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Investigating Stress-Strain Characteristics in Geopolymer Concrete with Recycled Aggregate

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ABSTRACT: This paper focuses on the stress-strain behavior of 25% recycled coarse aggregate-based geopolymer concrete (RAGC). In this study, an 8-molarity concentration of NaOH and an alkaline liquid ratio of 2.5 was used. This study includes the stress-strain behavior along with the Modules of elasticity for the GRM20, GRM30, and GRM40 grades. Tests were carried out on 150 x 300 mm cylindrical RAGC specimens. The test results experimental to theoretical elastic modulus were in good correlation. Stress-strain relations of RAGC under ambient curing conditions were satisfactory.

KEYWORDS: Geopolymer concrete, Recycled coarse aggregate, Fly ash, GGBS, Stress-Strain.

I. INTRODUCTION

The use of recycled aggregate in geopolymer concrete has garnered significant attention in recent years due to its potential to enhance sustainability in the construction industry. Geopolymer concrete, a type of inorganic polymer composite, is produced by activating aluminosilicate materials with alkaline solutions, offering a promising alternative to traditional Portland cement concrete due to its lower carbon footprint (Davidovits, 1991; Van Deventer et al., 2010). Incorporating recycled aggregates, typically sourced from demolished concrete structures, further amplifies the environmental benefits by reducing landfill waste and the demand for natural aggregates (Kou and Poon, 2009). Recent studies have focused on the mechanical properties of recycled aggregate geopolymer concrete (RAGC), particularly its stress-strain behavior, which is critical for structural applications (Deb et al., 2014; Nath and Sarker, 2014). The unique microstructure of geopolymer binders can influence the interfacial transition zone between the recycled aggregates and the binder matrix, potentially affecting the overall mechanical performance (Sathonsaowaphak et al., 2009). This research aims to investigate the stress-strain characteristics of RAGC, evaluating factors such as the slump, modulus of elasticity, and failure modes under various loading conditions (Rajamane et al., 2012; Gunasekara et al., 2015). The outcomes of this study will contribute to a better understanding of the suitability of RAGC for structural use, addressing both mechanical performance and sustainability aspects (Zuhua et al., 2009; Zhang et al., 2010). By integrating recycled aggregates into geopolymer concrete, this research supports the development of greener construction materials that align with circular economy principles (Sarker et al., 2013; Gao et al., 2014).

II. RESEARCH SIGNIFICANCE

In analyzing the flexural behavior of reinforced concrete beams, the stress-strain characteristic plays a crucial role as a significant parameter. Stress-block parameters can be determined based on the characteristics of the stress block. Therefore, a comprehensive understanding of the complete stress-strain curves of concrete is essential from a structural perspective. However, the existing research on the stress-strain behavior of geopolymer concrete has not yet reached a definitive conclusion. This study is designed to address these gaps by introducing an analytical model for the stress-strain curve and validating its accuracy through rigorous testing and validation processes.

A Materials

Alkaline binders used: For this experiment, dry fly ash from the Ramagundam thermal project was utilized. One batch of fly ash was purchased for the length of this study. Steel produces GGBS as a by-product. This experimental effort used GGBS, which was created and manufactured in as per IS: 12089-1987. The chemical and physical properties of the fly ash and GGBS are listed in Tables 1 and 2.

Table 1. Chemical composition of Fly ash and GGBS

Sr. No	***Description***	***Fly Ash***	***GGBS***
1	Loss on ignition	1.91	Nil
2	Silicon dioxide (SiO_2)	50.14	34.81
3	Alumina (Al_2O_3)	35.18	17.92
4	Iron (Fe_2O_3)	4.21	0.66
5	Calcium (CaO)	2.60	37.63
6	Magnesium (MgO)	Nil	7.80
7	Titanium dioxide (TiO_2)	1.93	-
8	Sodium (Na_2O)	1.33	-
9	Sulphur trioxide (SO_3)	2.70	0.2

Table 2. Physical composition of Fly ash and GGBS

Sr. No	***Description***	***Fly Ash***	***GGBS***
1	Specific gravity	2.3	3.15
2	Fineness (m^2/kg)	370	420
3	Lime Reactivity	4.8	-
4	Soundness by Autoclave Test	0.035	-

Aggregate: Natural sand from the local sources has been used. Table 3 display the test results for various properties on fine aggregate. According to IS 383:2016, zone II status for the sand was verified. The study utilized 20 mm coarse aggregate which is locally accessible coarse aggregates. Table 4 displays the test results for various natural coarse aggregate (NCA) and Recycled coarse aggregate (RCA) qualities. Coarse aggregates obtained from the processing of demolished concrete previously utilized in laboratory settings are known as recycled aggregates. combined aggregate (Coarse and Fine aggregate) taken as 70% of total mass concrete. In total coarse aggregate Natural coarse aggregate 75% and Recycled coarse aggregate of 25%. Figure 1. Illustrates NCA and RCA.

Figure 1. NCA, RCA

Table 3. Properties of Fine Aggregate

Sr. No	***Description***	***Values***
1	Specific gravity	2.67
2	Water Absorption (%)	2.63
3	Bulk Density (kg/m^3)	
	a) Loose	1533
	b) Compacted	1700
4	Grading	Zone – II

Table 4. Physical Properties of NCA and RCA

Sr. No	*Particulars*	*Values*	
		Natural coarse aggregates (NCA)	*Recycled coarse aggregates (RCA)*
1	Specific gravity	2.76	2.63
2	Bulking density (kN/m^3)	1514	1353
3	Fineness(Sieving method)	7.21	7.43
4	Water absorption (%)	1.90	2.70
5	Shape	Round	Round
6	Crushing value (%)	20.52	22.73
7	Impact value (%)	17.64	20.39

Alkaline activators: The alkaline activator solutions (AAS) for all mixes developed in this project were made by mixing sodium hydroxide and sodium silicate. Based on previous research, the sodium silicate-to-sodium hydroxide ratio was set at 2.5, alkaline activator to binder (Fly ash + GGBS) ratio was kept constant 0.5. The material was received from a local supplier. A liter of 8M NaOH solution contained 8x40 = 320 grams of NaOH solids (in flake form). The physical and chemical properties are listed in Tables 5 and 6. Table 7 summarizes physical and chemical properties of Sodium Silicate (Na2SiO3). The mixture was prepared 24 hours before adding to the dry concrete.

Table 5. Physical Properties of Sodium Hydroxide (NaOH)

Sr. No	*Description*	*Value*
1	Appearance	Flakes
2	Colour	White
3	Specific gravity	1.47

Table 6. Chemical Properties of Sodium Hydroxide (NaOH)

Sr. No	*Description*	*Mass (%)*
1	Assay	97
2	Carbonate (Na_2CO_3)	2.80
3	Chloride (CL)	0.02
4	Sulphate (SO_2)	0.05
5	Silicates	0.002
6	Led (P_b)	0.001
7	Potassium (K)	0.08
8	Zinc (Z_n)	0.01
9	Iron (F_e)	0.002

Table 7. Physical and Chemical Properties of Sodium Silicate (Na2SiO3)

Sr. No	*Description*	*Value*
1	Appearance	Liquid (Gel)
2	Colour	Color Less
3	Specific Gravity	1.60
4	Na_2O	15.00%
5	SiO_2	30.40%
6	H_2O	54.60%

III. EXPERIMENTAL PROGRAMMEPAGE

In the present investigation recycled coarse aggregate based geopolymer concrete (RAGC) stress-strain and modules of elasticity properties are investigated for three different grades of concrete viz., GRM20, GRM30 and GRM40. Based on the previous studies, the percentage replacement of GGBS 9.5%, 21%, and 28%, were fixed and considered for the above concrete grades respectively. The workability was measured by means of conventional slump test. Immediately after mixing, the fresh concrete was transferred into moulds. For each grade 3 No's standard cylinders (150mm diameter & 300mm long) have been considered in the present investigation. After 24 hours specimens were demoulded and kept under air dry at 27^0C in a laboratory until the day of testing i.e., at 28 days. The cylinders are tested in a 1000 kN universal testing machine as per the provision laid in IS 516-1999. Loading and strain measurements were carefully controlled. Readings were obtained up to the failure state. The mix proportions for GRM20, GRM30, and GRM40 are shown in Table 8. The following mix proportions are based on the mix design guidelines proposed by B.V. Rangan, Curtain University, Australia. Finally, a standard design mix has been adopted in the present experimental work.

Table 8. Mix proportions

Sr. No	*Grades*	*Fly Ash kg/m³*	*GGBS kg/m³*	*FA kg/m³*	*N.C.A kg/m³*	*R.C.A kg/m³*	*Alkaline Liquid kg/m³*	*Extra water kg/m³*
1	GRM20	434.4	45.6	740.6	686.5	228.8	240	18
2	GRM30	379.2	100.8	749.7	696.1	231.6	240	18
3	GRM40	345.6	134.4	755.2	700.2	233.3	240	18

A. *Preparation of RAGC Specimens*

The concrete ingredients were weight batched according to the mix proportions given in Table 8. Initially, the coarse and fine aggregates were dry mixed in a concrete mixer for 3 minutes. Then the binder (fly ash and GGBS) was added to the aggregates and mixed for about 3 minutes; the prepared alkaline solution was added. The mixing continued for about 4 minutes until a homogeneous mixture was obtained. Before casting the specimens, the workability of the RAGC in terms of slump was measured. Then 3 cylinders were cast simultaneously. The specimens were demoulded after one day and cured under direct sunlight until the testing day (28 days). The casting and curing of the specimens is shown in Figure 2. The mix proportions and slump values are given in Table 9.

Figure 2. Casted cylinder specimens

B. *Testing of RAGC Specimen*

The modulus of elasticity of RAGC was determined as the initial tangent modulus measured at a stress level of approximately 40% of the average compressive strength of concrete cylinders. The table displays the experimental modulus of elasticity values. As expected, the modulus of elasticity increases with increasing compressive strength. The tests were conducted in accordance with IS: 516-1999. All of the prepared cylinder specimens were connected to an extensometer to measure any deformations at the specified loads. The tests were carried out on a Universal testing machine with a 1000 kN capacity. The test setup is depicted in Figure 2. The modulus of elasticity of the RAGC cylindrical specimen was determined.

Figure 3. Test setup.

Table 9. Test results of slump

Sr. No	*Grades*	*GGBS (%)*	*Slump(mm)*
1	GRM20	9.5	230
2	GRM30	21.0	126
3	GRM40	28.0	90

Table 10. Modules of elasticity of RAGC grades.

Sr. No	*Grade of Concrete*	*Experimental (GPa)*	*Theoretical (GPa)*
1	GRM20	24.46	22.36
2	GRM30	29.32	27.38
3	GRM40	35.39	31.62

Table 11. Experimental Stress Strain values for GRM20 Grade

Sr. No	*Load (kN)*	*Stress, 'σ' (N/mm^2)*	*Strain (ϵ x 10^{-4})*
1	0	0.00	0.00
2	5	1.41	0.63
3	10	2.82	1.25
4	15	4.23	1.88
5	20	5.64	2.50
6	25	7.05	3.13
7	30	8.74	3.88
8	35	10.15	4.50
9	40	11.56	5.47
10	45	12.97	6.97
11	49	14.38	8.87
12	54	15.79	11.30
13	59	17.20	14.39
14	64	18.61	18.33
15	69	20.02	23.34
16	74	21.43	29.72

Table 12. Experimental Stress Strain values for GRM30 Grade

Sr. No	*Load (kN)*	*Stress, 'σ' (N/mm^2)*	*Strain (ϵ x 10^{-4})*
1	0	0.00	0.00
2	25	1.41	0.53
3	49	2.82	1.06
4	74	4.23	1.59
5	98	5.64	2.12
6	123	7.05	2.65
7	152	8.74	3.28
8	177	10.15	3.81
9	201	11.56	4.34
10	226	12.97	4.87
11	250	14.38	5.40
12	275	15.79	6.19
13	299	17.20	7.31
14	324	18.61	8.64

15	348	20.02	10.20
16	373	21.43	12.05
17	402	23.12	14.72
18	427	24.53	17.39
19	451	25.94	20.54
20	476	27.35	24.26
21	500	28.76	28.66
22	510	29.33	30.63

Table 13. Experimental Stress Strain values for GRM40 Grade

Sr. No	***Load (kN)***	***Stress, 'σ' (N/mm^2)***	***Strain (ϵ x 10^{-4})***
1	0	0.00	0.00
2	25	1.41	0.48
3	49	2.82	0.96
4	74	4.23	1.44
5	98	5.64	1.92
6	123	7.05	2.39
7	152	8.74	2.97
8	177	10.15	3.45
9	201	11.56	3.93
10	226	12.97	4.41
11	250	14.38	4.89
12	275	15.79	5.36
13	299	17.20	5.84
14	324	18.61	6.32
15	348	20.02	6.92
16	373	21.43	7.80
17	402	23.12	8.99
18	427	24.53	10.12
19	451	25.94	11.39
20	476	27.35	12.83
21	500	28.76	14.44
22	525	30.17	16.26
23	549	31.58	18.30
24	574	32.99	20.61
25	603	34.69	23.76
26	623	35.81	26.12
27	652	37.51	30.11
28	667	38.35	32.33

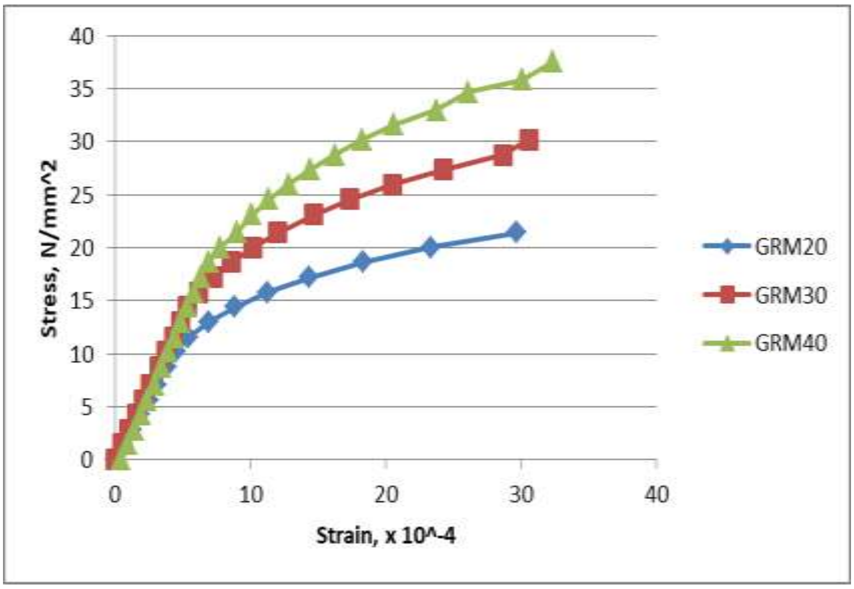

Figure 4. Stress - Strain curve of RAGC

IV. RESULTS AND DISCUSSION

A. *Workability of RAGC*

Table 9 shows the workability of RAGC concrete mixtures and demonstrates that GGBS content is indirectly proportional to workability. Higher GGBS content may promote faster polymerization, resulting in decreased workability.

B. *Modulus of elasticity*

The stress-strain curve for RAGC specimens evaluated under compression, while Table 10, displays the modulus of elasticity values. GRM20 is more ductile than GRM30 or GRM40. The GRM30 and GRM40 showed similar stress-strain behavior to some extent. The relationship specified in Indian Standard IS 456-2000 as 5000√fck of the characteristic compressive strength of concrete (fck) is consistent with values typically associated with conventional concrete mixes. The determined value is, approximately 2% greater than that of conventional concrete. This increase in value could be attributed to the GGBS content. Previous studies have noted similar results with increase of GGBS.

C. *Stress Strain*

The behavior of the cylinders under axial loads was similar to that of conventional concrete. RAGC cylinders fail in axial splitting parallel to the applied load. Also, the crack patterns of RAGC cylinders was observed to be similar to conventional concrete. Cracks are initiated through the aggregate by forming smoother cracked surfaces due to greater cement-matrix strength. The experimental values of stress and corresponding strains for each grade of concrete are shown in Table11, Table 12 and Table 13 for RAGC grades GRM20, GRM30 and GRM40.

V. CONCLUSIONS

1. Increasing the GGBS percentage in an RAGC mix leads to a reduction in its workability.
2. Substituting 25% of RCA with NCA is deemed appropriate with minimal variation compared to theoretical regular concrete.
3. The modulus of elasticity ranges from 24.46 GPa to 35.39 GPa for concrete grades GRM20 to GRM40, respectively. These values are slightly better, around 2% to 2.5%, than those of conventional concrete, indicating a negligible disparity.
4. As the compressive strength of concrete rises, the maximum strain diminishes, causing a transition from ductile to brittle failure in post-peak behavior.

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