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Investigating Flexural Behavior in Cyclic Loading of Fly Ash-Based Green Concrete

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Abstract

The construction industry is increasingly embracing sustainable materials, and geopolymer concrete (GPC) has emerged as a promising eco-friendly alternative to Ordinary Portland Cement (OPC). Derived from industrial by-products such as fly ash, GPC offers significant environmental advantages by reducing greenhouse gas emissions associated with conventional cement production. This study explores the monotonic and cyclic performance of fly ash-based GPC, with a focus on its mechanical and structural behavior. Key properties, including stress-strain relationships, load-deflection characteristics, flexural strength, modulus of elasticity, Poisson's ratio, and tensile strength, are evaluated through comprehensive experimental testing. Reinforced GPC beams are subjected to both uniaxial compressive and cyclic loading to assess their performance under static and dynamic conditions. A comparative analysis with conventional reinforced concrete (RC) is conducted to evaluate the load-bearing capacities, failure mechanisms, and fatigue behavior of GPC beams. The study investigates failure modes and crack patterns, emphasizing the structural reliability and durability of GPC under varying loading conditions. Results highlight the unique response of GPC to cyclic loading, its energy dissipation capabilities, and its suitability for structural applications. Additionally, the findings underscore the potential of GPC in reducing the environmental footprint of the construction sector while maintaining structural performance comparable to traditional materials. This research contributes valuable insights into the mechanical properties of GPC and its application in reinforced structures, offering a foundation for the development of future design codes and standards. By demonstrating the viability of GPC in both static and dynamic scenarios, the study advocates for its broader adoption in sustainable construction practices.

Keywords: Geopolymer concrete, cyclic loading, monotonic loading, flexural behavior, stress-strain curve, reinforced concrete, fly ash, blast furnace slag, fatigue testing

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INTRODUCTION

The concrete industry has evolved significantly with a shift towards sustainable and environmentally friendly alternatives. Among these, Geopolymer Concrete (GPC), made using industrial by-products like fly ash and slag, has shown considerable promise due to its reduced environmental impact and comparable mechanical properties to Ordinary Portland Cement (OPC).

This study investigates the monotonic and cyclic performance of GPC, comparing its stress-strain behavior, flexural strength, and failure mechanisms with conventional reinforced concrete (RC). The objective is to determine the viability of GPC for structural applications, including beams and columns, under varying loading conditions.

OBJECTIVES

The primary objective of this study is to investigate the monotonic and cyclic performance of Geopolymer Concrete (GPC) made with fly ash and Ground Granulated Blast Furnace Slag (GGBFS), with a focus on its mechanical properties, including compressive strength, stress-strain behavior, and flexural strength. This research aims to provide a comprehensive understanding of the structural behavior of GPC under both static and dynamic loading conditions. Specifically, the study evaluates the performance of GPC beams and cylinders under monotonic and cyclic loading to establish stress-strain curves and load-deflection relationships. Furthermore, the research aims to compare the performance of GPC with conventional Ordinary Portland Cement (OPC) concrete in terms of strength, ductility, failure modes, and fatigue resistance. Through this, the study seeks to assess the potential of GPC for use in structural applications, particularly for applications where resistance to cyclic and fatigue loading is crucial. Additionally, the study intends to contribute to the development of future design guidelines and codes for GPC-based structures [1–3].

MATERIAL

- *Fly ash*: Low-calcium, Class-F fly ash was sourced from an industrial area in Madhya Pradesh. The fly ash had an average particle size of 50 µm and was used as the primary binder in the geopolymer mix.
- *Ground granulated blast furnace slag (GGBFS):* Obtained from a steel plant in Bhilai, Chhattisgarh, GGBFS was used to enhance the mechanical properties of the geopolymer concrete.
- *Alkaline solution:* A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used as the alkaline activator. The molarity of the sodium hydroxide solution was 14 M, and the activator-to-fly ash ratio by mass was 0.55.
- *Aggregates*: Coarse and fine aggregates, sourced from local suppliers, were used in the mixture. The coarse aggregates were of granite type with a maximum size of 20 mm, and the fine aggregates were river sand [4–7].

Mix Proportion Based on The Research Literature

The following mix proportions were used:

- Fly ash and GGBFS were used in specified proportions to optimize strength and workability.
- The alkaline solution ratio was fixed at 2.5, and the sodium hydroxide molarity was maintained at 14 M.
- Coarse and fine aggregates made up approximately 77% of the total mix by mass, similar to the proportions used in traditional OPC concrete.

Testing Procedure

- *Cylinder testing*: A total of 20 cylindrical specimens were tested under uniaxial compressive monotonic and cyclic loading to generate stress-strain curves. The testing included deformation measurements using dial gauges [8–10].
- *Beam testing*: A total of 20 reinforced GPC beams were tested under two-point static and cyclic loading to evaluate flexural behavior, load-deflection characteristics, and failure modes. 19 additional beams were subjected to fatigue loading to analyze long-term performance [11–14].

RESULTS

Load Capacity of Beams under Monotonic and Cyclic Loading

The results of the tests conducted on the beams are presented in Tables 1 and 2. These tables summarize the performance of the beams under both monotonic and cyclic loading conditions, detailing the load capacities observed during the tests [15–19].

Table 1. Provides the load data for the Geopolymer Reinforced Concrete (GPRC) beams.

S. N.	Designation of beam	Load (kN)			Pfc/Pm	Py/Pm	Test method
		Pfc	***Py***	***Pm***			
1	GPRC01	14.1	32.2	38.5	0.37	0.83	Monotonic
2	GPRC02	17.2	36.6	40.4	0.43	0.91	Monotonic
3	GPRC03	16.3	31.9	39.9	0.41	0.80	Monotonic
4	GPRC04	17	35.7	40.3	0.42	0.89	Monotonic
5	GPRC05	16.3	34.9	41	0.40	0.85	Common point cyclic test
6	GPRC06	17.9	37.9	40.3	0.44	0.94	Common point cyclic test
7	GPRC07	14.7	33.6	37.8	0.39	0.89	common point cyclic test
8	GPRC08	15.8	32.9	39.1	0.40	0.84	common point cyclic test
9	GPRC09	14.8	33.5	38.2	0.39	0.88	Stability point cyclic test
10	GPRC10	16.4	34.1	39.9	0.41	0.85	Stability point cyclic test
11	GPRC11	16.1	33.1	38.8	0.41	0.85	Stability point cyclic test
12	GPRC12	15.7	34.8	41	0.38	0.85	stability point cyclic test
13	GPRC13	15.7	35.4	38.4	0.41	0.92	Stability point cyclic test

Table 2. Provides the load data for the Reinforced Concrete (RC) beams.

S. N.	Designation of beam	Load (kN)				Pfc/Pm	Py/Pm	Pm/Pu	Test method
		Pfc	***Py***	***Pm***	***Pu***				
1	RC01	17.33	37.80	42.21	44.84	0.41	0.90	0.94	Monotonic
2	RC02	18.90	42.26	46.20	49.09	0.41	0.91	0.94	Monotonic
3	RC03	15.15	30.80	37.20	38.50	0.41	0.83	0.97	Common point cyclic test
4	RC04	16.28	36.75	42.58	43.31	0.38	0.86	0.98	Common point cyclic test
5	RC05	16.80	33.71	39.69	40.95	0.42	0.85	0.97	Stability point cyclic test
6	RC06	17.59	36.23	42.16	43.58	0.42	0.86	0.97	Stability point cyclic test
7	RC07	16.80	36.23	42.00	43.58	0.40	0.86	0.96	Stability point cyclic test

Note: Pfc= Load at first crack, Pm= Peak load, Pu= Ultimate failure load, Py= Yield point load.

Load Capacity of Beams

A summary of the load capacities of beams at various stages of their load history is provided in Table 1. Analysis of the data in Tables 1 and 2 reveals that RC beams generally exhibit higher load capacities compared to GPRC beams [20–24].

The ductility of RC beams is approximately 25% greater than that of GPRC beams. This enhanced ductility enables RC beams to maintain linear behavior and resist higher loads until failure [25–27].

For both types of beams:

- The maximum load (Pm) is about 89 to 96% of the ultimate load (Pu).
- The yield load (Py) is 80 to 90% of the maximum load (Pm).
- The first cracking load is observed at 40 to 45% of the maximum load (Pm).

In conclusion, the strength of RC and GPRC beams under monotonic loading is comparable across all stages of loading, though RC beams show slightly higher load capacities and ductility [28].

CONCLUSION

Based on the comparison between GPRC and RC beams, it is evident that both materials exhibit comparable strength characteristics under monotonic loading, although RC beams demonstrate superior ductility and slightly higher load capacities. The first cracking load for GPRC beams falls between 14 and 17 kN, while for RC beams, it ranges from 15 to 18 kN. Both beam types show similar yield loads, with GPRC beams yielding between 30 and 36 kN, and RC beams yielding between 30 and 40 kN. The maximum load reached by GPRC beams is between 36 and 39 kN, while RC beams achieve a higher range of 37 to 44 kN. The ultimate load capacities of RC beams range from 39 to 47 kN, surpassing those of GPRC beams.

Despite the slight differences, the overall performance of both GPRC and RC beams is quite similar, with the strength values of GPRC being slightly lower. The ductility of RC beams is about 25% higher than that of GPRC beams, which contributes to their ability to resist higher loads and maintain linear behavior before failure. Notably, for both beam types, the maximum load is about 89 to 96% of the ultimate load, with the yield load being 80 to 90% of the maximum load, and the first cracking load occurring at 40 to 45% of the maximum load.

In conclusion, while GPRC beams show potential comparable to RC beams, RC beams still perform better in terms of load capacity and ductility, making them a more suitable choice for applications requiring greater load resistance and energy absorption. However, GPRC can still be a viable alternative in structural applications with appropriate design considerations.

Future Recommendations

Further research is recommended to explore the long-term durability of GPC under varying environmental conditions and to optimize mix designs for improved performance under cyclic and fatigue loading. Additionally, the development of updated design codes for GPC-based structures is essential for its widespread adoption in the construction industry.

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