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STRENGTH CHARACTERISTICS OF GEOPOLYMER CONCRETE INCORPORATING POLYPROPYLENE FIBRE UNDER FIRE CONDITION

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ABSTRACT

The widespread use of concrete in construction is driven by its adaptability, strength, and durability. However, the environmental repercussions associated with conventional concrete made from ordinary Portland cement (OPC) have raised concerns due to resource depletion, energy consumption, and greenhouse gas emissions. This study presents the results of compressive strength tests performed on multiple concrete mixes that utilize eco-friendly geopolymer technology and polypropylene fibres that were subjected to elevated temperatures. The study investigated a total of six concrete mix designs that utilize ground granulated blast furnace slag (GGBFS) and fly ash (FA) as a total replacement for conventional ordinary Portland cement (OPC). Sodium Hydroxide was used as an activator with identical proportions between the mixes. The results showed that the inclusion of 1 kg/m3 of PP fibres had no significant effect on compressive strength. The results reveal a notable increase in compressive strength of over 50% when incorporating GGBFS and PP fibres. Upon exposure to elevated temperatures, geopolymer-based mixtures exhibited significant compressive strength reduction, with certain samples experiencing nearly 70% strength loss. Future research should focus on devising strategies to mitigate these effects and enhance fire resistance for practical applications.

KEYWORDS: High-strength concrete, Geopolymer concrete, Fly ash, GGBFS

1. INTRODUCTION

Concrete is the most widely used construction material on the planet. This popularity is attributed to its versatility, durability strength characteristics. However, conventional concrete made with ordinary Portland cement (OPC) has a detrimental impact on the environment. The production of OPC depletes the earth's natural resources, requires a large amount of energy and releases significant quantities of greenhouse gasses into the environment. It is estimated that the production of 1 kg of OPC will release 800-900g of CO2 into the air [1]. These factors have pushed material scientists and engineers to find more environmentally friendly cement.

Nowadays, there is much interest in geopolymer concrete (GPC) and high-strength geopolymer concrete (HSGC). This type of concrete is made with geopolymers that are usually regarded as waste materials of other industries. The use of this waste material has a much-reduced impact on the environment compared to OPC. The most common geopolymers used for manufacturing concrete are fly ash (FA) and ground granulated blast furnace slag (GGBFS). FA is the result of coal combustion in power plants while GGBFS is a waste by-product of the steel industry. Both FA and GGBFS can be used

as a partial or total replacement of OPC with the help of an alkaline activator [2].

In real-world scenarios, concrete structures are often exposed to high temperatures, such as those occurring during fires or in industrial settings. These extreme temperatures can cause various detrimental effects, including reduced compressive strength, surface cracking, spalling, and even complete structural failure. One of the main aims of this research is to quantify the effects of elevated temperatures on concrete utilizing geopolymer technology.

2 LITERATURE REVIEW

The use of geopolymers in the production of concrete can result in high-strength concert (HSC) or even ultra-high-performance concrete (UHPC) due to the excellent binding properties of these materials. Sarathy and Dhinakaran studied the strength and durability characteristics of HSC made with GGBFS. In their study, the authors attempted to the strength and durability

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characteristics of M60 grade concrete made with partial replacement of the cement binder and fine aggregate with crusher dust (ROBO sand) and GGBFS respectively. The authors studied different replacement percentages (40, 50 and 60%) of OPC with GGBFS and (40, 60 and 80%) of fine aggregate with ROBO sand. The study found that concrete made with 40% GGBFS and 40% ROBO sand had the optimum compressive strength of 80MPa [3].

Aisheh et al. investigated ultra-high-performance geopolymer concrete (UHPGPC) made from micro silica and GGBFS with polypropylene fibre and steel fibre. For this aim, the first group of mixing ratios was utilized to create a control mixture with the highest compressive strength. In the second group, nine mixes were tested to see how the fibres affected the compressive strength, split strength, flexural strength, and modulus of elasticity of UHPGPC. Furthermore, scanning electron microscopy (SEM) investigations were carried out in order to comprehend the mechanism of strength enhancement based on reaction products and micromorphology. The results show that the addition of PP fibre in silica fume (SF) samples improves their mechanical characteristics. Furthermore, the results show that substituting SF for PP fibre diminishes mechanical strength while improving durability [4].

Erez N Allouche described a technique for optimizing fly ash geopolymer combinations, as well as a study of the mechanical qualities and durability of concrete created from the best mixes. The impacts of aggregate content, the alkaline solution to fly ash ratio, the sodium silicate to sodium hydroxide ratio, and the curing process were all included in the evaluation of nine combinations. A control mix of OPC concrete (OPCC) with a strength of 55 MPa was employed. Three best mixes (T4, T7, and T10) were found. The results reveal that geopolymer concrete may be manufactured with a compressive strength of 55 MPa in 28 days. They possessed greater tensile and flexural strength, less expansion and drying shrinkage, and moduli of elasticity 14.9-28.8% lower than the OPC [5].

The results of an experimental investigation were presented in a publication by Zhang et al. The study compared the durability properties of plain and fibre-reinforced geopolymer concrete to ordinary Portland cement-based concrete. water absorption, abrasion resistance, chemical resistance, the impact of alternating wetting and drying, and resistance to chloride ions are among the durability factors evaluated in that study. The results of the tests demonstrated that plain and fibre-reinforced geopolymer concrete had better durability qualities than conventional concrete of the same grade in most of the durability metrics [6].

In summary, the use of geopolymers in concrete production offers the potential for achieving high-strength and even ultra-high-performance concrete due to their superior binding properties. Several studies have been conducted to investigate the effects of various parameters on the mechanical and durability characteristics of geopolymer-based concrete.

3 EXPERIMENTAL PROGRAM

3.1 Materials

In order to produce GPC, FA and GGBFS have been chosen as geopolymer precursors. Both the FA and GGBFS have been sourced from local companies and are the same materials used in local construction. The specific gravity of GGBFS and FA were measure to be 2.86 and 2.75 respectively. For the alkaline activator, a 1:2.5 by weight solution of Sodium Hydroxide (NaOH) to Sodium Silicate ($Na2SiO3$) was used. Additionally, in order to improve the strength and workability of GPC, Sika ViscoCrete-735 which is a high-range superplasticizer and set retarder was used. The effect of Polypropylene (PP) fibres on the compressive strength of GPC was also studied. Finally, the OPC used in this study is type 1, and the course and fine aggregates are river-sourced with a maximum size of 10 mm and 1.5 mm respectively.

GGBFS is a by-product of the iron and steel industry that is created during the blast furnace smelting of iron ore. The appearance of FA is illustrated in Figure 1. Due to its cementitious characteristics, GGBFS is frequently employed in concrete as a partial replacement for Portland cement. The qualities of concrete, such as durability, workability, and resistance to chemical attacks, are improved when GGBFS is mixed with cement. Furthermore, it lowers the quantity of cement required and the temperature of hydration, both of which can result in economic savings and benefits for the environment.

Fig.(1):- Physical appearance of the GGBFS.

Fig.(2):- Physical appearance of the FA.

Fig.(3):- Physical appearance of the PP fibres.

FA on the other hand is a fine, powdery by-product obtained from the combustion of pulverized coal in coal-fired power plants. The appearance of FA is illustrated in Figure 2. It consists of inorganic mineral matter present in coal that becomes suspended in the flue gases during combustion and is collected as a residue. The use of FA in concrete offers several benefits. It improves the workability of concrete, reduces water demand, and enhances long-term strength and durability.

PP fibres are synthetic fibres made from polypropylene, which is a type of thermoplastic polymer. The appearance of PP fibres is illustrated in Figure 3. PP is derived from propylene monomers and is widely used in various industries due to its favourable properties. When added to concrete, polypropylene fibres help to control and reduce cracking, improve impact resistance, and enhance the overall durability of the concrete structure. The fibres disperse throughout the concrete matrix, providing reinforcement at a micro-scale level.

3.2 Mix design

Multiple GPC mixes were designed for this study. A total of six mix designs were obtained by means of trial and error. Mixes OPCC-1 and OPCC-2 utilize OPC, mixes HSGC-1 and HSGC-2 utilize FA; and mixes HSGC-3 and HSGC-4 utilize GGBFS. For the mixes designs utilizing OPC, the water-cement ratio was fixed at 0.31. While for the remaining mix designs, the water-binder ratio was kept under 0.04. The addition of water to mixes HSGC-1 through HSGC-4 is mainly to help improve the workability of the resulting GPC. The alkaline activator used for the GPC is a solution of 1 part NaOH to 2.5 parts Na2SiO3 by weight. Additionally, PP fibres were added to mixes OPCC-2, HSGC-2, and HSGC-4. This addition is meant to study the effect of PP fibres on the compressive strength of the concrete. Finally, for mixes utilizing GGBFS, Sucrose was added to combat the flash hardening of GPC. The exact mix designs that were used in this study are shown in Table 1.

Table 1
Mix Design Proportions (kg/m^3)

Mix	OPC	Slag	Ash	Sand	Gravel	Fiber	Na2SiO3	NaOH	Superplastisizer	Water
1	800	0	0	1050	2000	0	0	0	30	250
2	800	0	0	1050	2000	1	0	0	30	250
3	0	0	800	1050	2000	0	285	115	40	50
4	0	0	800	1050	2000	1	285	115	40	50
5	0	800	0	1050	2000	0	285	115	40	50
6	0	800	0	1050	2000	1	285	115	40	50

3.3 Sample preparation

The concrete mixer used is of the tilting drum type. Before any mixing took place, the mixer was thoroughly cleaned of any concrete residue from previous batches. The walls of the mixer were also slightly dampened with water, the aim of this is to account for any water that may stick to the walls and impact the mix negatively. For the OPCC mix designs, the mixing process was straightforward. All dry materials were added to the mixer and mixed in their dry state for about 1 minute to obtain a uniform dry mix. Similarly, all wet materials were mixed together to obtain a homogenous solution. The wet materials were then slowly and gradually added to the running mixer until everything was added. The mixer was left running for about 5 minutes and until a uniform concrete mix was produced.

Similar to the OPCC, the GPC mixing process followed the same steps described previously. However, there was one minor change which is the addition of the NaOH flakes to the wet material instead of the dry materials. It has been noticed that GPC has a tendency to flash harden. This behaviour was also observed by other researchers [7, 8]. To combat this problem, it is critical that the GPC is mixed continuously for the first 5 minutes at least. Additionally, Sucrose was also added to some of the mixes to retard the setting process and prevent flash hardening [9].

For each mix design, multiple cubes were cast to obtain statistical significance. Each cube was cast in three layers and subjected to vibration for 30 seconds after each layer. This ensures the production of a homogenous and void-free samples. The exact sampling procedure is as per ASTM C172M-17 [10]. After casting, the samples were left to cure underwater for 14 days. The curing procedure was carried out as per ASTM C31M-22 [11].

After the curing process, samples from mixes HSGC-1 and HSGC-3 were subjected to a temperature of 500 °C for 3 hours. Furthermore, samples from mixes HSGC-2 and HSGC-4 were subject to a temperature of 1000 °C for 3 hours as well. This is meant to simulate the conditions that concrete is subject to in the event of a fire. Samples subjected to heat will be compared to their counterparts that were not subjected to any heat.

3.4 Sample testing

The test for compressive strength was carried out as per ASTM C39M-21 [12] at the construction materials laboratory of Tishk International University. Figure 4 shows a sample from mix HSGC-4 that was subjected to 1000 °C and placed in the concrete compressive strength testing machine for testing.

Fig.(4):- Sample from mix HSGC-4 after being subjected to 1000 °C

4 RESULTS AND DISCUSSION

The results of the compressive strength test for all mix designs are presented in this section. Mixes OPCC-1 and OPCC-2 were tested normally in accordance with ASTM C39 [12]. Samples from mixes HSGC-1 and HSGC-3 were subjected to a temperature of 500 °C and then tested similarly to the OPCC samples. Similarly, samples from mixes HSGC-2 and HSGC-4 were subjected to a temperature of 1000 °C and then tested for compressive strength. The results of compressive strength tests conducted on the heated samples of each mix design were then compared to the results of the tests conducted on the unheated samples of the same max design.

The average compressive strength of mix designs OPC-1 and OPC-2 were 50.71 and 50.35 MPa respectively. This shows that the addition of PP fibres to the concrete mix has no considerable effect on the compressive strength of the concrete. The average strength of mixes HSGC-1, HSGC-2, HSGC-3, and HSGC-4 before exposure to heat were 52.02, 60.66, 72.85, and 76.43 MPa respectively. The strength of mixes HSGC-1 and HSGC-3 were reduced to 44.29 and 51.61 MPa (or 14.84% and 29.15%) respectively after being exposed to a temperature of 500 °C for 3 hours. The strength of mixes HSGC-2 and HSGC-4 were reduced to 24.96 and 23.59 MPa (or 58.85% and 69.14%) respectively after being exposed to a temperature of 1000 °C for 3 hours. A summary of the compressive strength test results is presented in Figure 5.

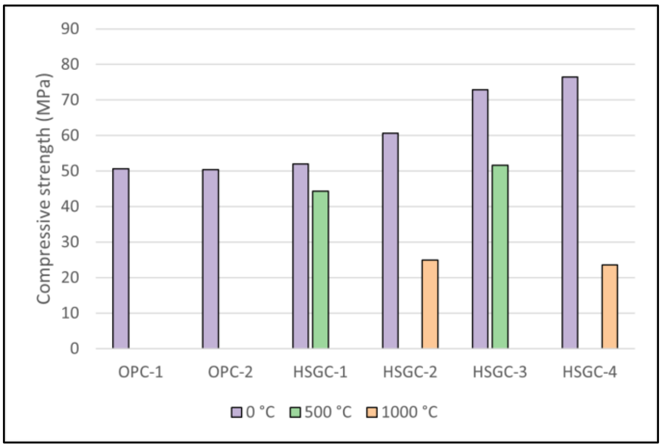

Fig.(5):-: Compressive strength test results summary.

The use of FA and GGBFS has been found to increase the compressive strength of the concrete. Compared to OPCC without PP fibres, replacing OPC with FA only, the compressive strength of the concrete increased to 52.02 MPa which is a 2.6% increase in strength, and when PP fibres are incorporated, the strength is further increased to 60.66 MPa which is 19.6% more than that of OPCC. Similarly, when replacing OPC with GGBFS only, the strength of the resulting concrete is 72.85 MPa which is 44% more than OPCC, and when incorporating PP fibres, the strength is increased to 76.43 MPa or 51%.

The test results of mixes HSGC-1, HSGC-2, HSGC-3, and HSGC-4, prior to heating show that PP fibres had a positive and significant impact on the strength of the samples. This can be attributed to a better bond between the geopolymer and the PP fibres. No direct comparison can be made after heating since there was no mix that isolates the effects of adding PP fibres to the mix design after being subjected to heating. However, it is safe to conclude that the effect after heating will be more or less identical since the samples were subjected to a temperature significantly higher than the ignite temperature of the PP fibres which is 360 °C.

Samples exposed to a temperature of 500 °C showed cracking on the surface of the samples as shown in Figure 6. This is mainly due to shrinkage of the sample material as the moisture escapes it as well as due to thermal stresses. Furthermore, the increased temperature appears to have damaged the cementitious matrix which is evident from the reduced strength.

Fig.(6):- Cracks on the surface of the sample after being subjected to 500 °C

Inspecting the results of the tests conducted on the samples that were exposed to a temperature of 1000 °C shows extensive damage to the material. Similar to HSGC-1 and HSGC-3, the samples showed surface cracks for the same reason. However, after testing, it has been revealed that the material of the samples has completely changed appearance as shown in Figure 7. The new appearance of the material after heating is charcoal-like. Additionally, the material also emits a distinctive odour which indicates that the geopolymer has been decomposed during the heating process.

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Fig.(7):- Chemical composition change of mix HSGC-4 after exposure to 1000 °C

5 CONCLUSION

From the presented research, the following conclusions can be drawn:

- The use of geopolymer increased the compressive strength of mixes HSGC-1 through HSGC-4 with the last mix gaining over 50% more compressive strength when utilizing GGBFS and PP fibres.
- The compressive strength test results indicate that the addition of PP fibres to OPCC does not have a significant impact on the compressive strength. However, adding PP fibres to geopolymer concrete demonstrate a positive and significant impact on the compressive strength which is attributed to the bond between the geopolymer and the PP fibres.
- After subjecting the samples to elevated temperatures, it was observed that the compressive strength of the geopolymer-based mixes decreased significantly with some samples losing nearly 70% of their original strength. Moderate damage is done to the GPC at a temperature of 500 °C which increases to severe damage when the temperature is increased to 1000 °C. This damage is permanent, non-reversible, and cannot be repaired.
- Although a direct comparison between heated and unheated samples with and without PP fibres could not be made, it can be inferred that no significant difference in strength will be observed beyond a temperature of 360 °C.
- These findings highlight the importance of considering the impact of elevated temperatures on the performance of geopolymer-based concrete mixes, particularly when incorporating additives such as PP fibres. Further research and experimentation are warranted to explore the potential mitigation strategies and enhance the fire resistance properties of geopolymer concrete in practical applications.

REFERENCES

G. Habert, “Environmental impact of Portland cement production,” in Eco-Efficient Concrete, 2013, pp. 3–25. doi: 10.1533/9780857098993.1.3.

A. A. Shahmansouri, M. Nematzadeh, and A. Behnood, “Mechanical properties of GGBFS-based geopolymer concrete incorporating natural zeolite and silica fume with an optimum design using response surface method,” Journal of Building Engineering, vol. 36, p. 102138, Apr. 2021, doi: 10.1016/j.jobe.2020.102138.

R. Sarathy and G. Dhinakaran, “Strength and durability characteristics of GGBFS based HPC,” Asian Journal of Applied Sciences, vol. 7, pp. 224–231, Apr. 2014, doi: 10.3923/ajaps.2014.224.231.

Y. I. A. Aisheh, D. S. Atrushi, M. H. Akeed, S. Qaidi, and B. A. Tayeh, “Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete,” Case Studies in Construction Materials, vol. 17, p. e01234, Dec. 2022, doi: 10.1016/j.cscm.2022.e01234.

Y. I. A. Aisheh et al., “Mechanical and fracture properties of steel fiber-reinforced geopolymer concrete,” Science and Engineering of Composite Materials, vol. 28, no. 1, pp. 299–313, 2021, doi: doi:10.1515/secm-2021-0030.

E. N. A. E. Ivan Diaz-Loya and Saiprasad Vaidya, “Mechanical Properties of Fly-Ash-Based Geopolymer Concrete,” ACI Materials

Journal, vol. 108, no. 3, Jan. 2011, doi: 10.14359/51682495.

Z. G. Ralli and S. J. Pantazopoulou, “State of the art on geopolymer concrete,” International Journal of Structural Integrity, vol. 12, no. 4, pp. 511–533, Jan. 2021, doi: 10.1108/IJSI-05-2020-0050.

A. Antoni, S. W. Wijaya, and D. Hardjito, “Factors Affecting the Setting Time of Fly Ash-Based Geopolymer,” Materials Science Forum, vol. 841, pp. 90–97, 2016, doi: 10.4028/www.scientific.net/MSF.841.90.

L. N. Assi, E. (Eddie) Deaver, and P. Ziehl, “Using sucrose for improvement of initial and final setting times of silica fume-based activating solution of fly ash geopolymer concrete,” Construction and Building Materials, vol. 191, pp. 47–55, Dec. 2018, doi: 10.1016/j.conbuildmat.2018.09.199.

“ASTM C172 - Standard Practice for Making and Curing Concrete Test Specimens in the Field.” https://www.astm.org/c0031_c0031m-22.html (accessed Jun. 09, 2023).

“ASTM C31 - Standard Practice for Sampling Freshly Mixed Concrete.” https://www.astm.org/c0172_c0172m-17.html (accessed Jun. 09, 2023).

“ASTM C39-21 - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.” https://www.astm.org/c0039_c0039m-21.html (accessed Jun. 09, 2023).