Mathematical Statistician and Engineering Applications
ISSN: 2094-0343
DOI: https://doi.org/10.17762/msea.v70i2.2182

A Study on Design and Development of Geopolymer Concrete

Mayank Kumar
Department of Civil Engineering, Graphic Era Hill University, Dehradun, Uttarakhand, India 248002

Article Info
Page Number: 1121-1135
Publication Issue:
Vol. 70 No. 2 (2021)

Article History
Article Received: 18 October 2021
Revised: 20 November 2021
Accepted: 22 December 2021

Abstract: Ordinary Portland Cement (OPC), the major element of concrete, has a significant effect on the environment and is one of the most energy-intensive building materials. Being a relatively new building material, geopolymer concrete is one of the technologies that scientists have spent the better part of the previous two decades trying to replace with OPC. It has also been shown that geopolymer can replace OPC as a concrete binder. Further research into geopolymer concrete's characteristics utilizing alternative waste materials like RHA and GGBS, which are high in aluminous or silicate content, is required.

Keywords: Geopolymer, concrete, silicates, ordinary portland cement.

1.Introduction

The present problems are acknowledged in an essay titled "Sustainable Development and Concrete Technology" published in Concrete International. ‘It is estimated that OPC contributes around 1.35 billion tons every year to global greenhouse gas emissions, or about 7% of the total GHG emissions to the earth's atmosphere. Cement production generates a lot of heat, which leads to the emission of carbon dioxide gas. Around half of the CO2 is emitted during the calcination process, when calcium carbonate is converted to calcium oxide, and the other half is released during the creation of the clinker, the main material used to make the cement, at temperatures of 1400°C. Around five percent of worldwide CO2 emissions come from cement manufacturing alone, and eighteen percent came from the G20 in 2015. The production of one kilo of cement results in around 0.81 kilos of carbon dioxide being released into the atmosphere each year, as reported by the International Energy Agency. Cement manufacturing results in millions of tons of Cement Kiln Dust (CKD), a respiratory hazard. [1]

Likelihood of an increase in average surface temperatures as well as its detrimental influence on sea levels is heightened by the ongoing release of GHG from the burning of fossil fuels and the dumping of waste materials into the earth. As a result, research into an eco-friendly building material is urgently required at the present time. By substituting industrial by-products like fly ash (FA), rice husk ash (RHA), and crushed granulated blast furnace slag for some of the Portland cement in the mix, scientists have been working to create concrete that is less harmful to the environment (GGBS). Consider the environmental effects and, by extension, the "global warming factor," of producing portland cement using a lifecycle analysis (LCA). [2-3]

When natural pozzolans are used in lieu of OPC, the product's "global warming factor" is reduced by an amount proportionate to the quantity of natural pozzolans used. That the majority of the available literature focuses on the existing state of cement manufacturing and the harm it does to the environment has been made abundantly obvious. The next phase in this research should be on figuring out how to either stop this damage from happening or provide an alternate binder to OPC that can be used to make concrete. Several academics believe that despite continued research into alternate binders, the usage of regular Portland cement in concrete will not decrease. [4-5]

Nevertheless, findings over the last three decades have disproved this theory. So, looking into the other binder material to make the concrete would be a sustainable choice. The alternative material must also have desirable properties such as cheap manufacturing cost, simple manipulation, the ability to be shaped into any desired form, attainment of acceptable strength in any range from very low to very high, and long service life. In addition, it has to sub in for the concrete's binder with something that leaves a less carbon imprint.[6-7]

From this, it should be abundantly clear that the building material of the future should be readily made, long-lasting, robust, and most importantly, environmentally benign. We may lessen our environmental impact by using fewer raw materials and more waste products from other industries in our building projects. Fly ash, granulated blast furnace slag, silica fume, and rice-husk ash are all byproducts that, if not disposed of correctly, constitute a harm to human health and the environment. Because of its granulometric and mineral content, shape, and filtration capabilities, deposition of these materials in storage locations might have a detrimental effect on water and soil. [8-9]

As a result, ensuring their proper disposal remains a top priority. Scientists have experimented with using waste materials with cementitious qualities to substitute cement in several applications. Nevertheless, substituting merely some of the cement in concrete with other materials is only marginally more effective than using no cement at all in reducing CO2 gas emissions.[10]

2.Material and Methods

Following the tried-and-true procedures developed for regular concrete, many researchers developed the GPC mix design approach. In traditional concrete, OPC is one of the key ingredients responsible for binding the aggregates together and providing the necessary strength and workability via the formation of hydration products such CSH, ettringite, and other silicates. The ratio of water to cement determines the concrete's strength and workability. Although aggregates serve the same purpose in geopolymer concrete as they do in traditional concrete, the GPC's other components have not been associated with the hydration process.

The study's conclusions were not applicable to conventional curing at room temperature, and the workability bands presented offered no guidance on how to calculate slump. For usage with pozzolanic materials high in alumino-silicate like FA, RHA, and GGBS, a novel lime-rich substance called alccofine has been presented; this material provided the synergistic effects of hydration and polymerization inside the matrix. Initial experiments were conducted with varying amounts of alccofine in the matrix, and thereafter, a constant proportion of 10% of alumino silicate material was determined for use in creating the design aids.

In order to achieve a desired compressive strength and workability, it was necessary to build design tools that could calculate the ideal mix proportions in terms of the quantity of alumino-silicate material, molarity of NaOH, curing temperature, and age of curing. Finally, the examples have been used to further verify the suggested technique by demonstrating its strength and practicality. X-ray diffraction and scanning electron microscopy analyses have also been conducted on the data.

Workability

The slump cone test was used to determine the workability of GPC mixtures. Slump-less concrete was created from new mixes of geopolymer concrete, and the mixes were reported to be especially harsh when GPC was made with unprocessed fly ash. It was also noted that adding 2% Naphthalene Sulphonate-based superplasticizer greatly enhanced the workability of fresh geopolymer mix. In the absence of alccofine, it was found that the workability of geopolymer concrete was very poor.

Compressive Strength

Shows the impact that changing the percentage of fly ash has on the compressive strength of GPC made with processed fly ash. By increasing the fly ash content from 350 kg to 370 kg and 400 kg, the compressive strength of GPC made with processed fly ash improved from 5 MPa to 7 MPa and 10 MPa, 7.5 MPa to 10 MPa and 16 MPa, and 12 MPa to 16 MPa and 25 MPa in the case of ambient curing. This means that the processed fly ash geopolymer concrete has the potential to meet the minimal compressive strength standards for usage in generic building applications.

3.Results

- **Concrete Made From Geopolymers: Its Applicability**

Concrete Made From Fly Ash

Workability findings for mixtures M1FAGC to M9FAGC are provided in Table in terms of slump value (mm) & compaction factor.

Table 1: Differences in slump and compaction factors for fly ash-based GPC

Mix Designation	Fly ash [Kg/m3] / Molarity	Slump (mm)	Compaction factor
M1FAGC	350 / 8M	60	0.79
M2FAGC	375 / 8M	110	0.87
M3FAGC	400 / 8M	160	0.95
M4FAGC	350 / 12M	55	0.76

M5FAGC	375 / 12M	105	0.85
M6FAGC	400 / 12M	155	0.93
M7FAGC	350 / 16M	50	0.75
M8FAGC	375 / 16M	100	0.82
M9FAGC	400 / 16M	140	0.90

At 350 kg/m3 of fly ash, GPC slumped by a noticeable 60 mm (M1FAGC). Also, raising the fly ash concentration from 350 to 370 (M2FAGC) or 400 (M3FAGC) kg/m3 enhanced the slump value from 60 mm to 110 mm & 160 mm, respectively. Compaction factor values for the same combinations showed a similar pattern. Slump may have increased because of the finer alccofine and superplasticizer content brought about by the addition of fly ash.

The impact of NaOH concentration on the ductility of the geopolymer concrete is further investigated by contrasting M3, M6, and M9 FAGC mixes. The slump of Mix M9FAGC was marginally lower (140 mm) than that of Mix M6FAGC (155 mm), whereas the slump of Mix M3FAGC was much greater (160 mm) than that of Mix M6FAGC (155 mm) as well as the slump collapse. The values of the compaction factor for the identical mixtures followed the same pattern. The aforementioned considerations make it abundantly evident that the molarity of NaOH influences the workability. The slump or compaction factors both went down when molarity was increased. Less workable geopolymer concrete may be due to the use of very viscous sodium hydroxide with sodium silicate solution, which rendered the geopolymer concrete more cohesive & rigid than traditional concrete.

Concrete Made From Recycled Rice Husk Ash

Workability findings for mixes M1RHAGC to M9RHAGC are provided in Table, broken down by slump value (mm) or compaction factor.

Table 2: There is a wide range of slump and compaction factors in GPC made from rice husk ash.

Mix Designation	**Rice husk ash [Kg/m3] / Molarity**	**Slump (mm)**	**Compaction factor**
M1RHAGC	350 / 8M	50	0.74
M2RHAGC	375 / 8M	95	0.80
M3RHAGC	400 / 8M	145	0.88
M4RHAGC	350 / 12M	45	0.71
M5RHAGC	375 / 12M	85	0.76

M6RHAGC	400 / 12M	135	0.85
M7RHAGC	350 / 16M	40	0.67
M8RHAGC	375 / 16M	75	0.70
M9RHAGC	400 / 16M	120	0.80

Slump patterns in RHA based GPC were comparable to those found with fly ash based GPC, although with smaller values (from 50 mm to 95 mm and 145 mm, respectively) when comparing M1RHAGC to M2RHAGC and M3RHAGC. Slump was found to be lower in the rice husk ash based geopolymer concrete than in the fly ash based geopolymer concrete . NaOH molarity had the same effect on the fresh qualities of the RHA based GPC as it did on the FA based GPC, as seen by Mix M9RHAGC having the lowest slump value of all the mixes. As was previously addressed for fly ash, alccofine and superplasticizer were shown to increase the workability of the RHA-based GPC.

Geopolymer Concrete Made From GGBS

Workability findings for mixtures M1GGBSGC to M9GGBSGC were shown in Table in terms of slump value (mm) or compaction factor.

Table 3: Differential slumping and compaction in GGBS-based GPC

Mix Designation	**GGBS [Kg/m3] / Molarity**	**Slump (mm)**	**Compaction factor**
M1GGBSGC	350 / 8M	50	0.82
M2GGBSGC	375 / 8M	85	0.89
M3GGBSGC	400 / 8M	140	0.96
M4GGBSGC	350 / 12M	45	0.81
M5GGBSGC	375 / 12M	75	0.87
M6GGBSGC	400 / 12M	125	0.95
M7GGBSGC	350 / 16M	40	0.77
M8GGBSGC	375 / 16M	70	0.86
M9GGBSGC	400 / 16M	110	0.93

The slump and compaction factor achieved in GGBS-based GPC are comparable to those obtained in RHA- and FA-based GPC. Nonetheless, the values were reduced. Slump values were lower for GGBS than for FA- and RHA-based geopolymer concrete, which may be attributable to GGBS's higher SiO2 and CaO content. In comparison to FA and RHA, GGBS was both more precise and finer.

In conclusion, the workability findings from this research show that geopolymer concrete made using FA/RHA/GGBS as a binder material is workable when made with the alccofine and superplasticiser.

- **Geopolymer Concrete's Structural Properties**

Concrete Made From Fly Ash

Fly ash based geopolymer concrete's compressive, split tensile, and flexural strengths, as well as the consequences of varying parameters, have been studied.

Compressive strength was investigated as a function of NaOH molarities, temperatures, and binder material amount when alccofine was added to geopolymer concrete. After 3, 7, and 28 days, the material's compressive strength was evaluated. Curing temperatures of 27, 60, and 90 degrees Celsius were used on the specimens, respectively. Table displays, for each formula, the average compressive strength of five specimens.

Table 4: Compressive strength of FA based GPC

Mixture	**Average compressive strength (MPa)**		
	3 days	**7 days**	**28 days**
M1FAGC	7.15	12.15	22.09
M2FAGC	8.05	14.17	25.12
M3FAGC	9.10	15.20	27.15
M4FAGC	8.04	14.06	30.05
M5FAGC	10.19	17.11	35.10
M6FAGC	12.10	20.10	38.17
M7FAGC	10.11	19.06	33.12
M8FAGC	12.05	21.05	38.18
M9FAGC	15.09	25.10	41.00
M10FAGC	14.18	23.63	26.25
M11FAGC	15.80	26.33	29.25
M12FAGC	17.82	29.70	33.02
M13FAGC	19.85	33.08	36.75
M14FAGC	21.06	35.10	39.00

M15FAGC	22.28	37.13	41.25
M16FAGC	26.33	43.88	48.75
M17FAGC	27.95	46.58	51.75
M18FAGC	29.57	49.28	54.75
M19FAGC	19.22	32.15	35.20
M20FAGC	21.65	36.35	39.15
M21FAGC	23.43	39.17	44.08
M22FAGC	28.26	47.05	49.10
M23FAGC	29.43	49.12	52.05
M24FAGC	31.20	52.06	55.11
M25FAGC	37.22	62.17	65.12
M26FAGC	39.05	65.10	69.11
M27FAGC	40.80	68.08	73.00

Compressive strength at 3, 7, and 28 days at varying temperatures and binder contents is tabulated.

Rice Husk Ash Based Geopolymer Concrete

Here, we've spoken about how many factors might affect the structural qualities of geopolymer concrete made from rice husk ash.

The effects of NaOH molarities, temperatures, and the amount of binder material with the addition of alccofine into RHA based geopolymer concrete on compressive strength were investigated; findings were found to be within the same range as those obtained for FA based GPC. After 3, 7, and 28 days of curing at 27 °C, 60 °C, and 90 °C, the specimens' compressive strength was determined. Compressive strength was measured on five different samples and is shown in Table.

Table 5: Strength in compression of RHA-based GPC

Mixture	**Average compressive strength (MPa)**		
	3 days	**7 days**	**28 days**
M1RHAGC	5.02	10.15	20.01
M2RHAGC	6.10	12.23	23.08
M3RHAGC	7.11	15.04	25.22
M4RHAGC	6.09	12.17	28.34
M5RHAGC	8.20	15.35	33.29

M6RHAGC	10.07	19.20	36.17
M7RHAGC	8.25	14.33	31.60
M8RHAGC	10.23	18.15	36.05
M9RHAGC	13.02	23.06	39.00
M10RHAGC	12.18	21.63	24.25
M11RHAGC	13.80	24.33	27.25
M12RHAGC	15.11	27.76	31.00
M13RHAGC	17.85	31.08	34.75
M14RHAGC	19.06	33.10	37.00
M15RHAGC	20.28	35.13	39.25
M16RHAGC	24.33	41.88	46.75
M17RHAGC	25.95	44.58	49.75
M18RHAGC	27.57	47.28	52.75
M19RHAGC	17.20	30.05	33.12
M20RHAGC	19.62	34.18	37.10
M21RHAGC	21.41	37.02	42.11
M22RHAGC	26.22	45.14	47.15
M23RHAGC	27.44	47.19	50.16
M24RHAGC	29.27	50.08	53.12
M25RHAGC	35.23	60.20	63.04
M26RHAGC	37.08	63.19	67.03
M27RHAGC	38.83	66.13	71.00

The correlation between 60oC and 90oC cured samples is shown in Table. Compressive strength was shown to grow with temperature, and this trend held true across increases in molarity, curing time, and RHA concentration. The only real difference was the percentage rise in compressive strength; while the typical 7-day strength for conventional concrete is around 65-70% of the 28-day strength, the 3-day compressive strength of heat healed geopolymer specimens was found to be 51-53%, and the 7-day compressive strength was found to be 92-93%.

The Geopolymer Concrete Made With GGBS

Compressive, split tensile, and flexural strengths, as well as other structural characteristics, of ground granulated slag from blast furnaces derived geopolymer concrete are examined, along with the implications of various factors.

It is the most widely used and reliable indication of concrete's structural quality, and it is also associated with the material's other qualities. The effects of NaOH molarities, temperatures, and binder material amount with the addition of alccofine on the compressive strength of GGBS based geopolymer concrete were investigated, as was the case with FA and RHA based GPC. Compressive strength was measured by testing five replicates of each mixture and the results are shown in Table.

Table 6: GGBS-based GPC compressive strength

Mixture	**Average compressive strength (MPa)**		
	3 days	**7 days**	**28 days**
M1GGBSGC	10.10	16.55	19.50
M2GGBSGC	17.25	21.65	27.20
M3GGBSGC	23.85	29.45	33.50
M4GGBSGC	19.88	26.05	30.67
M5GGBSGC	28.23	33.20	38.31
M6GGBSGC	34.55	40.15	45.25
M7GGBSGC	29.65	35.55	41.84
M8GGBSGC	39.20	44.75	49.42
M9GGBSGC	45.25	50.85	57.00
M10GGBSGC	31.55	38.00	40.95
M11GGBSGC	38.70	43.10	48.65
M12GGBSGC	45.30	50.90	54.95
M13GGBSGC	41.73	47.90	52.52
M14GGBSGC	50.08	55.05	60.16
M15GGBSGC	56.40	62.00	67.10
M16GGBSGC	51.43	57.33	63.62
M17GGBSGC	60.98	66.53	71.20
M18GGBSGC	67.03	72.63	78.78
M19GGBSGC	35.80	42.25	45.20

M20GGBSGC	42.95	47.35	52.90
M21GGBSGC	49.55	55.15	59.20
M22GGBSGC	45.58	51.75	56.37
M23GGBSGC	53.93	58.90	64.01
M24GGBSGC	60.25	65.85	70.95
M25GGBSGC	55.35	61.25	67.54
M26GGBSGC	64.90	70.45	75.12
M27GGBSGC	70.95	76.55	82.70

- **Analysis**

Using the experimental data provided in Tables for the inquiry, AF-GPC-Graphs (Alccofine, Geopolymer-Graphs) were generated, and these graphs form the basis of the established design mix method. At a given molarity and curing setting, these graphs originally represented the connection between raw material quantity and compressive strength. The suggested AF-GPC- Graphs were created using the tabulated findings of the mixtures' compressive strengths. In addition, AF-GPC plots for compressive strength at 3, 7, and 28 days have been presented. Table provides workability bands for varying amounts of raw materials, allowing for a more precise mix selection. The fresh GPC's malleability was evaluated with the use of the slump test. According to the compaction condition, slump values were categorized using clause 7 of IS 456:2000 . GPC was rated as either "very highly workable," "very workable," "medium workable," or "low workable" based on the range of slump values it exhibited. British standards and the American concrete institute have both established workability for similar reasons. The observed slump values for the various mixtures are plotted and shown. Also, the quantity of raw material (fly ash, rice husk ash, and crushed granulated blast furnace slag) has been connected to the aforementioned criteria, as indicated in Table.

Table 7: Workability bands used for geopolymer concrete

Raw material [RM] Kg/cum	**RM<350**	**350< RM<375**	**375< RM<400**	**RM>400**
Degree of workability/Slump	Less [<75]	Medium [>75 but <100]	High [>100 but <150]	Very High [>150]

- **Gpc Elastic Modulus**

The modulus of elasticity was determined by using all of the GPC mixtures used for the development of the design aids and the research of the stress strain behavior. These proportions, which included alccofine in addition to FA, RHA, and GGBS as independent binders, encompassed compressive strengths from 15MPa to 82MPa. After 28 days of curing, the Young's modulus of geopolymer concrete was calculated using secant modulus measurements taken at a stress level equal to 33% of the average compressive strength. Moreover, all tests were conducted according Indian regulations. The values of Young's modulus for each specimen are tabulated. Compressive strength and modulus of elasticity both rose as a result of tweaking the binder's quantum, NaOH concentration, and curing temperature. Heat cured GPC specimens made with FA, RHA, and GGBS with alccofine have a Young's modulus of 0.215 x 105 MPa to 0.381 x 105 MPa, whereas ambient cured specimens have a modulus of 0.157 x 105 MPa to 0.313 x 105 MPa.

Both the American Concrete Institute (ACI) code as well as the Indian Standard (IS) provide the elastic modulus for conventional concrete in the form of a cylinder (Eq.) and a cube (Eq.) as a direct consequence of the parameters compressive strength.

$$E_c = 4733 \times \sqrt{f_c} \quad (5.4)$$

$$E_c = 5000 \times \sqrt{f_c} \quad (5.5)$$

Where, E_C = *Elastic modulus and* f_C *= Compressive strength*

Table 8: FA-based GPC elastic modulus, also known as Young's modulus (Em).

Mixture	**Em, MPa (x 105)**	**Ec, MPa (x 105) As Per IS**	**Em, MPa (x 105)**	**Ec, MPa (x 105) As Per ACI**
M1FAGC	0.188	0.235	0.193	0.201
M2FAGC	0.205	0.251	0.197	0.212
M3FAGC	0.215	0.261	0.220	0.232
M4FAGC	0.227	0.274	0.231	0.246
M5FAGC	0.249	0.296	0.268	0.276
M6FAGC	0.259	0.309	0.259	0.288
M7FAGC	0.245	0.288	0.233	0.259
M8FAGC	0.266	0.309	0.254	0.276
M9FAGC	0.275	0.320	0.258	0.284

M19FAGC	0.237	0.297	0.266	0.280
M20FAGC	0.257	0.313	0.271	0.288
M21FAGC	0.274	0.332	0.294	0.303
M22FAGC	0.291	0.350	0.289	0.317
M23FAGC	0.303	0.361	0.298	0.331
M24FAGC	0.312	0.371	0.338	0.345
M25FAGC	0.343	0.403	0.366	0.382
M26FAGC	0.357	0.416	0.377	0.393
M27FAGC	0.367	0.427	0.384	0.404

Table 9: Young's modulus (Em) is the elasticity modulus used in RHA-based GPC.

Mixture	**Em, MPa (x 105)**	**Ec, MPa (x 105) As Per IS**	**Em, MPa (x 105)**	**Ec, MPa (x 105) As Per ACI**
M1RHAGC	0.179	0.224	0.182	0.189
M2RHAGC	0.192	0.240	0.192	0.206
M3RHAGC	0.201	0.251	0.206	0.217
M4RHAGC	0.221	0.266	0.218	0.232
M5RHAGC	0.242	0.288	0.247	0.255
M6RHAGC	0.253	0.301	0.241	0.268
M7RHAGC	0.239	0.281	0.221	0.246
M8RHAGC	0.258	0.300	0.246	0.268
M9RHAGC	0.269	0.312	0.255	0.280
M19RHAGC	0.230	0.288	0.242	0.255
M20RHAGC	0.253	0.305	0.256	0.272
M21RHAGC	0.268	0.324	0.283	0.292

M22RHAGC	0.282	0.343	0.282	0.310
M23RHAGC	0.294	0.354	0.289	0.321
M24RHAGC	0.306	0.364	0.325	0.331
M25RHAGC	0.337	0.397	0.349	0.364
M26RHAGC	0.348	0.409	0.361	0.376
M27RHAGC	0.358	0.421	0.368	0.387

Table 10: Young's modulus of elasticity (Em) of GGBS-based GPC

Mixture	**Em, MPa (x 105)**	**Ec, MPa (x 105)** **As Per IS**	**Em, MPa (x 105)**	**Ec, MPa (x 105)** **As Per ACI**
M1GGBSGC	0.179	0.221	0.179	0.186
M2GGBSGC	0.211	0.261	0.212	0.228
M3GGBSGC	0.237	0.289	0.244	0.257
M4GGBSGC	0.227	0.277	0.230	0.244
M5GGBSGC	0.263	0.309	0.269	0.277
M6GGBSGC	0.286	0.336	0.274	0.304
M7GGBSGC	0.275	0.323	0.262	0.291
M8GGBSGC	0.302	0.351	0.293	0.319
M9GGBSGC	0.325	0.377	0.314	0.345
M19GGBSGC	0.269	0.336	0.289	0.304
M20GGBSGC	0.302	0.364	0.311	0.331
M21GGBSGC	0.327	0.385	0.341	0.352
M22GGBSGC	0.308	0.375	0.312	0.343
M23GGBSGC	0.332	0.400	0.330	0.367
M24GGBSGC	0.354	0.421	0.380	0.387

M25GGBSGC	0.345	0.411	0.362	0.377
M26GGBSGC	0.368	0.433	0.383	0.399
M27GGBSGC	0.391	0.455	0.399	0.420

Hence, the elastic modulus of geopolymer concrete is overestimated by the formulae obtained for traditional concrete in ACI and IS. In addition, the quality or stiffness of the aggregates, the geometry of the matrix, etc., might account for the lower Young's modulus values seen for GPC. Geopolymer concrete, like regular concrete, may be bent and stretched elastically. Since the measured values of the elastic modulus may prevent the excessive deformation, geopolymer concrete can be effectively utilized in compression structural components like columns. Prestress loss in the form of elastic shortening is mitigated by a material's greater elastic modulus, leading to optimism for its use in the prestressed geopolymer concrete industry.

4.Conclusion

Other than water, concrete is the most often utilized material in construction worldwide. OPC is an essential component, but its manufacturing has a negative environmental effect because to the energy-intensive processes involved and the carbon dioxide emissions that result (CO2). Compressive, split tensile, and flexural strengths, as well as other structural parameters of geopolymer concrete, were described in depth. Consequently, it can be stated that the geopolymer concrete created with fly ash, rice husk ash, ground granulated blast furnace slag is acceptable for precast and cast in situ works based on the aforementioned findings of compressive, split, and flexural strengths.

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