGC after for 28 days ambient curing. Based on the test findings, the F_t of HRGC at 28 days is 3.5 MPa for GRM70 and 3.7 MPa for GRM80. Whereas the theoretical F^1_t for both M70 and M80 conventional concrete is 3.329 MPa and 3.559 MPa, respectively. In comparison to the limiting value of F^1_t [19], the increase in F_t for 28 days is in range of 1.6% to 3.8% respectively. The correlation between F_t and F^1_t for both grades (i.e., GRM70 and GRM80) is approximately equal to one in fig 8.

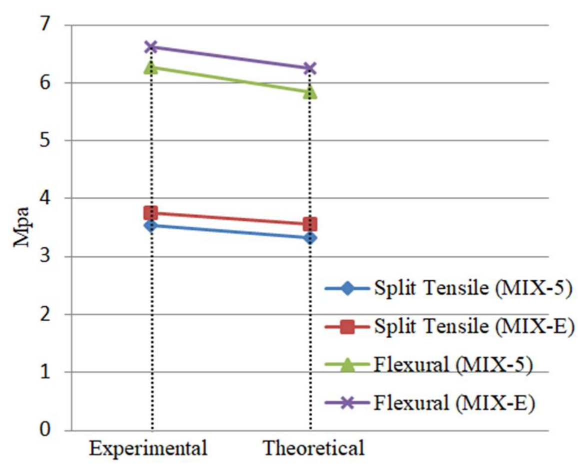

Figure 8: Split tensile strength and Flexural strength of HRGC compared with target strengths of conventional concrete.

- **Flexural Strength Test**

Fig 8 demonstrates the HRGC values for flexural strength after 28 days of natural curing for each grade. The flexural strength of GRM70 and GRM80 were 6.2 MPa and 6.6 MPa, respectively. This might be as a result of the addition of UFGGBS, which significantly increased the rate of flexural strength. Higher strength is the result of the UFGGBS's faster reaction than the FA's [20]. All grades of F_y based HRGC showed a range of around 0.3%

to 14% when compared to F^1_y concrete. The F^1_y of M70 and M80 grades is calculated according to Equation 3 and F^1_y is shown in fig 8, respectively. It was also observed that, the F_y of GRM70 and GRM80 is high compared to F^1y. fig 8 highlights the relation between target strengths of conventional concrete and achieved flexural strength of HRGC.

V. CONCLUSIONS

The article presents the initial research findings on the impact of 25% RCA on GPC for two related grades (GRM70 to GRM80) with different UFGGBS percentages. The activator liquids were Na_2SiO_3 and NaOH. Test specimens were tested for workability and mechanical properties after 7 and 28 days of ambient curing. The results were compared to ordinary concrete's limiting values.

The results of the experiment have led to the following conclusions.

- The GRM70 and GRM80 grades slump values have reduced as the percentage of UFGGBS content increases.
- The compressive strength has increased for both the GRM70 and GRM80 grades in proportion to a rise in UFGGBS content.
- At seven days of ambient curing for GRM70 and GRM80 grades, the amount of compressive strength achieved is 80–85%.
- The necessary compressive strength (i.e., GRM70 and GRM80) is attained at Mix-5 and Mix-E mixes after GGBS is 100% replaced with UFGGBS.
- Splitting tensile and flexural strengths in HRGC (GRM70 & GRM80) have shown promising results when compared to conventional concrete limiting values.
- This study shows that GRM70 and GRM80 GPC grades can be attained with UFGGBS and a 25% replacement of RCA without affecting any characteristics of existing sustainable concrete.

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