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EXPERIMENTAL INVESTIGATIONS ON HYBRID GLASS FIBER REINFORCED SLAG FLY ASH BLENDED GEOPOLYMER CONCRETE

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Abstract

In this study, the effects of various combinations and volume fractions of hybrid glass fibres (GF) addition on the characteristics of geopolymer concrete made with slag-fly ash blended are assessed. Two separate GF kinds (A and B) with lengths of 24 and 43 mm each were taken into consideration. GF were either fully or partially integrated. With an A:B ratio of 3:1, 1:1, or 1:3, and a constant volume percentage of 1%, three different hybrid GF combinations were employed. A GF hybrid combination with a 1:1 A:B ratio was used with three volume fractions (0.5, 1.0, and 1.5%). Workability, 1- and 7-day compressive strength, and 7-day splitting tensile strength were used to describe the performance. The outcomes of the experimental tests demonstrated that the addition of GF had a negative impact on the workability of geopolymer concrete. However, hybrid GF blends performed better than their equivalents generated from a single kind of GF. In addition, compared to the plain control mix, the inclusion of hybrid GF combinations boosted the compressive and splitting tensile strengths by up to 26 and 59%, respectively. The strengths improved as the hybrid GF volume fractions were raised by up to 1%. More long GF was added to the hybrid GF combination, resulting in the mix having a 1:3 A:B ratio, and exceptional strengths were seen. The results show that employing hybrid GF, the workability of slag-fly ash blended geopolymer concrete can be maintained while the hardened characteristics can be improved.

***Keywords*:** Geopolymer, concrete, glass fibers, hybrid, workability, compressive strength, splitting tensile strength.

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1. Introduction

Concrete made of cement is being used a lot more frequently as a result of urban development's ongoing advancement [1]. The use of such concrete topped 3 billion metric tonnes in 2020, and by 2030, it is anticipated to exceed 4 billion metric tonnes [2, 3]. In China, cement output has topped 2 billion metric tonnes, while India has produced over 300 million tonnes and the United States has produced about 100 million tonnes [4]. Energy is consumed and carbon dioxide is released during the manufacture of cement for use in building applications. As a result, up to 7% of the global carbon dioxide emissions are currently accounted for by cement manufacturing, and that number is predicted to rise to 10% in the near future [5]–[8]. The generated CO2 is one of the greenhouse gases that is trapped in the atmosphere, increasing global warming and the likelihood of natural disasters such storms, heat waves, floods, and droughts [9].

A number of research have focused on the use of supplemental cementitious materials (SCMs) in concrete as a solution to this problem, including fly ash, granulated blast furnace slag, silica fume, rice husk ash and metakaolin. However, it was determined that it was impossible to produce concrete with complete cement substitution that underwent a conventional hydration response. With the help of alkali-activated geopolymer technology, cement may be completely replaced in the production of concrete by employing a different substance as the only binder. Alkaline activator solution and aluminosilicate minerals are used to create geopolymer binders. The formation of the geopolymer binder has been studied in many research [5, [10]–[12] using various types and combinations of aluminosilicate materials and alkaline activator solutions. Depending on the features of the aluminosilicate components, the makeup of the alkaline activator, and the chosen curing setting, the geopolymer binder's qualities may change. Geopolymers outperform cement-based binders in terms of bond, alkaliaggregate expansion, sulphate and corrosion resistance, and acid and fire resistance [3], [13]. However, geopolymer concrete was frequently distinguished from cement-based counterparts by higher brittleness and lesser resilience to cracking [14].

Numerous research [15]–[19] examined the use of fibre reinforcement to geopolymer and cement-based concrete to increase ductility and fracture resistance. More often than other types of fibres, steel fibres (SF) have been used in geopolymer concretes [20]–[23]. The results showed that the inclusion of SF decreased the workability while improving the mechanical and durability qualities. Geopolymer concrete has been used in other research with carbon, glass, and propylene fibres. Geopolymer concrete composites' overall mechanical characteristics, such as compressive strength, elastic modulus, flexural strength, impact resistance, and hardness, were improved by the use of carbon fibres (CF) [24, 25]. In the meanwhile, studies [26]–[29] have looked at how glass fibres (GF) affect the characteristics of geopolymer concrete. Upon the addition of GF over 3%, by volume, Lakshmi and Rao [30] found a reduction in the mechanical performance of fly ash-based geopolymer concrete. In a different study, the addition of 0.03% GF volume fraction (vf) to geopolymer concrete made it stronger [31].

A few research have looked into the use of GF in geopolymer concrete, according to a summary of the literature. However, it has not yet been determined how different hybrid combinations of micro- and macro-GFs, as well as volume percentage, affect the workability and compressive and tensile strengths of geopolymer concrete made with slag-fly ash mixed. The early-age strength and workability of hybrid GF-reinforced slag-fly ash mixed geopolymer concrete are hence the focus of this investigation. In this work, numerous hybrid GF combinations and hybrid GF volume fractions were taken into consideration.

2. Materials and Methods

In order to create the geopolymer binder, glass-granulated blast furnace slag and class F fly ash were employed as the aluminosilicate precursor binding materials. The binder was activated using an alkaline activator solution made up of grade N sodium silicate (SS) and 14 M sodium hydroxide (SH) solutions. Sand from local desert dunes was utilised as fine aggregates. There are more sources for information on the chemical makeup, particle size distribution, scanning electron microscopy, and X-ray diffraction patterns of slag, fly ash, and dune sand [7]. They each weighed 1209, 1262, and 1663 kg/m3, respectively. Natural dolomitic limestone with a nominal maximum size of 20 mm, dry rodded density of 1635 kg/m3, absorption of 0.2%, abrasion mass loss of 16%, specific surface area of 2.5 cm2/g, and specific gravity of 2.82 were the coarse aggregates utilised in the geopolymer concrete mixtures. To prevent mixing water absorption, the natural aggregates were employed under saturated, dry conditions on the surface. To improve the workability, more tap water and a superplasticizer based on a polycarboxylic ether polymer were added, as suggested in prior work [32]. The two varieties of GFs utilised have matching aspect ratios of 35 and 62, and differing lengths (short or long) of 24 and 43 mm. Both types of GFs had equal diameters, tensile strengths, Young's moduli, and specific gravities.

3. Mixture Proportioning

The mixing proportions of the geopolymer concrete mixes used in this investigation are shown in Table 1. The benchmark mix A0B0GF0, which was taken from a prior research [6], was created to attain a slump of at least 150 mm and a cube compressive strength (fcu) of 30 MPa. All of the mixtures had comparable ratios, but distinct GF combinations and volume percentages. Slag and fly ash were blended in a 3:1 ratio together with an alkaline activator solution to create the binder. Such a mixture was suggested by earlier research since it performed better than others [11]. Additionally, the combination of both slag and fly ash in the creation of the binder intended to decrease shrinkage brought on by the alkali-activated slag concrete and avoid the heat curing associated with fly ash-based geopolymer. Sodium silicate and sodium hydroxide solution were mixed at a ratio of 1.5 to create the alkaline activator solution. The sodium hydroxide solution had a 14 M concentration, as suggested by earlier research [33]. In all combinations, the amounts of coarse aggregate and dune sand were constant at 725 and 1210 kg/m3, respectively. All mixes had the same fixed extra water content of 75 kg/m3 and superplasticizer content of 7.5 kg/m3 (equal to 2.5% of binder mass).

The purpose of the geopolymer mixtures was to study the impact of various GF lengths, hybrid GF combinations, and hybrid GF volume fractions. Two versions of GF, type A (short) and type B (long), with lengths of 24 and 43 mm, respectively, were used. The uncomplicated control mix, which lacked GF, served as a comparison. To evaluate the impact of fibre length, two mixtures were reinforced with a single kind of GF, either type A (24 mm) or type B (43 mm), at a constant vf of 1.0%, by volume. To assess the impact of various hybrid GF volume percentages, three mixes were reinforced with an equal mixture of A and B (A:B = 1:1) at volume fractions of 0.5, 1.0, and 1.5%. Additional two mixes were reinforced with various hybrid GF combinations of A:B ratios of 3:1 and 1:3, at a fixed vf of 1%, in order to examine the effects of various hybrid GF combinations. These mixes were then compared to mixes made with a single type of fibre (non-hybrids) and a hybrid GF combination at

A:B ratio of 1:1 and vf of 1%. The mixtures were given the name GFx-AyBz, where x stands for the volume fraction of GF and y and z for the proportion of Type A and B GF, respectively, to the total volume of fibre. A hybrid GF combination with a 1:3 (A:B) ratio at a volume fraction of 1.0%, for example, is represented by the formula GF1.0-A25B75 in geopolymer concrete.

Table 1: Mixture proportioning of geopolymer concrete (in kg/m^3)

Mix ID	Aluminosilicate materials		Fine aggregates	Natural coarse aggregates	Alkaline activator		SP	Water Content	GF	
	Slag	Fly ash	Dune sand		SS	SH			Proportions (A:B)	v_f (%)
GF0.0-A0B0	225	75	725	1210	99	66	7.5	75	-	0
GF1.0-A100B0	225	75	725	1210	99	66	7.5	75	1:0	1.0
GF1.0-A25B75	225	75	725	1210	99	66	7.5	75	3:1	1.0
GF1.0-A50B50	225	75	725	1210	99	66	7.5	75	1:1	1.0
GF1.0-A75B25	225	75	725	1210	99	66	7.5	75	3:1	1.0
GF0.5-A50B50	225	75	725	1210	99	66	7.5	75	1:1	0.5
GF1.5-A50B50	225	75	725	1210	99	66	7.5	75	1:1	1.5
GF1.0-A0B100	225	75	725	1210	99	66	7.5	75	0:1	1.0

4. Sample Preparation and Testing

The samples of geopolymer concrete were made and cast in a laboratory environment with ambient temperatures of 25°C and 50% relative humidity. The sodium silicate and sodium hydroxide solutions were first combined to create the alkaline activator solution, and the heat generated by the exothermic processes was then allowed to escape. Prior to casting, the dry premixed ingredients—namely, slag, fly ash, coarse aggregates, dune sand, and GFs—were gradually added to the alkaline activator solution along with the extra water and superplasticizer, if necessary. The freshly made geopolymer concrete was then poured into 100 mm cubes and 100 mm 200 mm cylinders (diameter height) and vibrated on a vibration table for around 10 seconds. Finally, samples were demoulded after 24 hours and covered in plastic to avoid solution evaporation.

Using the slump, in line with ASTM C143 [34], the workability of the plain and GF-reinforced slag-fly ash mixed geopolymer concrete was assessed. The compressive and splitting tensile strengths were used to assess the attributes of early-age hardened materials. According to BSI 12390 [35], the cube compressive strength was measured at 1 and 7 days of age. However, the cylinder compressive strength may be calculated using a previously used correlation for predicting the cylinder compressive strength from the cube counterpart of such concrete [7]. The splitting tensile strength, on the other hand, was measured at 7 days in line with ASTM C496 [36]. For each early-age mechanical test, three replicate specimens were utilised, and an average result was calculated.

6. Experimental results and discussion

6.1 Slump

The slump of plain and GF-reinforced slag-fly ash mixed geopolymer concrete mixtures is shown in Figure 1. The most workable mixture, with a workability of 160 mm, was the basic control mix. The impact of various GF addition kinds and mixtures on the slump of geopolymer concrete was assessed. In comparison to the plain concrete mix (GF0-A0B0), the slump was reduced to 80 and 50 mm, respectively, by the addition of short (24 mm) and long (43 mm) GF at a constant vf of 1%, by volume. Evidently, the workability of the mix decreased by 19% when the GF length was increased to 43 mm from the mix with short GF. Long GF has such a negative effect because there is a higher chance of fibre aggregation and overlap. Similar results were found.

Through the mixes GF1.0-A75B25, GF1.0-A50B50, and GF1.0-A25B75, respectively, the impact of substituting long GF for short GF by 25, 50, and 75% was assessed. As a baseline, non-hybrid mixtures (GF1.0-A100B0 & GF1.0-A0B100) were employed. Slump values of 110, 100, and 55 mm, respectively, were obtained by substituting long GF for short GF at the aforementioned percentages. This demonstrates that the slump rises when short GF are replaced with longer ones up to 50% of the time, but that increasing the short GF replacement percentages with longer ones (75-100%) resulted to a subsequent decline. As a result, it can be observed that adding hybrid GF combinations might improve the workability of geopolymer concrete made from a blend of slag and fly ash, provided that there are more short GF than long GF in the mixture. This is due to hybrid GF's decreased capacity for cross-linking and fibre interlocking when compared to a single kind of GF. Self-consolidating concrete reinforced with steel-glass hybrid fibre combinations showed similar results [38].

Through the mixes GF0.5-A50B50, GF1.0-A50B50, and GF1.5-A50B50, the impact of various volume fractions of a hybrid combination of GFs on slag-fly ash blended geopolymer concrete was assessed. In comparison to the plain control mix, the introduction of 0.5, 1.0, and 1.5% hybrid GF mixture produced slump values of 110, 100, and 90 mm, or 31, 38, and 44% less slump, respectively. It appears that a hybrid GF combination's workability was effected greatly by raising the vf. Additionally, the slump values for GF1.0-A75B25 and GF0.5-A50B50 were comparable. This suggests that the workability of slag-fly ash blended geopolymer concrete was not significantly affected by increasing the volume fraction of hybrid GF or the proportion of short GF replaced by long ones.

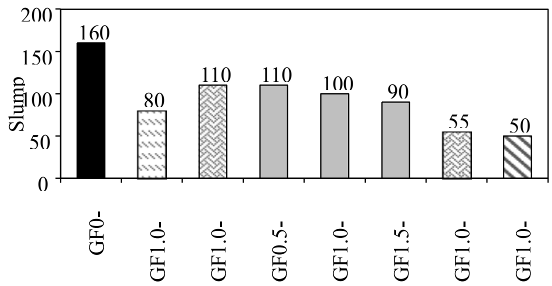


Figure 1: Slump values of geopolymer concrete mixes

6.2 Compressive Strength

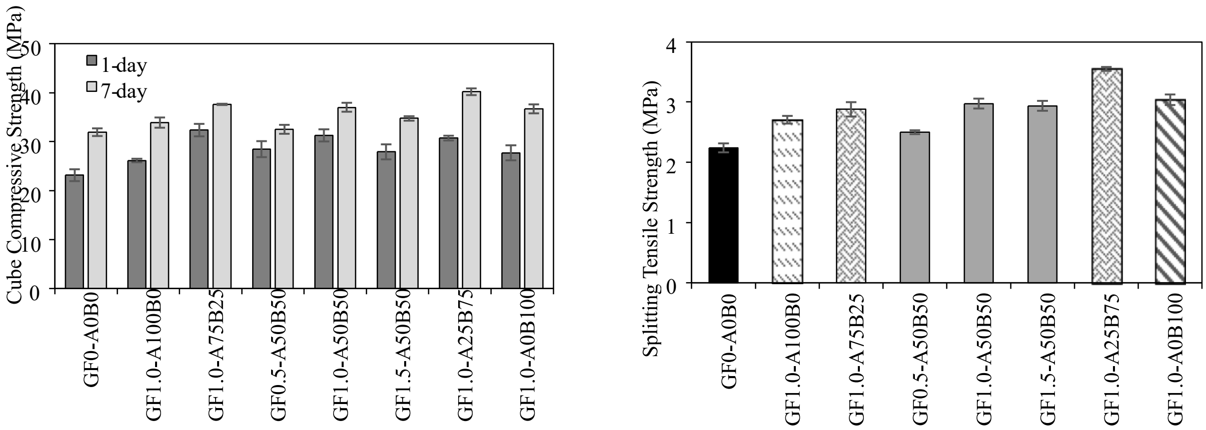
The compressive strength (fcu) of plain and GF-reinforced slag-fly ash blended geopolymer concrete is shown in Figure 2(a). The 1-day fcu for the basic control mix was 23.2 MPa. Slag-fly ash blended geopolymer concrete's 1- and 7-day compressive strengths were improved by the addition of GF. The 1-day fcu rose to 26.2 and 27.7 MPa, respectively, with the addition of either short or long GF at 1% vf, which corresponds to increases of 13 and

19%, respectively, above the plain control mix. This demonstrates that longer GFs have a greater influence on strength than shorter ones. Similar trends were observed at the age of 7 days, although the addition of long GF was more pronounced. The control blend produced a strength of 31.9 MPa.

A 7-day strength of 33.9 and 36.7 MPa, respectively, was achieved with the addition of short and long GFs at 1% vf, which is an increase of 6 and 15% over the plain control mix. The geopolymerization process, which occurs during the first seven days of the activation reaction, produces gels of calcium aluminosilicate (C-A-S-H) and calcium silicate hydrate (N-A-S-H), which are primarily responsible for the strength increase from 1 to 7 days [11], [19].

Through the use of GF1.0A75B25, GF1.0-A50B50, and GF1.0-A25B75 mixes, the impact of introducing hybrid GF combinations at 1% vf, by volume, on the 1-day fcu was investigated. At a comparable vf of 1%, these mixtures were compared to their non-hybrid counterparts. In comparison to the plain control mix, substituting 25, 50, and 75% of the short GF with long ones produced 1-day strength values of 32.4, 31.3, and 30.7 MPa, respectively. These values indicate increases of 40, 35, and 32%. This indicates that using a hybrid mix of GF rather than a single kind of GF will result in an additional improvement of at least 13% on the 1-day fcu. Nevertheless, it appears that the 1day strength values were somewhat lowered when more long GF was included in a hybrid combination at 1% vf. In comparison to the control plain mix, those mixes produced fcu increases of 62, 60, and 73% at 7 days of age, indicating increased strength due to the inclusion of more long GF (Type B) in the mix. This is because long GF have stronger bridging capabilities than short ones.

Through the use of GF0.5-A50B50, GF1.0-A50B50, and GF1.5-A50B50 mixes, the impact of adding hybrid GF combination at various volume fractions (0.5, 1.0, and 1.5%) was assessed. Incorporated hybrid GF mixtures of 0.5, 1.0, and 1.5% produced mixes with 1-day fcu of 28.5, 31.3, and 27.9 MPa and 7-day fcu of 32.5, 37, and 34.8 MPa, respectively. The 1-day fcu of the aforementioned mixes increased by 5, 35, and 20%, respectively, in contrast to the control plain mix, whereas the 7-day fcu increased by 2, 16, and 9%. These results show that hybrid GF inclusion had a greater impact after one day. In addition, it is clear that a volume fraction of hybrid GF of at least 1% is required to affect the 1- and 7-day strengths, with greater vf having a more noticeable impact. Due to their bridging effect and capacity to delay crack formation and propagation, it can be inferred that adding more long GF to a hybrid combination or including a hybrid GF combination of equal proportions at 1% vf, by volume, would increase fcu [23], [39], [40]. It is important to note that the error bars in Figure 2(a) show that the test results' dispersion is relatively low, indicating good accuracy, repeatability, and little uncertainty.



(a) (b)

Figure 2: (a) Compressive and (b) splitting tensile strength of geopolymer concrete mixes

6.3 Splitting Tensile Strength

Figure 2(b) shows the splitting tensile strength (fsp) of the 7-day slag-fly ash mixed geopolymer concrete. The tensile strength value for the simple control mix was 2.24 MPa. In comparison to the control mix, the inclusion of short (Type A) or long (Type B) GF at a fixed vf of 1% boosted fsp by 21 and 35%, respectively. Due to long GF's superior bridging capacity over shorter GF, there is a corresponding rise in fsp when using long GF.

At a given vf of 1%, the impact of various hybrid GF combinations was assessed. as replacing 25, 50, and 75% of the short GFs with long GFs, respectively, the tensile strength rose by 29, 33, and 58% as compared to the plain mix, suggesting a considerable improvement in fsp as the replacement proportion of short GF with long GF rises. In addition, the fsp of these hybrid GF mixes was 6, 10, and 31% greater than that of the non-hybrid mix with short GFs (GF1.0-A100B0), and it was nearly identical to that of the non-hybrid mix with long GFs. This is primarily attributable to the bridging effect and capacity of GF with two distinct lengths to restrain the development and spread of micro and macro fractures..

A:B = 1:1) hybrid GF combination's impact on fsp at various volume fractions was assessed. Comparing the plain control mix to those with 0.5, 1.0, and 1.5% volume fractions of hybrid GF, the increase in fsp was 12, 33, and 31%, respectively. It is obvious that raising the vf of hybrid GF to 1.0% caused an increase in fsp. Fsp was unaffected outside of this volume fraction, though. Additionally, it was shown that mixes containing an equal mixture of types A and B GF at volume fractions of 1.0-1.5% had fsp values that were comparable to those of mixes containing just long GF and higher than those of mixes containing short GF, both at volume fractions of 1%. However, GF1.0-A25B75 had better fsp than any other hybrid or single GF. These findings suggest that a hybrid mix produced better fsp by including more lengthy GF. The error bars in Figure 2(b) also show that the test findings' dispersion is quite low, which denotes good accuracy, repeatability, and little uncertainty.

7. Conclusions

The workability and early-age strength of slag-fly ash blended geopolymer concrete are examined in this article in relation to the effects of GF length, hybrid combination, and volume percentage. The following conclusions may be derived from the test results:

• When GF was added, the slump was lessened. Geopolymer concrete mixes that used hybrid GF combinations performed better in terms of slump than those that only used one kind of GF. The workability was negatively impacted by lengthening the GF in a non-hybrid combination or by increasing the proportion of long GF in a hybrid combination. Additionally, a hybrid GF mix's slump values were reduced by raising the vf, but less significantly than by increasing the amount of long GF.

- The early age compressive strength of a geopolymer concrete mix was improved by the addition of GF. Greater 1- and 7-day strengths were obtained by lengthening the GF. In fact, it was shown that including long GF solo resulted in a better strength growth between 1 and 7 days than its counterpart mix with short GF, showing a reduction in strength development between 1 and 7 days when incorporating short GF.
- Better strengths were achieved at both ages by including various hybrid GF combinations at a constant vf of 1%. The hybrid GF combo reinforced mixtures were stronger than their non-hybrid equivalents. In a hybrid combination, increasing the fraction of long GF further enhanced the strength and sped up the pace at which strength developed. The average improvements in the 1- and 7-day strengths over the plain mix were 35 and 10%, respectively, when additional GF was added to the hybrid mixture of A:B = 1:1.
- After GF was added, the splitting tensile strength rose. The amount of long GF or the percentage of long GF in a hybrid combination enhanced the fsp of geopolymer concrete made from slag-fly ash mixed. Additionally, utilising more GF in a hybrid A:B = 1:1 combination increased fsp by up to 33% in comparison to the basic equivalent.

Due to its promising endurance due to chemical and heat resistance, geopolymer concrete has recently been used in a number of infrastructural and structural applications. Precast pavers and slabs, railway sleepers, bricks, pre-cast pipes and structural elements, such as columns, beams, tunnel segments, etc. were only a few examples of the previous uses of geopolymer concrete. In order to enhance sustainability, geopolymer concrete has the potential to completely replace traditional cement-based concrete in building applications. The structural behaviour of hybrid-GF reinforced geopolymer concrete beams and columns warrants further study.

References

[1] A. L. Almutairi, B. A. Tayeh, A. Adesina, H. F. Isleem, and A. M. Zeyad, “Potential applications of geopolymer concrete in construction: A review,” *Case Studies in Construction Materials*, vol. 15, p. e00733, Dec. 2021, doi: 10.1016/j.cscm.2021.e00733.

[2] National Minerals Information Center, “Cement Statistics and Information | U.S. Geological Survey,” *Cement Statistics and Information*, Nov. 2021. https://www.usgs.gov/centers/national-minerals-information-center/cement-statisticsand-information (accessed Feb. 12, 2022).

[3] P. D. A. M. I. Abdul Aleem, “Geopolymer Concrete - A review,” *IJESET*, vol. 1, no. 2, pp. 118–122, Feb. 2012, doi: 10.7323/ijeset/v1_i2_14.

[4] “Worldwide Cement Production From 2015 to 2019 | Datis Export Group,” *Datis Export Group*, Dec. 07, 2021. https://datis-inc.com/blog/worldwide-cement-production-from-2015-to-2019/ (accessed Feb. 12, 2022).

[5] Q. Fu, W. Xu, X. Zhao, M. Bu, Q. Yuan, and D. Niu, “The microstructure and durability of fly ash-based geopolymer concrete: A review,” *Ceramics International*, vol. 47, no. 21, pp. 29550–29566, Jul. 2021, doi: 10.1016/j.ceramint.2021.07.190.

[6] M. Zuaiter, H. El-Hassan, B. El-Ariss, and T. El-Maaddawy, “Early-Age

Properties of Slag-Fly Ash Blended Geopolymer Concrete Reinforced with Glass Fibers – A Preliminary Study," p. 7.

[7] M. Zuaiter, H. El-Hassan, T. El-Maaddawy, and B. El-Ariss, "Properties of Slag-Fly Ash Blended Geopolymer Concrete Reinforced with Hybrid Glass Fibers," *Buildings*, vol. 12, no. 8, p. 1114, Jul. 2022, doi: 10.3390/buildings12081114.

[8] C.-K. Ma, A. Z. Awang, and W. Omar, "Structural and material performance of geopolymer concrete: A review," *Construction and Building Materials*, vol. 186, pp. 90–102, Oct. 2018, doi: 10.1016/j.conbuildmat.2018.07.111.

[9] H. Shaftel, S. Callery, R. Jackson, and D. Bailey, "Overview: Weather, Global Warming and Climate Change," *Climate Change: Vital Signs of the Planet*, 2022. https://climate.nasa.gov/resources/global-warming-vs-climate-change (accessed Feb. 12, 2022).

[10] A. M. Azad *et al.*, "Pervious geopolymer concrete as sustainable material for environmental application," *Materials Letters*, vol. 318, p. 132176, Jul. 2022, doi: 10.1016/j.matlet.2022.132176.

[11] N. Ismail and H. El-Hassan, "Development and Characterization of Fly Ash–Slag Blended Geopolymer Mortar and Lightweight Concrete," *J. Mater. Civ. Eng.*, vol. 30, no. 4, p. 04018029, Apr. 2018, doi: 10.1061/(ASCE)MT.19435533.0002209.

[12] G. M.G., K. K. Shetty, and G. Nayak, "Synthesis of Fly-ash and Slag Based Geopolymer Concrete for Rigid Pavement," *Materials Today: Proceedings*, p. S2214785321073429, Dec. 2021, doi: 10.1016/j.matpr.2021.11.332.

[13] J. Davidovits, "High-Alkali Cements for 21st Century Concretes," *ACI Symposium Publication*, vol. 144, Mar. 1994, doi: 10.14359/4523.

[14] R. J. Thomas, D. Lezama, and S. Peethamparan, "On drying shrinkage in alkali-activated concrete: Improving dimensional stability by aging or heat-curing," *Cement and Concrete Research*, vol. 91, pp. 13–23, Jan. 2017, doi: 10.1016/j.cemconres.2016.10.003.

[15] H. El-Hassan and S. Elkholy, "Enhancing the performance of Alkali-Activated Slag-Fly ash blended concrete through hybrid steel fiber reinforcement," *Construction and Building Materials*, vol. 311, p. 125313, Dec. 2021, doi: 10.1016/j.conbuildmat.2021.125313.

[16] H. El-Hassan, A. Hussein, J. Medljy, and T. El-Maaddawy, "Performance of Steel Fiber-Reinforced Alkali-Activated Slag-Fly Ash Blended Concrete Incorporating Recycled Concrete Aggregates and Dune Sand," *Buildings*, vol. 11, no. 8, p. 327, Jul. 2021, doi: 10.3390/buildings11080327.

[17] J. Medljy, H. El-Hassan, and T. El-Maaddawy, "Effect of Recycled Aggregate and Steel Fibers on the Mechanical Properties of Alkali-Activated Slag/Fly Ash Blended Concrete," *ACI Symposium Publication*, vol. 349, Apr. 2021, doi: 10.14359/51732748.

[18] N. Kachouh, H. El-Hassan, and T. El-Maaddawy, "Effect of steel fibers on the performance of concrete made with recycled concrete aggregates and dune sand," *Construction and Building Materials*, vol. 213, pp. 348–359, Jul. 2019, doi: 10.1016/j.conbuildmat.2019.04.087.

[19] Y. N. Kumar, B. Dean Kumar, and B. L. P. Swami, "Mechanical properties of geopolymer concrete reinforced with steel and glass fibers with various mineral admixtures," *Materials Today:*

Proceedings, p. S2214785321065317, Oct. 2021, doi: 10.1016/j.matpr.2021.10.050.

[20] D. Gao, L. Zhang, and M. Nokken, "Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear," *Cement and Concrete Composites*, vol. 79, pp. 1–8, May 2017, doi: 10.1016/j.cemconcomp.2017.01.006.

[21] A. D. de Figueiredo and M. R. Ceccato, "Workability Analysis of Steel Fiber Reinforced Concrete Using Slump and Ve-Be Test," *Mat. Res.*, vol. 18, no. 6, pp. 1284–1290, Nov. 2015, doi: 10.1590/1516-1439.022915.

[22] K. Holschemacher, T. Mueller, and Y. Ribakov, "Effect of steel fibres on mechanical properties of high-strength concrete," *Materials & Design (1980-2015)*, vol. 31, no. 5, pp. 2604–2615, May 2010, doi:

10.1016/j.matdes.2009.11.025.

[23] W.-C. Liao, W. Perceka, and E.-J. Liu, "Compressive Stress-Strain Relationship of High Strength Steel Fiber Reinforced Concrete," *ACT*, vol. 13, no. 8, pp. 379–392, Aug. 2015, doi: 10.3151/jact.13.379.

[24] P. Payakaniti, N. Chuewangkam, R. Yensano, S. Pinitsoontorn, and P. Chindaprasirt, "Changes in compressive strength, microstructure and magnetic properties of a high-calcium fly ash geopolymer subjected to high temperatures," *Construction and Building Materials*, vol. 265, p. 120650, Dec. 2020, doi: 10.1016/j.conbuildmat.2020.120650.

[25] K. Korniejenko, M. Łach, and J. Mikuła, "The Influence of Short Coir, Glass and Carbon Fibers on the Properties of Composites with Geopolymer Matrix," *Materials*, vol. 14, no. 16, p. 4599, Aug. 2021, doi: 10.3390/ma14164599.

[26] B. Ali, L. A. Qureshi, S. H. A. Shah, S. U. Rehman, I. Hussain, and M. Iqbal, "A step towards durable, ductile and sustainable concrete: Simultaneous incorporation of recycled aggregates, glass fiber and fly ash," *Construction and Building Materials*, vol. 251, p. 118980, Aug. 2020, doi: 10.1016/j.conbuildmat.2020.118980.

[27] J. Asanammal Saral, S. Gayathri, M. Tamilselvi, and B. Raghul Raj, "An Experimental Study on Fibre Reinforced Geopolymer Concrete Composites- Glass Fibre, Copper Slag," *IJET*, vol. 7, no. 3.34, p. 433, Sep. 2018, doi: 10.14419/ijet.v7i3.34.19344.

[28] P. Bishetti, "Glass Fiber Reinforced Concrete," *IJCE*, vol. 6, no. 6, pp. 23–26, Jun. 2019, doi: 10.14445/23488352/IJCE-V6I6P105.

[29] T. Sathanandam, P. O. Awoyera, V. Vijayan, and K. Sathishkumar, "Low carbon building: Experimental insight on the use of fly ash and glass fibre for making geopolymer concrete," *Sustainable Environment Research*, vol. 27, no. 3, pp. 146–153, May 2017, doi: 10.1016/j.serj.2017.03.005.

[30] K. Lakshmi and M. S. N. Rao, "Experimental Study on Geopolymer Concrete by using Glass Fibers," *International Research Journal of Engineering and Technology (IRJET)*, vol. 06, no. 11, p. 6, Nov. 2019.

[31] K. Vijai, R. Kumutha, and B. G. Vishnuram, "Properties of Glass Fibre Reinforced Geopolymer Concrete Composites," *Asian Journal of Civil Engineering (Building and Housing)*, vol. 13, no. 4, pp. 511–520, 2012.

[32] C. Jithendra and S. Elavenil, "Role of Superplasticizer on GGBS based Geopolymer Concrete under ambient curing," *Materials Today: Proceedings*, vol. 18, pp. 148–154, 2019, doi: 10.1016/j.matpr.2019.06.288.

[33] G. Mathew and B. M. Issac, "Effect of molarity of sodium hydroxide on the aluminosilicate content in laterite aggregate of laterised geopolymer concrete," *Journal of Building Engineering*, vol. 32, p. 101486, Nov. 2020, doi: 10.1016/j.jobe.2020.101486.

[34] ASTM, "Standard Test Method for Slump of Hydraulic-Cement Concrete," ASTM International, West Conshohocken, PA, Standard C143/C143M – 10, 2010. doi: 10.1520/C0143_C0143M.

[35] BSI, "Testing hardened concrete. Compressive strength of test specimens," British Standards Institution, London,

United Kingdom W4 4AL, Standard 12390–3, 2009. [Online]. Available: www.bsi-global.com/

[36] ASTM, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA, Standard C496, 2011.

[37] B. Nematollahi, J. Sanjayan, J. X. H. Chai, and T. M. Lu, "Properties of Fresh and Hardened Glass Fiber Reinforced Fly Ash Based Geopolymer Concrete," *KEM*, vol. 594–595, pp. 629–633, Dec. 2013, doi:

10.4028/www.scientific.net/KEM.594-595.629.

[38] J. Ganta, M. S. Rao, S. Ojarestaghi, C. Bhojaraju, and S. Vempada, "Hybrid steel/glass fiber-reinforced selfconsolidating concrete considering packing factor: Mechanical and durability characteristics," *Structures*, vol. 28(3), pp. 956–972, 2020, doi: 10.1016/j.istruc.2020.09.042.

[39] 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.

[40] R. Alyousef, B. Ali, A. Mohammed, R. Kurda, H. Alabduljabbar, and S. Riaz, "Evaluation of Mechanical and Permeability Characteristics of Microfiber-Reinforced Recycled Aggregate Concrete with Different Potential Waste Mineral Admixtures," *Materials*, vol. 14, no. 20, p. 5933, Oct. 2021, doi: 10.3390/ma14205933.