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Experimental Investigation on Properties of FlyAsh based Geopolymer Concrete Blended with GGBS and Lime

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The main aim of the experimental investigation is to characterize M20 grade Geopolymer concrete (GPC) prepared using Fly Ash, Ground Granulated Blast Furnace Slag and Lime and cured at ambient temperature. Additionally, the durability of GPC in a temperature and chemical environment was investigated. Initially, 100% Fly Ash based control GPC Test specimens were molded using alkali activating solution. The control GPC prepared using 100% FA has not attained the required strength. Then, two types of test specimens were cast, the first type consists of alkali activating solution and 90% FA, 1-5% of GGBS and 9-5%, Lime and the second type consists of alkali activating solution and 95% FA and GGBS 4 -1% and Lime 1-4% combination. According to the test findings, it can be observed that the required target compressive strength is acquired with an economical GPC mix proportions of 90% FA + 1% GGBS + 9% Lime and 95% FA + 2% GGBS + 3% Lime from type1 and type2 combinations, respectively. Additionally, experimental studies were conducted on the above two sets of economical GPC mix proportions. The GPC test specimens were exposed to different elevated temperatures in the range from 1000C to 8000C and then the durability study was conducted utilizing 5% concentration of HCl, H2SO4, MgSO4 and NaCl environment. The test results indicate reduced compressive strength of GPC when is exposed to the temperatures in the range from 2000C to 8000C and also chemical attack. The weight loss of GPC of various proportions adopted is discovered to be moderate to minimum when subjected to elevated temperatures and chemical attack. However, the durability of GPC prepared using 95% FA+ 2% GGBS +3% Lime is superior to 90 % FA+ 1% GGBS + 9% Lime with respect to the temperature and chemical attack. The results are also supported by XRD and SEM analysis.

Keywords: GPC, FA, GGBS, Lime, Compressive Strength, Temperature, Chemical Environment and Durability.

1. Introduction

The population, industrialization, and urbanization is increasing worldwide, and the depletion of natural resources is occurring at a faster rate by the construction sector among the principal sectors in the world. The research investigation is committed to growing sustainable materials fit for the present environment. Use of Geopolymer Concrete is among the most effective to reduce consumption of Portland cement and reduce global warming (Tafheem, et.al, 2011; Naik, T. R, 2008; Malhotra, V. M, 2002; Juenger, M. C. G, et.al 2011) In Geopolymer concrete, an inorganic sodium silicate hydrate is used to activate the materials such as Fly Ash, metakaolin, GGBS, silica fume Rice husk to form very strong binding material sodium alumina silicate hydrate in the alkaline activating solution (Davidovits, J. 1994; Davidovits, J. (Ed.), 2005; Wallah, S.E. & Rangan, B. V, 2006). The alkali solution concentration, the silicate solution to hydroxide solution ratio (Álvarez-Ayuso, E, et.al, 2008; Singh, B, et.al, 2016), and the solids to activating solution ratio (Saranya, P., et.al, 2019; Ryu, et.al, 2013; Yasemin, A., et.al, 2009) are the parameters having more impact on the mechanical properties of geopolymer concrete. Further, few more studies reveal the positive impact of a solution of sodium hydroxide concentration on the strength of geopolymer concrete (Nagalia, G., et.al, 2016; Wang, H., et.al, 2005; Tho-In, T., et.al, 2012). Now-a-days, more fire accidents are happening in buildings due to various reasons. The types and characteristics of materials in construction sector are playing a significant role to reduce impact of fire effect in buildings. Research (Lahoti, M., et.al, 2019; Lahoti, M., et.al, 2018; Fernández-Jiménez, A., et.al, 2010) reveals that geopolymer concrete is one which is performing better during fire accidents even at high temperatures where OPC concrete can't compete with geopolymer concrete. (P.K. Sarker, et al,2014) observed that fly ash geopolymer concrete experience minor surface cracking even exposed to higher temperature 800^0C, this is mainly because of heat travels faster in geopolymer concrete than in OPC concrete, resulting in lesser temperature gradient inside the concrete made of geopolymer. (Z.Zhang, J.L. et al., 2015) discovered that fly ash geopolymer concrete possesses superior thermal insulating qualities than OPC concrete, at the same density and strength. (Tian Lingyu, et al., 2021) noted that Fly Ash-based GPC has performed better, such as low shrinkage, strong resistivity and low permeability to temperature, good durability and good mechanical strength. (Hake, S. L., et al., 2018) found that addition of 10% lime content yields highest compressive strength. At higher lime percentages GPC become harsher, compromising fresh and hardened properties. (Lekshmi, S., et al., 2022) reveals that incorporation of lime and GGBS enhanced resistance to abrasion and defense against chemical assaults. (Nagalia, G., et al., 2016) discovered that fly ash with high CaO improved compressive strength significantly. (Diab, M. A. 2022) reveals that compact microstructure with reduced voids with addition of 2% lime content in Fly Ash GPC cured in steam. (M.Y.J. Liu, et al., 2014) found that 20% fly ash substitution with palm oil fuel ash attained compressive strength of 30 MPa and higher strength over age for ambient cured Oil palm shell Geopolymer concrete. However, attaining good strength and performance in aggressive environmental conditions of geopolymer concrete can be challenging due to variations in mineral admixtures properties, Proper mix design and curing protocols are crucial. Hence, an experimental examination was conducted in the current study to produce M20 grade Concrete made of geopolymer with ambient curing and to evaluate its performance.

2. Geopolymer Concrete

The geopolymer concrete is prepared with coarse aggregates (nominal maximum size of 20 mm), river sand, alkali activating solution made of sodium hydroxide and sodium silicate solutions, low-calcium Fly Ash, Ground Granulated Blast Furnace Slag and Lime. Studies on

GPC's durability were conducted in terms of exposure to high temperature, and various chemical environmental conditions (Sulfuric acid, Hydrochloric acid, Sodium Chloride and Magnesium Sulphate).

2.1. Control Geopolymer Concrete Mix

The alkali activating solution is prepared by mixing 8M NaOH solution with Na_2SiO_3 solution with Na_2SiO_3 to NaOH ratio of 2 and the proportion of liquid to Fly Ash plus additives is 0.5. The control mixture was geopolymer concrete made solely with fly ash. The amounts of the control GPC mix utilized in this experimental study are listed in Table 1.

Table 1 Quantities of Ingredients of Control GPC Mix (kg/m^3)

Fly Ash	Aggregate			Na_2SiO_3	NaOH	Alkali Solution
	Fine	20 mm	12 mm			
372	501.5	603.9	402.6	124	19.84	186

According to the test results, the control GPC's 28-day compressive strength after being cured at room temperature fell short of M20 grade. Hence, two different types of GPC mixes were prepared. 90% FA was employed in the first type, and 1–5% GGBS and 9–5% lime were used to replace the remaining 10% of FA. With the second type, 95% FA was used, and the remaining 5% of FA was substituted with GGBS 1–4% and Lime 4–1%. Table No. 2 displays the various combinations of fly ash (FA), ground granulated blast furnace slag (GGBS), and lime used to prepare geopolymer concrete.

Table 2. Various Types of GPC Mixes using GGBS and Lime

Type of GPC	Mix Id	FA (%)	GGBS %)	Lime (%)	Alkali Activating Solution (%)
Control	CM	100	0	0	50
Type-A	A1	90	5	5	50
	A2	90	4	6	50
	A3	90	3	7	50
	A4	90	2	8	50
	A5	90	1	9	50
Type-B	B1	95	1	4	50
	B2	95	2	3	50
	B3	95	3	2	50
	B4	95	4	1	50

3. Preliminary Experimental Investigation

3.1 Test Specimens

In order to determine compressive strength of GPC, cubes of size 100 mm were used and for flexural strength, test samples of size 100 mm×100 mm×500 mm were used. Every test specimen was tested at 3, 7, 28, 90, 180, and 365 days after being cured at room temperature.

3.2 Compressive Strength of 90% Fly Ash, (5-1%) GGBS and (5-9%) Lime Geopolymer Concrete Mixes

Figure 1 illustrates how the cube compressive strength of geopolymer concrete varies for different fly ash, GGBS, and lime combinations at varying curing times at room temperature.

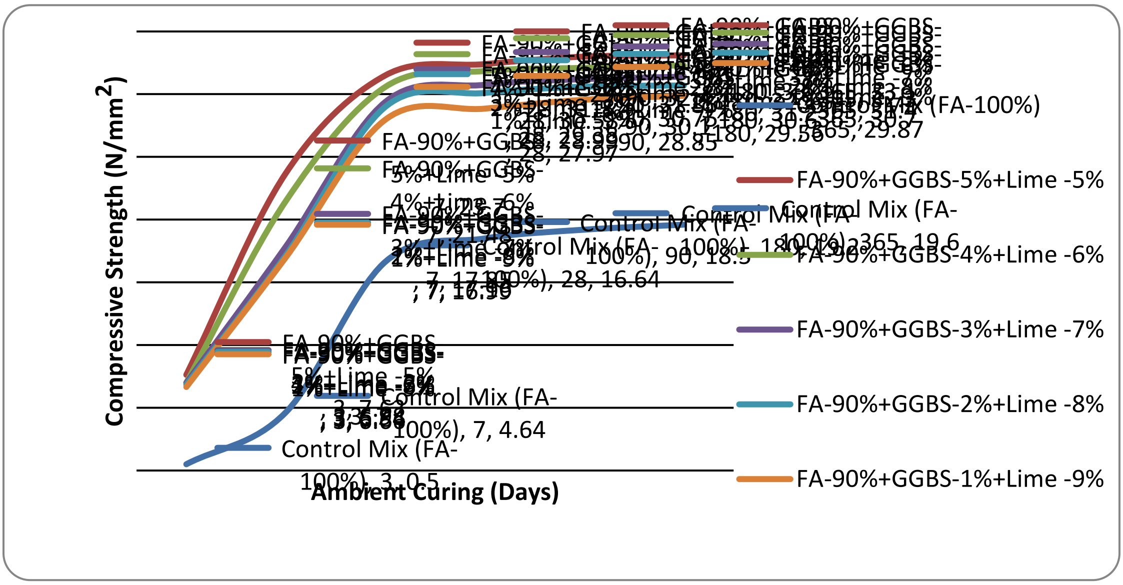

Figure 1 Variation of cube compressive strength of Geo-polymer Concrete with Age for various combinations of Fly-Ash, GGBS and Lime

The test findings show that after 28 days of ambient curing, the Geo-Polymer concrete mixes made with different Fly-Ash, GGBS, and Lime combinations had reached the desired target strength. Geo-polymer concrete prepared using 90% FA + 5% GGBS + 5% Lime exhibits enhanced compressive strength compared to control mix and other combinations for varying ages of ambient curing.

3.3 Flexural Strength of 90% FA, (5-1%) GGBS and (5-9%) Lime GPC

The variation of flexural strength of Control Geopolymer Concrete and also with different combinations of Fly Ash, Ground Granulated Blast Furnace Slag and Lime, i.e., (90% FA + 5% GGBS+5% Lime), (90% FA + 4% GGBS+6% Lime),(90% FA + 3% GGBS+7% Lime), (90% FA + 2% GGBS+8% Lime) and (90% FA + 1% GGBS+9% Lime), with age is shown in Figure 2.

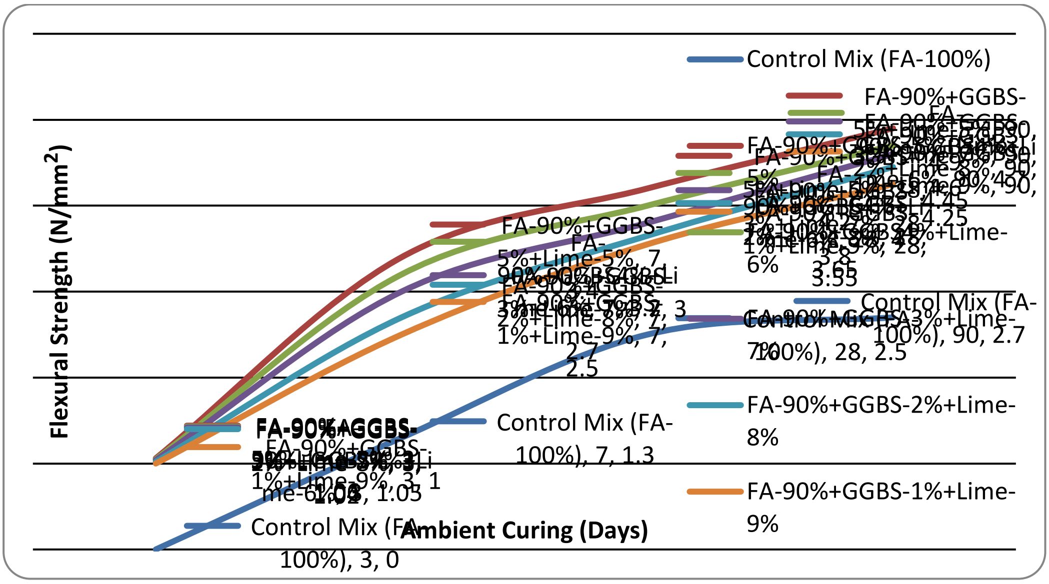

Figure 2 Variation of Flexural strength of Geo-polymer Concrete with age for various combinations of Fly Ash, GGBS and Lime

It's fascinating to observe that the variation of flexural strength is also similar to compressive strength. It is evident from the flexural strength test findings that geo-polymer concrete prepared with (90% FA + 5% GGBS+5% Lime) exhibits excellent flexural strength in contrast to control GPC and remaining combinations for varying ages of ambient curing.

3.4 Compressive Strength of 95% FA, (1-4%) GGBS and (4-1%) Lime GPC

Figure 3 shows the compressive strength variation of Geo-polymer Concrete mixes for various combinations of Fly-ash GGBS and Lime at different periods of curing at ambient temperature.

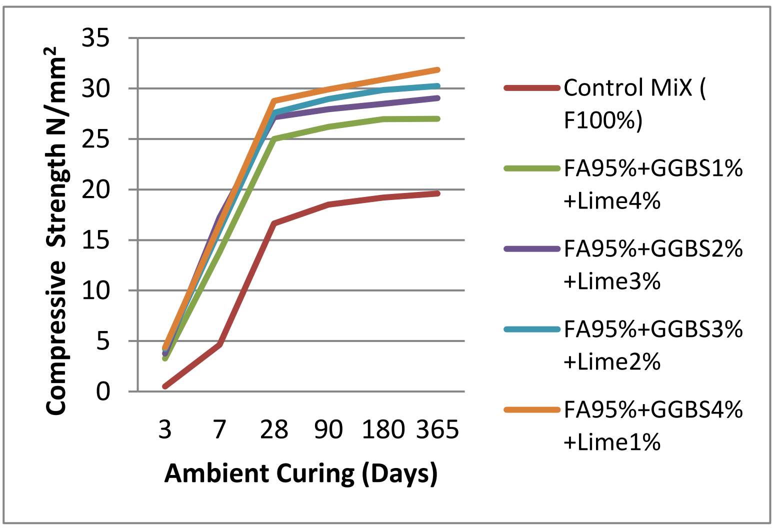

Figure 3 Variation of compressive strength of Geo-polymer Concrete with Age for various

combinations of Fly-Ash, GGBS and Lime

Based on test results, at 28 days of ambient curing, Geo-Polymer concrete mixes made with different Fly-Ash, GGBS, and Lime combinations have exceeded the necessary target strength except 95% FA + 1% GGBS + 4% Lime Additionally, it has been noted that at three days of ambient curing, geopolymer concrete made with different mixes of fly ash, GGBS, and lime has achieved compressive strength that is roughly 15% of the desired strength.. It is evident that geo-polymer concrete prepared with (95% FA + 4% GGBS + 1% Lime) exhibits superior compressive strength compared to control mix and other combinations of GPC at different periods of ambient curing.

3.5 Flexural Strength of 95% FA, (1-4%) GGBS and (4-1%) Lime GPC

The variation of flexural strength of Control Geopolymer Concrete and also with different combinations of Fly Ash, Ground Granulated Blast Furnace Slag and Lime i.e., (95% FA + 1% GGBS+4% Lime), (95% FA + 2% GGBS+3% Lime),(95% FA + 3% GGBS+2% Lime) and (95% FA + 4% GGBS+1% Lime) with age is shown in Figure 4.

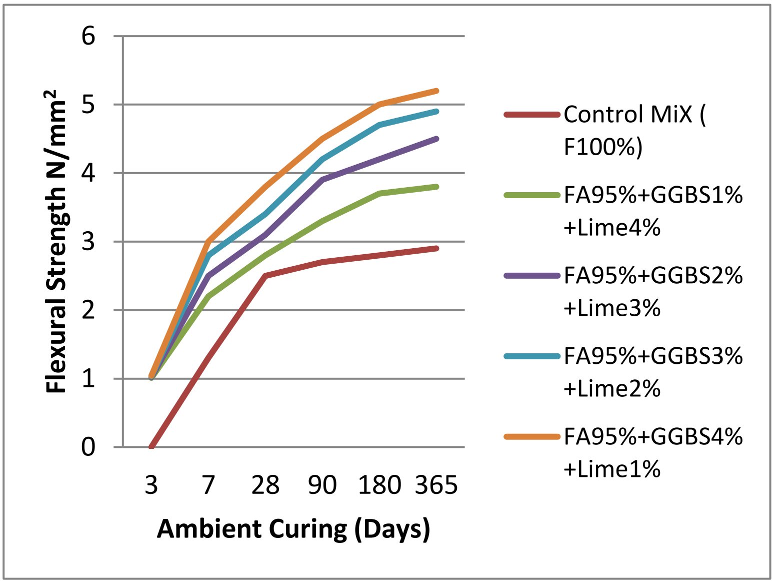

Figure 4 Variation of Flexural Strength of Geopolymer Concrete with age for various combinations of Flyash, GGBS and Lime

Interestingly, it is noteworthy that the variation of flexural strength is also similar to compressive strength. Based on the flexural strength test results it is evident that geo-polymer concrete prepared with (95% FA + 4% GGBS+1% Lime) exhibits excellent flexural strength compared to control Mix, (95% FA + 1% GGBS+4% Lime), (95% FA + 2% GGBS+3% Lime) and (95% FA + 3% GGBS+2% Lime). Additionally, it can be seen that GPC made with a mixture of 90% FA + 5% GGBS + 5% Lime has a higher flexural strength than GPC made with 95% FA + 4% GGBS + 1% Lime. Considering the test findings, the required target compressive strength is acquired with an economical GPC mix proportions of (90% FA + 1% GGBS + 9% Lime) and (95% FA + 2% GGBS + 3% Lime) from type1 and type2 combinations, respectively. Additionally, experimental studies were conducted on the above two combinations of GPC mix proportions.

4. Durability Properties of GPC

The test specimens were also exposed to 100^0C, 200^0C, 400^0C, 600^0C and 800^0C for 1 to 4 hours period with a rise in step size of 1 hr. Then the compressive strength of GPC test specimens was determined. The test specimens were also exposed to 5% of hydrochloric acid, sulfuric acid, sodium chloride and magnesium sulphate environment for 28,56 and 90 days.

4.1 Effect of Temperature

(i) Compressive Strength Variation in Geopolymer Concrete (90%FA+1%GGBS+9%Lime)

Figure 5 (a) and (b) illustrates the percentage change in compressive strength of geopolymer concrete that was exposed to different temperatures for varied exposure times (90% FA+1% GGBS+9% Lime and 95 % FA+2% GGBS+3% Lime). As may be seen, there is no change in compressive strength at 1-hour exposure and compressive strength moderately increased at 100^0C exposed from 2 hr to 4 hr duration. The results reveal that from 200^0C the compressive strength dramatically dropped with increasing temperature and exposure time.

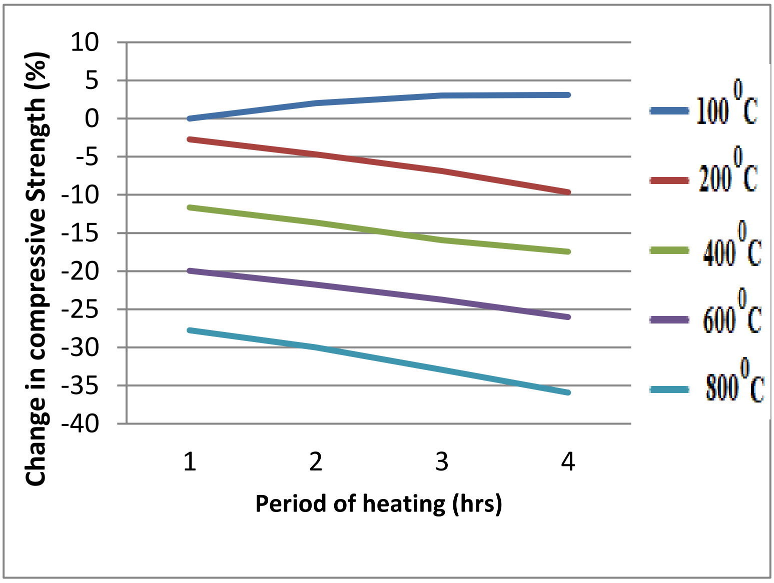

Figure 5(a) Percentage change in compressive strength of Geopolymer concrete with FA90%+GGBS1%+ Lime9% Exposed to different temperatures and durations

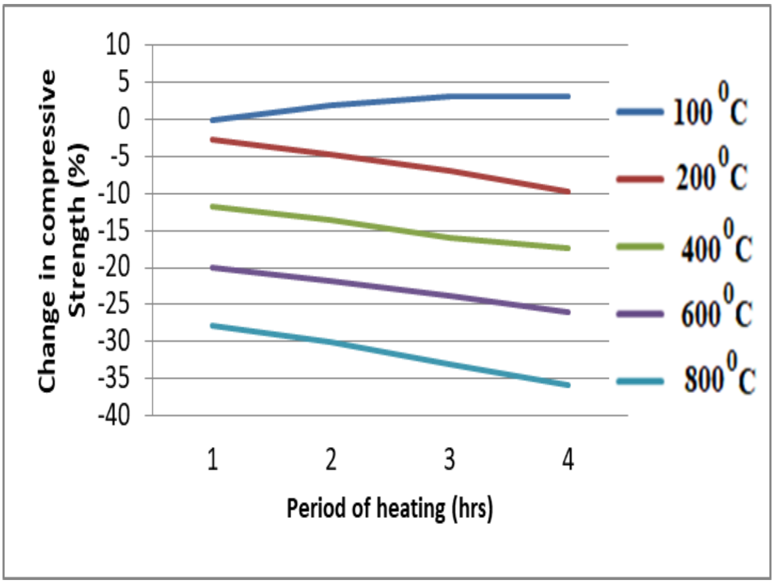

Figure 5(b) Percentage change in compressive strength of Geopolymer Concrete with FA95% + GGBS2% + Lime3% Exposed to different temperatures and durations

(ii) Weight Loss of Geopolymer Concrete (90%FA+1%GGBS+9% Lime)

The change in weight of Geopolymer concrete (90%FA+1%GGBS+9% Lime) and (95% FA+2% GGBS+3% Lime) exposed to various temperatures and different durations is displayed in Figure 6 (a) and (b). It is evident from the test findings that no change in weight at 100^0C but weight loss can be observed when the temperature and time of exposure is increased. It is observed that the loss in weight is significantly decreased from 200^0C to 400^0C at 1, 2, 3 and 4hr period of heating but not significant from 400^0C to 800^0C respectively.

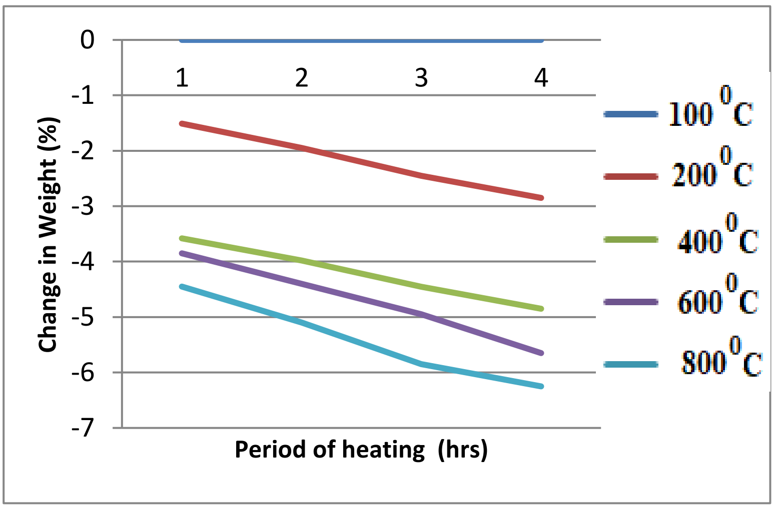

Figure 6 (a) Percentage Change in Weight of Geopolymer Concrete with 90%FA+1%GGBS+9% Lime subjected to different temperatures and exposure period

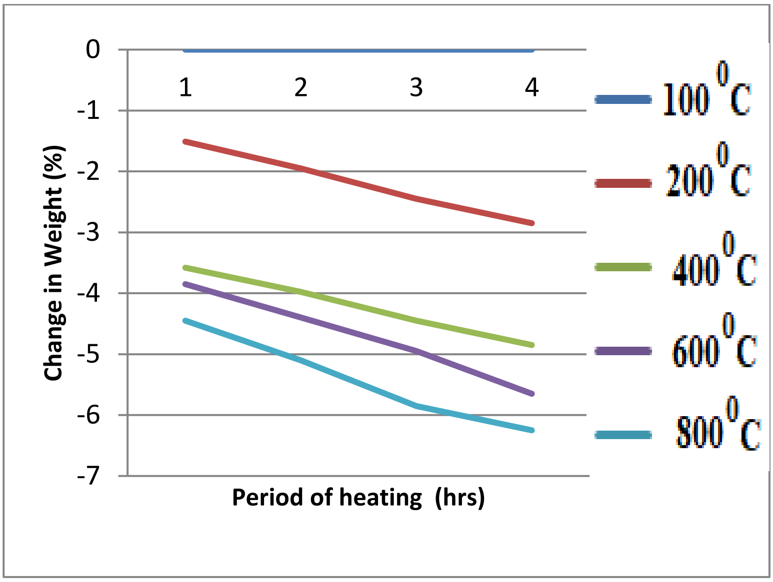

Figure 6(b) Percentage Change in Weight of Geopolymer concrete with 95%FA +2% GGBS + 3%Lime subjected to different temperatures and exposure period

4.2 Effect of Chemical Attack

4.2.1 Effect of Chemical Attack on Compressive Strength of Geopolymer Concrete

The impact of chemical attack on GPC (90%FA+1%GGBS+9% Lime) and (95% FA+2% GGBS+3% Lime) is studied by immersing the test specimens separately for 28 days, 56 days and 90 days in a solution containing 5% HCl, 5% H_2SO_4, 5% $MgSO_4$, and 5% NaCl concentration. Figure 7 (a) and (b), shows the fluctuation in compressive strength of GPC exposed to different chemical environmental conditions for various periods.

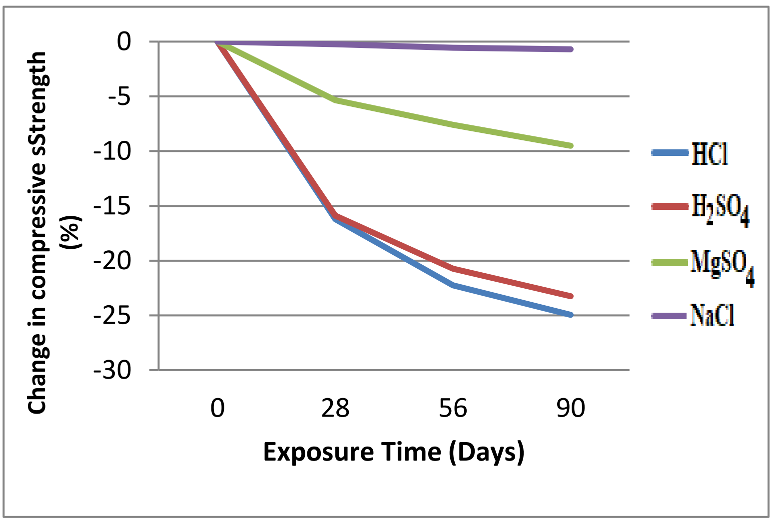

Figure 7(a) Percentage Change in Compressive Strength of GPC (FA90% + GGBS1% +

Lime9%) Exposed to different periods of various chemicals environment.

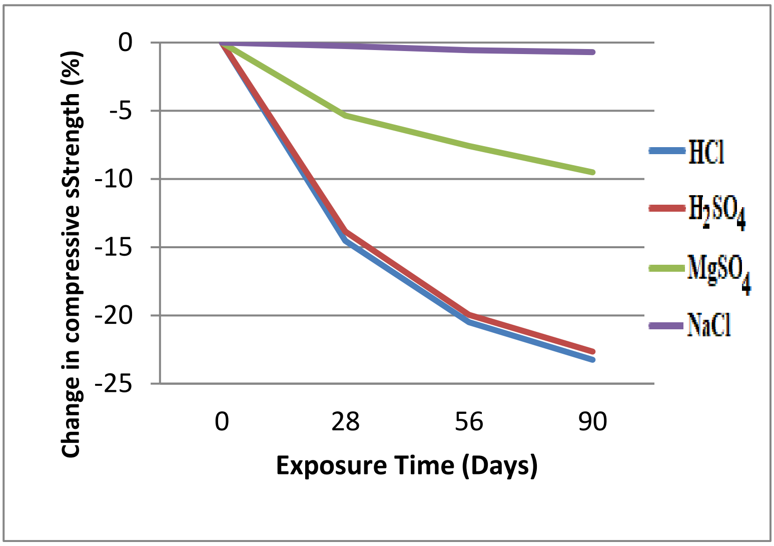

Figure 7(b) Percentage Change in Compressive Strength of GPC (FA95% + GGBS 2% + Lime 3%) Exposed to different periods of various chemicals environment

Regardless of the kind of chemical attack, GPC's compressive strength drops as exposure duration increases. GPC's compressive strength decreases significantly when exposed to HCl and H_2SO_4, but not much when exposed to $MgSO_4$ and NaCl. It is evident that GPC exposed to an HCl atmosphere experiences a maximum loss in compressive strength of -25%.

4.2.2 Effect of Chemical Attack on Weight Loss of Geopolymer Concrete

The individual influence of 5% concentration of HCl, H_2SO_4, $MgSO_4$ and NaCl on weight loss of Geopolymer Concrete (90% FA + 1% GGBS + 9% Lime) and (95% FA+2% GGBS+3% Lime), is shown in Figure 8 (a) and (b).

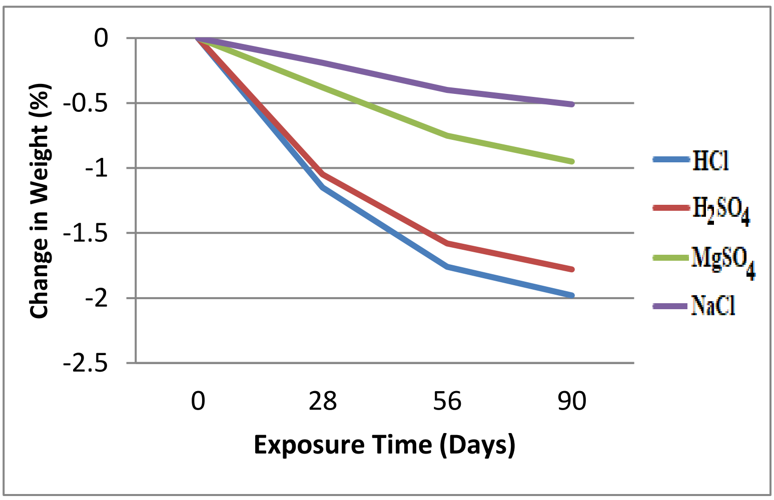

Figure 8(a) Percentage Loss of Weight of (90% FA + 1% GGBS+ 9% Lime) GPC Exposed to different periods under Various Types of Chemical Environment

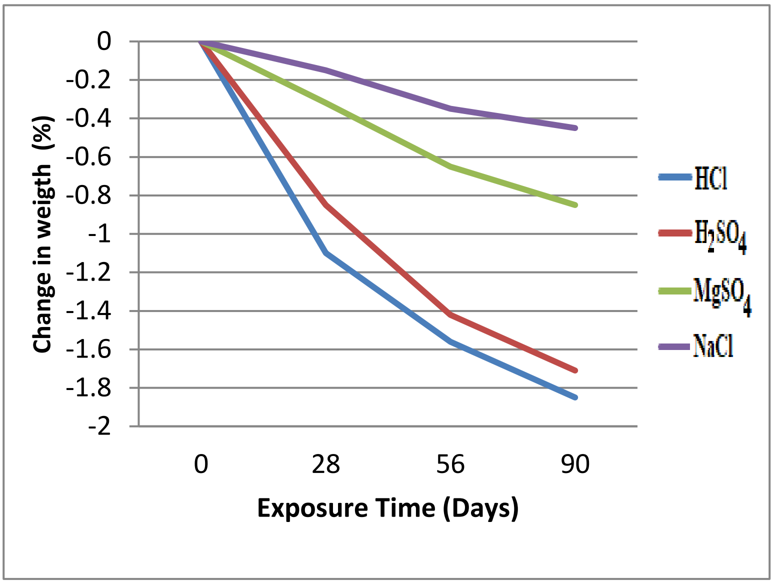

Figure 8(b) Percentage Loss of Weight of (95% FA + 2% GGBS+ 3% Lime) GPC Exposed to different periods under Various Types of Chemical Environment

Regardless of the kind of chemical attack, the weight loss of GPC rises as the exposure duration increases. GPC's weight loss % is noteworthy in case of HCl and is insignificant in NaCl environment. It is evident that maximum percentage of GPC exposed to HCl environment is around 2% when exposed to 90 days.

5. Microstructure Analysis of Flyash based Geo-polymer Concrete

5.1 X-Ray Diffraction (XRD) Analysis

X-Ray Diffraction (XRD) analysis is a one of the methods to find mineral composition present in the Geo-polymer concrete. Figure 9(a),9(b) and 9(c) show the peak intensities for control mix, (FA90% + GGBS5% + Lime5%), and (FA95% + GGBS4% + Lime1%) GPC for 28 days at ambient curing. When GGBS is present, the intensity of SiO2 (Quartz) at $2\theta=28^0$ has increased compared to Control GPC.

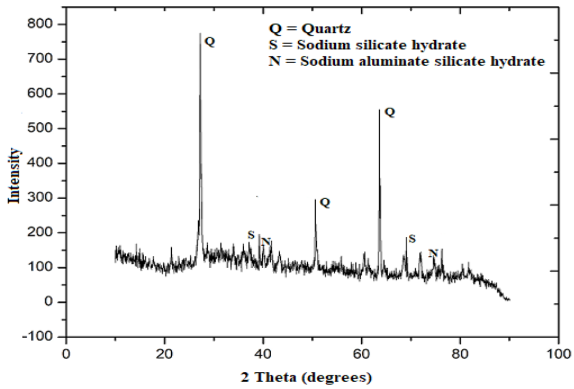

Figure 9 (a) XRD analysis of Control GPC at 28 Days

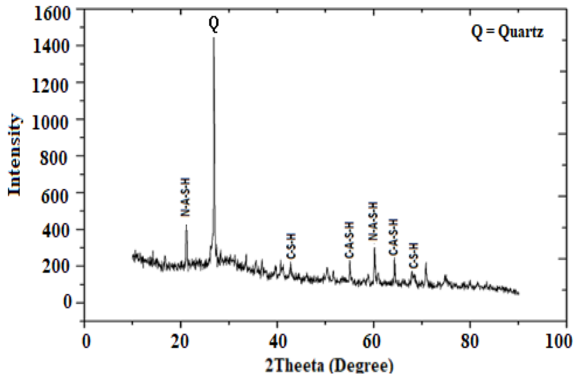

Figure 9 (b) XRD analysis of FA90%+GGBS5%+Lime5% GPC at 28 Days

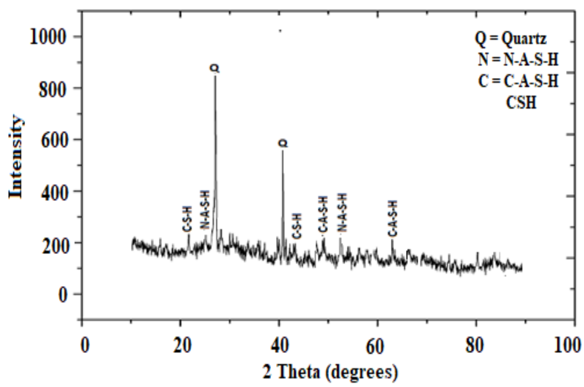

Figure 9 (c) XRD analysis of FA95%+GGBS4%+Lime1% GPC at 28 Days

Quartz (Q), Sodium silicate hydrate (N-S-H) and sodium aluminum silicate hydrate (N-Al-S-H) are found in the XRD analysis of fly ash based control GPC. When fly ash-based GPC made with GGBS and lime is present, calcium aluminum silicate hydrate (C-Al-S-H) and calcium silicate hydrate (C-S-H) are also detected in addition to quartz (Q) and sodium aluminum silicate hydrate (N-Al-S-H). This results in gain in compressive strength of concrete.

5.2 SEM Analysis of Control GPC

With SEM analysis the electrons interact with fly ash based geopolymer concrete atoms and information is captured on surface topography. The SEM analysis is done on the samples cured at 28 days of ambient curing condition.

The Figure 10(a),(b) and (c) show that the SEM analysis of control geopolymer concrete, (FA90% + GGBS5% + Lime5%) GPC and (FA95% + GGBS4% + Lime1%) GPC. Figure shows the formation of homogeneous matrices of N-S-H and N-A-S-H in case of control GPC and N-A-S-H, C-A-S-H and C-S-H in fly ash based geopolymer concrete with GGBS and Lime. Sodium aluminum silicate hydrate (N-Al-S-H) is the product of the interaction between fly ash and (N-S-H). In the presence of an activator (N-S-H) and the reaction product of (FA + GGBS+Lime), N-Al-S-H and C-Al-S-H are formed. As N-Al-S-H and C-Al-S-H have significant binding properties, resulting in the geo-polymer concrete's increased strength.

Figure 10 (a) SEM analysis of Control GPC at 28 Days

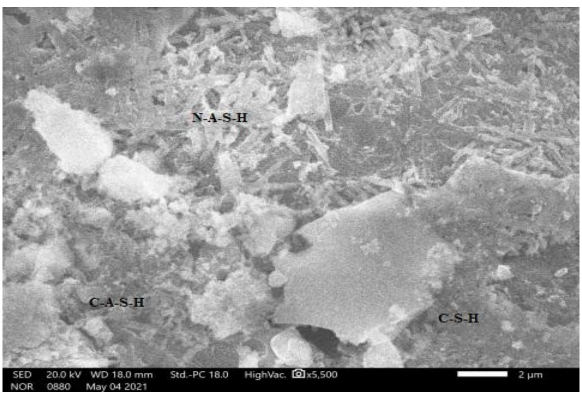

Figure 10 (b) SEM analysis of FA90%+GGBS5%+Lime5% GPC at 28 Days

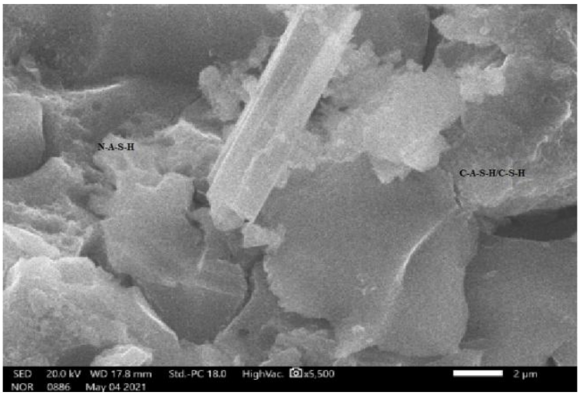

Figure 10 (c) SEM analysis of FA95%+GGBS4%+Lime1% GPC at 28 Days

In a geopolymer concrete mix made with fly ash and GGBS and lime, as the GGBS content decreased and lime content is increased for constant fly ash content (90%), results in reduced aluminum and increased calcium oxide content. Hence, the formation of N-A-S-H content is decreases while C-A-S-H and C-S-H increases. This leads to improved performance of (FA90%+GGBS5%+Lime5%) geopolymer concrete with respect to strength. In case of 95% fly ash based geopolymer concrete if the GGBS content increases and lime content is decreased, leads to increase in aluminum content and decrease in calcium oxide. This results in formation of more N-A-S-H content and less quantity of C-A-S-H and C-S-H. Hence the superior performance of (FA95%+GGBS4%+Lime1%) geopolymer concrete in terms of strength that can be acquired.

6. Conclusions

The following conclusions are drawn from the present experimental investigation:

- Among the various combinations of 90% Fly ash based geopolymer concrete mixes, geopolymer concrete mix with 90% FA+1% GGBS+9% Lime is discovered to be an economical and satisfying the strength requirements. It is evident that the various 90% fly ash based geopolymer concrete mixes exhibit better strength properties compared to the 100% fly ash based geopolymer concrete. The excellent strength properties of 90% fly ash based geopolymer concrete can be attributed to the formation of sodium aluminum silicate hydrate(N-Al-S-H), calcium aluminum silicate hydrate (Ca-Al-S-H) and Calcium silicate hydrate(C-S-H) compounds. Similar observations were made in case of 95% Fly ash based geopolymer concrete mixes and 95% FA+2% GGBS+3% Lime geopolymer concrete mix is found to be an economical and exhibited good strength properties. FA95%+GGBS2%+Lime3% has shown improved performance in terms of flexural and compressive strength compared to FA90%+GGBS1%+Lime9% geopolymer concrete.

- When the economical geopolymer concrete is exposed to temperature, 100^0C to 800^0C, the geopolymer concrete exposed to 100^0C for 4 hr, gain in compressive strength is seen in contrast to ambient curing. However, geopolymer concrete's strength has declined as the degree and duration of temperature is increased. The Weight loss is insignificant even at high temperature. The FA95%+GGBS2%+Lime3% geopolymer concrete has performed better than FA90%+GGBS1%+Lime9% geopolymer concrete.

- Under chemical environmental exposure, geopolymer concrete FA95%+GGBS2%+Lime3% has done better in relation to weight loss and strength compared to FA90%+GGBS1%+Lime9% geopolymer concrete. Compared to sulfuric acid, the hydrochloric acid environment is more susceptible.

References

1. Tafheem, Zasiah, ShovonaKhusru, and SabreenaNasrin.(2011). Environmental impact of green concrete in practice. International Conference on Mechanical Engineering and Renewable Energy. Vol. 22.
2. Naik, T. R. (2008). Sustainability of concrete construction. Practice periodical on structural design and construction, 13(2), 98-103.
3. Malhotra, V. M. (2002). Introduction: sustainable development and concrete technology. Concrete International ,24(7).
4. Juenger, M. C. G., Winnefeld, F., Provis, J. L., &Ideker, J. H. (2011). Advances in alternative cementitious binders. Cement and concrete research, 41(12), 1232-1243.
5. Davidovits, J. (1994). Geopolymers: man-made rock geosynthesis and the resulting development of very early high strength cement. Journal of Materials education, 16, 91-91.
6. Davidovits, J. (Ed.). (2005). Geopolymer, green chemistry and sustainable development solutions: proceedings of the world congress geopolymer 2005. Geopolymer Institute.
7. Wallah, S.E. & Rangan, B. V. (2006). Low-calcium fly ash-based geopolymer concrete: long-term properties.Curtin University of Technology.
8. Álvarez-Ayuso, E., Querol, X., Plana, F., Alastuey, A., Moreno, N., Izquierdo, M., Font, O.,Moreno, T., Diez, S., Vázquez, E., and Barra, M. (2008). Environmental, physical and structuralcharacterisation of geopolymer matrixes synthesised from coal (co-)combustion flyashes. Journal of Hazardous Materials, 154(1–3), 175–183.
9. Singh, B., Rahman, M. R., Paswan, R., and Bhattacharyya, S. K. (2016). Effect of activator concentration on the strength, ITZ and drying shrinkage of fly ash/slag geopolymer concrete. Construction and Building Materials, Elsevier Ltd, 118, 171–
179.
10. Saranya, P., Nagarajan, P., and Shashikala, A. P. (2019). Performance evaluation of geopolymer concrete beams under monotonic loading. Structures, 20 (June), 560–569.
11. Ryu, G. S., Lee, Y. B., Koh, K. T., and Chung, Y. S. (2013). The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Construction and Building Materials, Elsevier Ltd, 47, 409–418.
12. Yasemin, A., Doğan, M., and Bayramlı, E. (2009). The effect of red phosphorus on the fire properties of intumescent pine wood flour – LDPE composites Yasemin. Finnish-Swedish Flame Days , (August 2008), 4B.
13. Nagalia, G., Park, Y., Abolmaali, A., &Aswath, P. (2016). Compressive strength and microstructural properties of fly ash–based geopolymer concrete. Journal of Materials in Civil Engineering, 28(12), 04016144.
14. Wang, H., Li, H., and Yan, F. (2005). Synthesis and mechanical properties of metakaolinite-based geopolymer. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 268(1–3), 1–6.
15. Tho-In, T., Sata, V., Chindaprasirt, P., and Jaturapitakkul, C. (2012). Pervious high-calcium fly ash geopolymer concrete. Construction and Building Materials, Elsevier Ltd, 30(325), 366–371.

16. Lahoti, M., K. H. Tan, and E.-H. Yang. (2019). A critical review of geopoly- mer properties for structural fire-resistance applications. Construction and Building Materials, Elsevier Ltd, 221, 514-526.
17. Lahoti, M., K. K. Wong, E.-H. Yang, and K. H. Tan. (2018). Effects of Si/Al molar ratio on strength endurance and volume stability of metakaolin geopolymers subject to elevated temperature. Ceramics International, 44(5), 5726–5734.
18. Fernández-Jiménez, A., J. Y. Pastor, A. Martín, and A. J. J. A. s.Palomo. (2010). High-temperature resistance in alkali-activated cement. Journal of American Ceramic Society, 93(10), 3411–3417.
19. P.K. Sarker, S. Kelly, Z. Yao, (2014). Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete, Materials & Design. Elsevier Ltd, 63, 584-592.
20. Z.Zhang, J.L. Provis, A. Reid, H. Wang, (2015). Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete, Cement .and Concrete .Composites. Elsevier Ltd, 62, 97-105.