An Experimental and Analytical Study of the Flexural Capacity of reinforced Geopolymer Concrete Beams

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ABSTRACT

This study investigates the flexural strength of reinforced Geopolymer Concrete (GPC) beams using experimental and analytical methods. Five sets of reinforced beams were cast, each containing three beams with dimension of 150 mm x 200 mm x 1200 mm. One set was made with conventional concrete, while the other sets were made with GPC with different percentages of reinforcement. In order to determine compressive strength, three cube samples of conventional and GPC were also cast. The experimental flexural capacity of the beams was evaluated using a four-point loading test. The analytical flexural capacity was predicted deploying the IS 456:2000 standard method for reinforced concrete beams. The findings revealed that the predicted flexural capacity was similar or lower than the experimental values for GPC beams. Therefore, the IS 456:2000 approach can be utilized to predict the flexural capacity of reinforced GPC beams.

Keywords-geopolymer concrete; flexural capacity; fly ash; alkaline activator

I. INTRODUCTION

With the rapid infrastructure development, the demand for cement concrete is increasing, as it is one of the most utilized materials [1]. Consequently, the need for cement production is also growing, causing more consumption of its raw components, which are non-renewable. Additionally, the cement production is responsible for 5-7% of global CO_2 emissions, which generate approximately 0.8 tons per ton of cement manufactured [2, 3]. It is also stated that 2-8% of the world power is utilized in the cement industry [3]. Looking at the significant environmental impact of cement production, there is a need to explore alternative materials.

In 1957, a close relationship between alkalis and cementitious materials was established [4], while in 1988 an alkaline liquid was employed to produce binders by reacting with silicon and aluminum in a geologically derived substance [5]. These binders, including alkaline liquid (a combination of sodium hydroxide and sodium silicate solution), binding materials, fine and coarse aggregate, and admixture, were called geopolymers and led to the development of GPC, a cement-free concrete. Fly ash, rice husk ash, and Ground Granulated Blast Furnace Slag (GGBS) are some examples of binding materials. Since GPC properties are comparable to those of conventional concrete, it has received significant attention. The mechanical properties of GPC are influenced by various factors, and numerous studies have been conducted to understand these effects [6-9]. The concentration of alkaline liquid is major parameter affecting the GPC strength. The existing literature suggests that 12 M is the optimum concentration of the alkaline liquid, while the proposed ratio of NaOH to Na_2SiO_3 is 2.5 [10-12]. Curing conditions also play a crucial role in determining the mechanical properties of GPC [13-16]. A curing temperature of 120 ^oC and a curing duration of six hours were estimated for the highest compressive strength [17].

Additionally, several researchers have investigated the flexural capacity of reinforced GPC for large-scale applications [18-21]. The behavior of the reinforced GPC beam-column joint was observed to be similar to that of Portland cement concrete [22]. Authors in [23] conducted both experimental and analytical studies on the flexural capacity of reinforced GPC beams, using the ANSYS model, and they demonstrated that the difference between the experimental and analytical results was about 20%. Similarly, the flexural capacity of reinforced GPC was found to be comparable to that of reinforced conventional concrete with a strong correlation between the test computed results [24]. It is evident that GPC adoption as an alternative of cement concrete can significantly reduce carbon emission [25-27].

In this study, both experimental and analytical methods were employed to assess the flexural strength of reinforced GPC beams, using different percentages of reinforcement. For the comparison, three reinforced beams were also cast utilizing conventional concrete. The flexural strength of all beams was evaluated according to IS 456:2000 standard [28].

II. MATERIALS AND METHODS

In the current study, fly ash and GGBS were employed as binders, with a composition of 60% and 40%, respectively. The fly ash was obtained from the Kanti thermal power plan, in Muzaffarpur, Bihar, India. Locally available sand/and was used as the fine aggregate. A mixture of two sizes, 20 mm (60%) and 10 mm (40%) made up the coarse aggregate. An alkaline activator, composed of sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3) was utilized, with a molarity of 12 M and a ratio of 1:2.5, respectively.

A. Casting of Geopolymer Concrete Samples and Strength Test

To create a 12 M of sodium hydroxide solution, 480 grams of NaOH were dissolved in 500 grams of water and were mixed well. Following mixing, the volume was measured, and more water was added to reach a total volume of 1 liter. The same process was followed to prepare the alkaline activator in the required quantity. The solution was made 24 hours before use. The fine to coarse aggregate ratio was determined as 1:1.5:3, in order to produce the binder dry mix. Once the dry mix was prepared uniformly, the alkaline activator was added, with an alkaline activator to binder ratio of 0.55. A plasticizer, amounting to 1% of alkaline activator was added. After that, a uniformly mixed wet GPC mix was created. The GPC mix proportions are presented in Table I, and the manufacturing process is illustrated in Figure 1.

TABLE I. MIXING COMPONENTS OF GEOPOLYMER COCNRETE MIX

Materials	Dnesity (kg/m^3)
NaOH solution	85
Na_2SiO_3 solution	212
Fly ash	267
GGBS	178
Fine aggregate	668
Coarse aggregate (10 mm)	534
Coarse aggregate (20 mm)	801
Plasticizer	2.97

For the compressive strength testing, three cube samples of 150 mm x 150 mm x 150 mm were cast and tested. Additionally, different reinforced GPC beam samples were prepared with varying percentages of tensile and compressive reinforcement. For the comparison, three cube samples and three reinforced beams were also cast using conventional concrete with an M20 nominal mix. Ambient curing was provided for 28 days for all cube and reinforced GPC beam samples. Water curing was provided to cubes and beams made with conventional concrete for the same period. The beams had a cross-section of 150 mm x 200 mm and a length of 1200 mm. The reinforcement details of the prepared beams are presented in Figure 2.

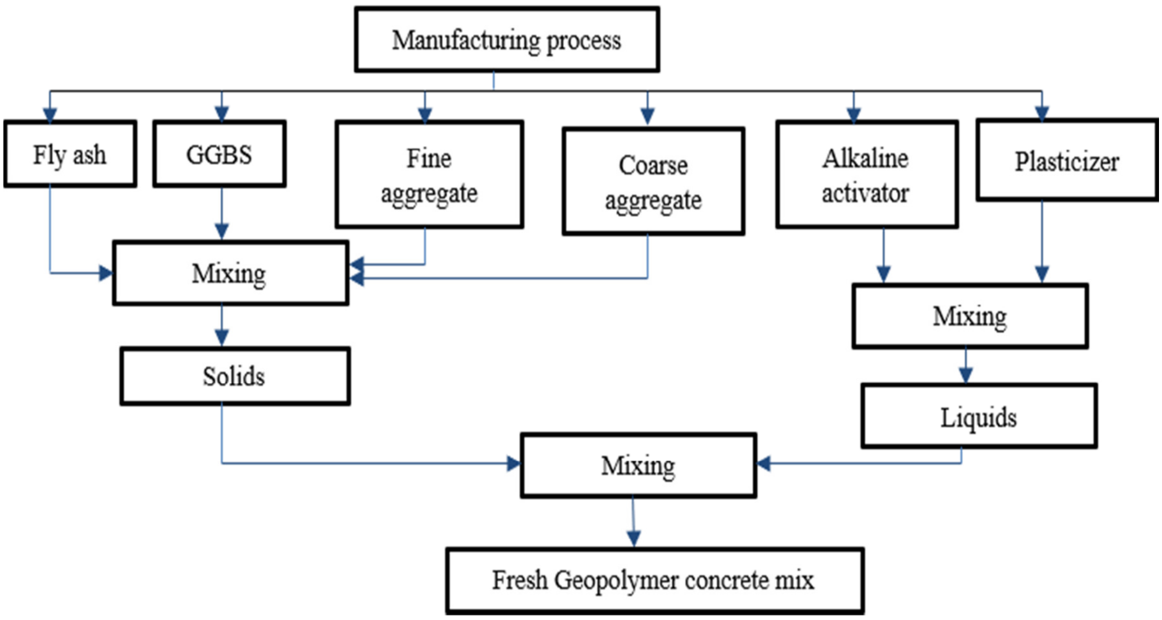

Fig. 1. Manufacturing process of GPC mix.

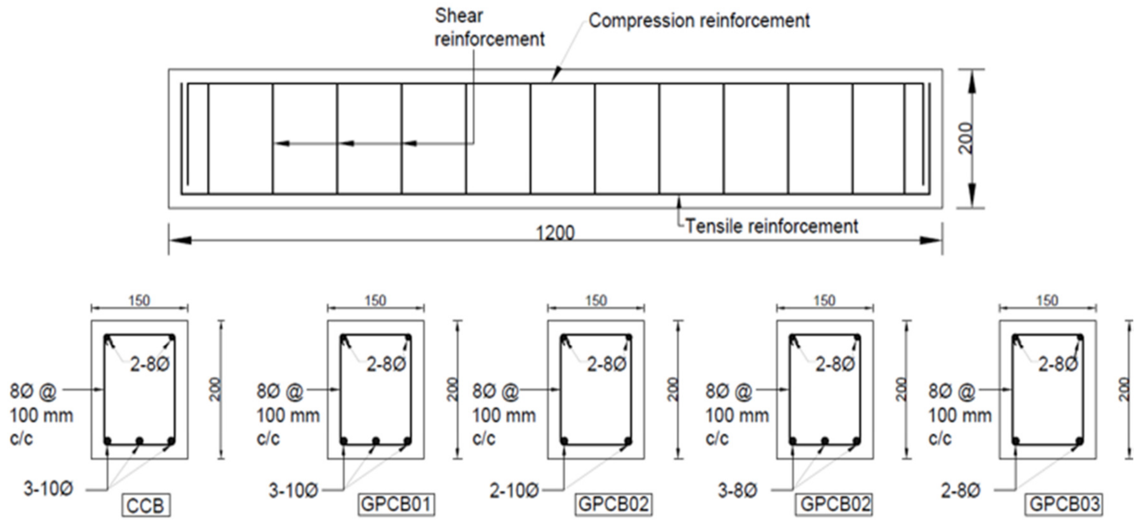

Fig. 2. Reinforcement details of beams.

B. Theoretical Prediction of Flexural Strength

The flexural strength of all beam specimens was calculated based on the stress-block diagram of IS 456:2000 [28], as shown in Figure 3. The tensile as well as compressive reinforcement of the beams were considered for the calculation of flexural strength, while material safety factors were not included.

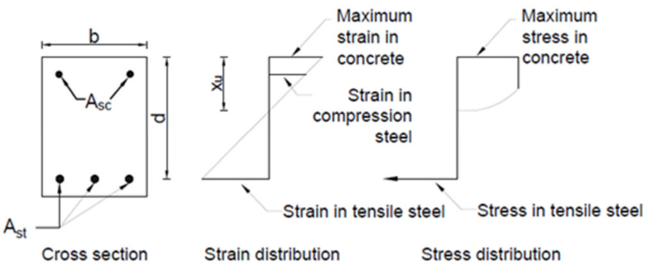

Fig. 3. Strain and stress distribution.

1) Balanced Neutral Axis Calculation

$$\frac{x_{ulim}}{d} = \frac{0.0035}{0.0035+0.002+\frac{f_y}{E_s}} \quad (1)$$

where:

x_{ulim} = Neutral axis depth of balanced section,

d = Effective depth of cross section,

f_y= Yield strength or proof strength of reinforcement used,

E_s= Modulus of elasticity of reinforcement used.

2) Actual Depth Calculation of Neutral Axis

- Total tensile force = Total compressive force

$$f_y A_{st} = 0.81 f_{ck} b x_u + f_{sc} A_{sc} \quad (2)$$

$$x_u = \frac{f_y A_{st} - f_{sc} A_{sc}}{0.81 f_{ck} b} \quad (3)$$

where:

x_u = Actual depth of neutral axis,

f_{ck}= Characteristic compressive strength,

b = Width of section,

f_{sc}= Stress in compression steel,

A_{st}= Area of tensile steel, A_{sc}= Area of compression steel.

- Actual moment capacity of the beams

$$M_u = 0.81 f_{ck} b x_u (d - 0.42 x_u) + f_{sc} A_{sc} (d - d') \quad (4)$$

where $d'$is the effective depth for compression reinforcement.

3) Experimental Prediction of Beams' Flexural Strength

After the 28-day curing period, GPC samples were tested for their strength in the material testing laboratory. The cube samples, displayed in Figure 4, were tested for compressive strength, while the beam samples, depicted in Figure 5, were tested for flexural strength using a Universal Testing Machine (UTM) and a four-point flexural test.

Fig. 4. Compressive strength test.

Fig. 5. Flexural strength test.

III. RESULTS AND DISCUSSION

Initially, the cube samples were tested for compressive strength. The average calculated strength was found to be 20.43 MPa for the GPC cube samples and 20.81 MPa for the conventional concrete samples. The experimental and theoretical values of the reinforced GPC beams' flexural capacity are portrayed in Table II and Figure. 6. The results indicate that the experimentally obtained flexural capacity of the reinforced GPC beams (GPCB01) is comparable to that of the Conventional Concrete Beams (CCBs). The difference between their experimental and theoretical flexural capacities was 7.53% and 6.67%, respectively. Similarly, for GPCB02, GPCB03, and GPCB04, the difference was found to be 23.45%, 24.77%, and 22.28%, respectively.

TABLE II. FLEXURAL CAPACITY OF BEAMS

Beams	Experimental flexural capacity (Mu_{exp})	Theoretical flexural capacity (Mu_{theo})	Mu_{exp}/Mu_{theo}
CCB	20 kN m	18.6 kN m	1.075
GPCB01	19.84 kN m	18.6 kN m	1.067
GPCB02	15.74 kN m	12.75 kN m	1.235
GPCB03	15.16 kN m	12.15 kN m	1.248
GPCB04	10.21 kN m	8.35 kN m	1.223

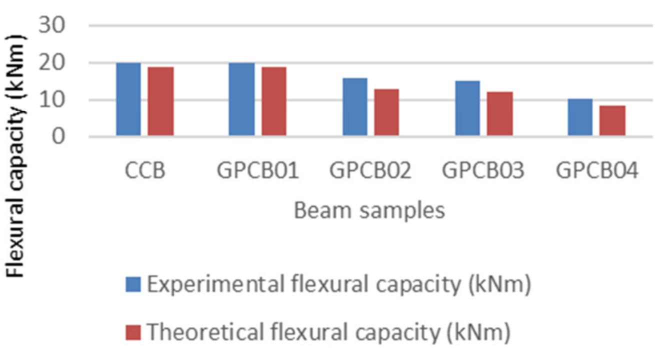

Fig. 6. Comparison of experimental and theoritical flexural capacity.

IV. CONCLUSION

This study aimed to evaluate the flexural capacity of reinforced Geopolymer Concrete (GPC) beams and compare the experimental results with theoretical predictions based on IS 456:2000. The key conclusions are:

- The experimental flexural capacity of the reinforced GPC beams was found to be approximately equal to that of the reinforced Conventional Concrete Beams (CCBs) with the same reinforcement.
- The flexural capacity of the reinforced GPC beams was depended on the provided reinforcement, as expected.
- The cracking moment of the GPC beams was greatly influenced by the provided reinforcement.
- The theoretical prediction of the flexural capacity obtained by IS 456:2000 standard was found to be similar or lower than the experimental obtained values. This means that the standard method can be used to predict the flexural capacity of reinforced GPC beams

These findings support the feasibility of using reinforced GPC as a sustainable alternative to conventional reinforced concrete, contributing to reduced carbon emissions in the construction industry.

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