Effect of elevated temperature on properties of geopolymer concrete: A review

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Abstract - *Geopolymers have been identified as a potentially effective alternative binder to ordinary Portland cement (OPC) for lowering carbon dioxide emissions and increasing waste recycling efficiency. Because of their availability and high silica and alumina concentrations, fly ash (FA) and ground-granulated blast-furnace slag (GGBFS) has been preferred raw materials for geopolymer concrete (GPC). The FA/GGBFS-based GPC offers a green technological solution for long-term development. As a consequence, the specialized evaluation of FA/GGBFS-based GPC used to replace traditional concrete has become incredibly important, as the relevant study results on the FA/GGBFS-based GPC may stimulate further research and implementation of this green building material. The response process of geopolymers, as well as the characteristics and durability of fresh and hardened FA/GGBFS-based GPC when subjected to extreme temperatures, are examined in this paper. Because of their ceramic-like characteristics, geopolymers are often thought to have superior fire resistance. Various experimental factors and their effects on the compressive strength of geopolymer concrete at increased temperatures have been researched, including specimen sizing, aggregate sizing, aggregate type and superplasticizer type, molarities of NaOH, and additional added water. The study identified specimen size and aggregate size as the two most important elements governing geopolymer performance at high temperatures (800 °C). The thermal mismatch between the geopolymer matrix and the aggregate causes strength loss at high temperatures.*

***Key Words*: Elevated temperature, Fly ash, Ground granulated Blast furnace Slag, Geopolymer concrete, Compressive strength.**

1. INTRODUCTION

Because of manufacturing methods of constituent materials such as cement binder, coarse and fine aggregates, and reactions in the cement hydration process, conventional Portland cement concrete, which is commonly used in civil construction, has a considerable impact on the greenhouse effect. According to reports, the cement sector contributed roughly 5% of world CO_2 emissions. Then, Geopolymer Concrete (GPC) emerged as one of the most significant technologies in the concrete industry for lowering carbon dioxide emissions in civil engineering operations. Geopolymer is created by the geopolymerization of aluminosilicate materials such as fly ash, metakaolin, and silica fume with an alkaline liquid activator such as sodium hydroxide and/or sodium silicate. In compared to cement, the use of fly ash or silica fume in GPC manufacture decreased CO_2 emissions by up to 5-6 times. As a result, experts throughout the world are paying close attention to this alternative cement-free material for both environmental and economic reasons.

When exposed to extreme temperatures, such as in a fire, concrete experiences major physical-chemical changes. This exposure, among other things, can cause significant deterioration in the concrete, such as loss of strength, reduction of modulus of elasticity, and degradation of durability, as well as cracking, spalling, destruction of the bond between the cement paste and the aggregates, and gradual deterioration of the hardened cement paste. Because of moisture loss, the density of concrete reduces as temperature rises. The thermal and mechanical qualities of concrete influence the fire resistance of structural components. These properties change dramatically with temperature and are also affected by the composition and qualities of the materials, as well as the pace of heating and other external factors.

Significant study has been undertaken on geopolymer concrete, with mechanical and durability qualities being intensively explored. However, nothing is known about the behavior of geopolymer concrete at high temperatures. The majority of the published papers indicated the residual strength of geopolymer concrete measured at room temperature following exposure to increased temperatures of up to 800°C. The compressive strength of geopolymer concrete under fire is extremely beneficial in the design and stability of reinforced concrete constructions. There is currently little information available on the compressive strength of geopolymer concrete at extreme temperatures. The behavior of geopolymer concrete at increased temperatures would differ from that of concrete due to thermal incompatibility between geopolymer paste and aggregates. The compressive strength of fly-ash-based geopolymer concrete is investigated in this review work at various raised temperatures of 200, 400, 600, and 800°C.

2. Literature Review

(Kotha & Rao, 2020) evaluated the compressive and flexural strength of geopolymer concrete formed of M sand subjected to heat curing at 60°C and 70°C with varied activator solution ratios, molarities of alkaline solution exposed to increased temperature are investigated. When compared to heat cured cubes at 60 °C, the compressive strength of GPC cubes exposed to 200°C cured at temperature 70°C is degraded by about 3.2 %, 1.15 %, and 4.5 % for 1:2.5 ratio of activator solution with molarities at 12, 16, and 20 molarity and about 1.35 %, 11.9 %, and 9.55% for 1:2 ratio of alkaline activator combination with concentrations of 12, 16, and 20 M of sodium hydroxide. Cubes with a ratio content of 1:2 at 16 molarity have higher strength than all other conditions that are heat cured at 60°C, whereas cubes with a ratio content of 1:2.5 at 20 molarity cured at 70°C have the lowest strength. As a consequence, the compressive strength of GPC heat cured at 60°C for 24 hours outperformed specimens cured at 70°C after being exposed to a high temperature to test thermal resistance.

(Luo, S.H., K.M, H.J.H, & Yu, 2021) analyses and shows the synergetic impact of physicochemical characteristics such as crystalline phase and binder gel stability, skeleton and bulk density, pore structure, cracking behavior, and mechanical strength of AAFS up to 800°C. To understand about cracking behavior, a quantitative evaluation of the crack is created. The findings indicate that fracture density has a linear correlation with ultrasonic pulse velocity. Before 100°C, fracture density and compressive strength have a positive connection, while beyond 100°C, they have a negative association. The incorporation of slag into geopolymers reduces geopolymeric behaviors such as additional geopolymerization and viscous sintering, but also exacerbates thermal damage due to its modular structure and unstable hybrid gel. The AAF and AAFS conceptual models are developed to describe the degrading mechanism of low slag containing geopolymers at increased temperatures.

(Zhang, et al., 2020) examines the behavior of ambient-cured and heat-cured low-calcium fly ash geopolymer concrete after prolonged exposure to high temperatures The concrete specimens were heated at 5°C/min to 100, 200, 400, 600, 800, and 1000°C. The effect of increasing exposure duration on geopolymer concrete was investigated using visual examination, mass loss, cracking extent, residual strength, and microstructure analysis. The overall length of cross-section cracks and surface cracks peaked at 800°C before declining at 1000°C. The findings reveal that all the concrete specimens could be heated at 600°C for 2 hours without losing strength. For all exposure temperatures, heat-cured geopolymer concrete specimens had greater compressive strengths than ambient-cured specimens. A crushing index of 7.7 % might be considered the lower limit for coarse aggregate in order to sustain the initial concrete's compressive strength at temperatures up to 600°C. Thus, SEM pictures demonstrate microstructural degradation, thermogravimetric analysis shows dehydration of geopolymer, and reduced strength of coarse aggregate as contributing reasons to strengths losses at temperatures over 600°C. Lastly, several prediction equations are developed that match very well with test findings of this work as well as those reported in the literature.

(L.Y. Kong & Sanjayan, 2009) The effect of higher temperature on geopolymer paste mortar and concrete prepared using fly ash as a precursor is investigated. Sodium silicate and potassium hydroxide solutions were used to create the geopolymer. Several experimental factors, including specimen size, aggregate size, aggregate type, and superplasticizer type, have been investigated. The study identified specimen size and aggregate size as the two most important elements governing geopolymer performance at high temperatures (800°C). Larger aggregate sizes produced good strength performances at both ambient and higher temperatures. The thermal mismatch between the geopolymer matrix and the particles initiates strength loss in geopolymer concrete at high temperatures.

(Y., K.M., H.J.H, & Qingliang, 2022) studies the activation of LS in conjunction with Class F fly ash, as well as the effect of ladle slag on fly ash geopolymer, with an emphasis on activation, hydrates assembly, conversion process, and thermal behavior. The results suggest that the distinct reaction process of ladle slag in an alkali activation system has a favorable effect on fly ash geopolymers. The initially hydrated CAH phases change into C-A-S-H in an alkaline environment rich in soluble Si, which not only delays conversion and increases mechanical strength but also preserves geopolymerization. The hybrid geopolymer system outperforms pure fly ash geopolymers in terms of thermal performance, especially at high temperatures. At high temperatures, more stable crystalline phases are generated as ladle slag replacement increases. With 25 wt. % ladle slag addition, a high residual compressive strength of 64.7 MPa is attained after 800 °C exposure, compared to 55.2 MPa in pure fly ash geopolymers.

(Hager, Mateusz, & Katarzyna, 2021) The effect of temperature exposure (up to 1000°C) on the microstructure and mechanical characteristics of geopolymer mortars is assessed. Four mixes with fly ash as the major precursor and four amounts of slag replacement (0, 10, 30, and 50 wt. %) were examined. The following mechanical performances and identification tests were carried out to determine damage evolution: ultrasonic pulse velocity, scanning electron microscope, mercury intrusion porosimetry, thermal strain measurements, differential thermal analysis, and thermogravimetry. The study sought to create a mortar composition that is thermally stable at high temperatures. Although slag inclusion significantly enhances the mechanical properties of fly ash geopolymer mortar (compressive strength above 100 MPa), the mortar without slag addition performed better at high temperatures. At 200°C, produced mortars increased their strength by 30% and doubled their tensile strength. Furthermore, compressive strength recovery of up to 90% at 1000°C was reported for developed mixtures, revealing the potential of fly ash geopolymer as a high-temperature application material.

(Valencia Saavedra & de Gutiérrez, 2017) Alkaline activated concretes made of fly ash (FA) and blast furnace slag (GBFS), as well as FA and Portland cement (OPC) in an 80:20 ratio, were subjected to temperatures ranging from 25°C to 1100°C. The physicochemical and mechanical changes were then assessed. The results show that the activated concretes outperform the control concretes (100 percent OPC). The residual strengths of the FA/GBFS and FA/OPC concretes at 1100°C are 15 and 5.5 MPa, respectively, but the OPC concrete lost 100 % of its strength. The activated matrix densifies at temperatures exceeding 900°C, and crystalline phases including such sodalite, nepheline, albite, and akermanite are found.

(Zhang, et al., 2020) offers a review of FA/GGBFS-based GPC used to replace traditional concrete has become critical because the associated study results on the FA/GGBFS-based GPC may support further research and implementation of this green building material. The reaction process of geopolymers, as well as the characteristics and durability of fresh and hardened FA/GGBFS-based GPC, are covered in this paper. Furthermore, the most recent statistics on the FA/GGBFS-based GPC are provided. The GPC offers great characteristics and a diverse set of application possibilities. However, there remain barriers to its widespread use in engineering and industry. As a result, researchers and engineers must do more study to give a comprehensive set of theory and technical applications for the FA/GGBFS-based GPC system.

(Amin, Elsakhawy, Abu-Al-Hassan, & Abdelsalam, 2022) Industrial wastes such as fly ash, metakaolin, and granulated blast furnace slag were employed as the foundation for this paper's high strength geopolymer concrete (HSGC). Four Portland cement-based high strength concrete (HSC) mixes were created for comparison with fifteen different geopolymer concrete mixes. All of the mixtures were cast, cured, and tested. As fresh qualities, slump and air content were assessed for both HSC and HSGC mixtures. Mechanical parameters examined and assessed were compressive strength at 3, 7, 28, and 91 days, splitting tensile strength, flexural strength, and modulus of elasticity. Water permeability coefficient, drying shrinkage at 3, 7, 14, 21, 28, 56, and 91 days, as well as temperature studies from 100 °C to 700 °C, were explored. The cement and geopolymer concrete mixes were analyzed using scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) spectroscopy. In terms of fresh properties, the geopolymer concrete based on slag with 500 kg/m3 demonstrated 225 mm slump, whereas in terms of hardened properties, the mix contained 200 kg of metakaolin with 300 kg of slag had the greatest compressive strength in both early and late age 63.3, 82.6 MPa, respectively, as well as the greatest splitting tensile strength 6.2 MPa, flexural strength reached 9.2 MPa, and modulus of elasticity was 37. Furthermore, the coefficient of permeability falls with increasing granulated blast furnace slag. Mineral additions helped to reduce dry shrinkage in geopolymer concrete. SEM pictures revealed that the geopolymer matrix had more scattered small-sized holes, indicating that it had a stronger compressive strength than the other experimental mixes.

(Toufigh & Alireza , 2021) based on the chemical compositions of its parts, gives a complete model for forecasting the compressive strength of fly ash-based geopolymer concrete (FAGC). To accomplish this purpose, 172 mix designs were collected from published studies between the years 2000 and 2020. To determine the relationship between input and output variables, the Bayesian linear regression technique was utilized. The findings emphasized the significance and influence of the chemical compositions of fly ash and sodium silicate solution on the compressive strength of FAGC, and these parameters could clearly explain discrepancies between optimal mix designs established in previous investigations. Finally, the suggested model could accurately predict the compressive strength of low calcium FAGC, saving time and money. When the intended compressive strength is between 10 and 75 MPa, the suggested model can correctly estimate the compressive strength of FAGC.

(Su, Xu, & Ren, 2015) carry out The mechanical characteristics of geopolymer concrete (GC) subjected to dynamic compression at extreme temperatures are investigated experimentally. As the data show, weight loss is spectacular at temperatures ranging from ambient temperature to 200°C, as well as 600°C to 800°C. At 200°C, the dynamic compressive strength of GC increases more than at ambient temperature, but drops dramatically at 800°C. At extreme temperatures, the critical strain is greater than at ambient temperature. Its energy absorption capability is superior to that of room temperature at 200°C and 600°C, respectively. However, at 400°C and 800°C, it performs worse than at ambient temperature.

(Hui-Teng, et al., 2022) The thermal stability of fly ash (FA) and fly ash-ladle furnace slag (FA-LS) geopolymers was compared. FA-LS geopolymer was created by combining FA and LS (in an 80:20 weight ratio) with an alkali activator. Geopolymers were matured for 28 days at room temperature before being subjected to high temperatures (200°C - 1000°C). When compared to unexposed FA geopolymer, the compressive strength of FA geopolymers fell by 6.5 - 38.4 % from 200°C (42.8 MPa) to 1000°C (24.0

MPa) (38.9 MPa). When compared to unexposed FA-LS geopolymers, the compressive strength of FA-LS geopolymers reduced by just 2.2 - 8.7 % from 200°C (43.1 MPa) to 1000°C (39.2 MPa) (40.5 MPa). As a result of their superior compressive strength retention, FA-LS geopolymers outperformed FA geopolymers in mechanical and thermal performance. This was due to the fact that the exposed FA-LS geopolymers did not crack and had lower bulk density (2.9 - 5.5 %) and volume (2.3 - 6.8 %) changes than the exposed FA geopolymers (density change of 2.9 - 25.2 % and volume change of 2.3 - 19.5 %), as well as lower water absorption (7.4 - 13.2 %) and apparent porosity (17.4 - 23.0 %) (water absorption of 9 – 20 % and apparent porosity of 19 – 30 %). The combined influence of LS as a filler and precursor, as well as the existence of coexisting C-A-S-H and N-A-S-H matrices, improved microstructure compactness in FA-LS geopolymers. Crystalline phases were generated in both FA and FA-LS geopolymers at high temperatures, but FA-LS geopolymers had a higher crystalline content (53.0 - 74.5 %) than FA geopolymers (40.3 - 69.6 %), resulting in increased strength in FA-LS geopolymers. The final compressive strength of geopolymers was influenced by porosity, microstructure compactness, internal and external damages, and the development of crystalline phases. The inclusion of LS effectively enhanced the thermal and structural integrity of FA geopolymers. Instead of FA geopolymers, FA-LS geopolymers are recommended as a heat-resistant material.

(Hai Yan Zhang, Venkatesh Kodur, Bo Wu, Jia Yan, & Zhen Sheng Yuan, 2017) offers experimental findings on the bond behavior of geopolymer concrete and rebar. Pull-out experiments were performed on geopolymer concrete specimens implanted with plain and ribbed rebars at room temperature and after exposure to 100, 300, 500, and 700°C. The test specimens were prepared using two batches of geopolymer concrete with compressive strengths of 48 and 64 MPa, respectively, and five rebar diameters (of 10, 12, 14, 18, and 25 mm). Benchmark tests on ordinary Portland cement (OPC) concrete specimens were also performed. The results of these experiments demonstrate that geopolymer concrete displays little bond strength decline up to 300°C but suffers severe deterioration after that. The test results show that the rate of bond strength deterioration in geopolymer concrete is like that of splitting tensile strength but more than that of compressive strength. Furthermore, the findings suggest that geopolymer concrete has equivalent or superior bond characteristics as OPC concrete, both at room temperature and after exposure to higher temperatures. Thus, where fire resistance is a primary design factor, geopolymer concrete can be a viable alternative to OPC concrete in reinforced concrete structures.

(F. U. A. Shaikh & V. Vimonsatit, 2014) The compressive strength of fly-ash-based geopolymer concretes at 200, 400, 600, and 800°C is shown. The results reveal that fly-ash-based geopolymer concretes lose their initial compressive strength at all higher temperatures up to 400°C, regardless of molarity or coarse particle size. All geopolymer concretes showed an improvement in compressive strength at 600°C compared to 400 °C. It is, however, lower than that measured at room temperature. At 800°C, the compressive strength of all geopolymer concretes is lower than that at ambient temperature, with the exception of geopolymer concrete containing 10 M NaOH. At 600 and 800°C, the compressive strength of the latter rose. Higher molarity NaOH solution geopolymer concretes (e.g., 13 and 16 M) demonstrate more compressive strength loss at 800 °C than 10M NaOH. At increased temperatures, geopolymer concrete with smaller size coarse aggregate retains the majority of its initial compressive strength. At all increased temperatures, the addition of more water reduces the compressive strength of geopolymer concretes. However, prolonged steam curing enhances compressive strength at high temperatures.

(Hai Yan Zhang, Venkatesh Kodur, Bo Wu, Liang Cao, & Fan Wang, 2016) mechanical and thermal characteristics of geopolymer mortar produced by alkaline solution activating metakaolin and fly ash mix Bending, compressive, tensile, and bond strength tests were performed on large sets of geopolymer mortar, Portland cement mortar, and commercially used repair mortar specimens at ambient and increased temperatures. Geopolymer paste and mortar were also subjected to thermogravimetry and differential scanning calorimetry analyses, as well as dilatometric testing. These studies reveal that geopolymer mortar has higher temperature-induced deterioration in bending and tensile strength but lower temperature-induced degradation in compressive and bond strength than conventional Portland cement mortar and widely used repair mortar. Specifically, the bond strength of geopolymer mortar on cement mortar or concrete substrate is close to or even higher than that of commercially used repair mortar throughout 25–700°C range. The microstructural damage due to temperature-induced dehydration and dehydroxylations, and thermal incompatibility between geopolymer paste and aggregates is the main reason for the strength degradation of geopolymer mortar at high temperatures.

(Daniel L.Y. Kong & Jay G. Sanjayan, 2009) The effect of higher temperature on geopolymer paste, mortar, and concrete prepared using fly ash as a precursor is investigated. Sodium silicate and potassium hydroxide solutions were used to create the geopolymer. Several experimental factors, including specimen size, aggregate size, aggregate type, and superplasticizer type, were investigated. The study identified specimen size and aggregate size as the two most important elements governing geopolymer performance at high temperatures (800°C). Larger aggregate sizes produced good strength performances at both ambient and higher temperatures. The thermal mismatch between the geopolymer matrix and the particles causes strength loss in geopolymer concrete at high temperatures. The rate of aggregate expansion with temperature is an important component in the performance of geopolymer concrete at high temperatures.

(Sasi Rekha M. & Sumathy S.R., 2021) created in order to better understand the feasibility of Geopolymer Concrete cured at room temperature in the building sector, as well as the influence of molarity on strength qualities By varying the molarities of sodium hydroxide, five different types of Geopolymer Concrete mixes were created: 4M, 6M, 8M, 10M, and 12M. For the aforementioned molarities, compressive strengths (1, 3, 7, 14, and 28 days), splitting tensile strengths (7, 14, and 28 days), and flexural strengths at 28 days were investigated. In general, increasing molarity improves compressive strength. The integration of calcium contained in GGBS has increased the strength at early ages in FA and GGBS based Geopolymer Concrete. Except for 4M geopolymer concrete, the 3-day and 7-day compressive strengths were roughly 50-75 % and 80-93 % of the 28-day compressive strength, respectively. At 28 days, the maximum strength of 8M Geopolymer Concrete reached 57.53MPa. Non-Destructive tests (NDT) (Rebound Hammer and Ultrasonic pulse velocity) were performed at a same age of curing to validate the compressive strength predicted by the Destructive test (DT). A regression analysis is also performed between the compressive strength determined by DT and the NDT results. The obtained linear regression equations were well associated with the experimental data, with R^2 values ranging from 0.8970-0.9967.

3. CONCLUSIONS

The geopolymer reaction process, workability, mechanical characteristics, and durability of fresh and hardened FA/GGBFS-based GPC were all examined. The following conclusions can be taken from the review results:

- According to the talks, geopolymer concrete offers significant potential for usage as a building material in a variety of applications. A variety of critical features have been studied, and extremely high strengths have been achieved.

- Because the primary raw materials utilised in GPC are industrial wastes such as FA and GGBFS, its usage can minimise CO_2 emissions, simplify waste recycling, and improve societal sustainability. As a result, the FA/GGBFS-based GPC might possibly be used as a substitute for OPC. However, this will only happen if the raw material supply chain is efficient.

- The integration of calcium contained in GGBS has increased the strength at early ages in FA and GGBS-based Geopolymer Concrete. The 3-day and 7-day compressive strengths were around 50-75% and 80-93% of the 28-day compressive strength, respectively.

- The compressive strength of Geopolymer Concrete typically increases as the molarity of sodium hydroxide increases. The creation of better alumina-silicate networks during geopolymerization, as well as high melting temperature phases such as nepheline ($NaAlSiO_4$), albite ($NaAlSi_3O_8$), and tridymite (SiO_2), resulted in increased compressive strength at all raised temperatures. Because of further geopolymerization over time, geopolymer concrete that experienced longer heat curing displayed better compressive strength at all raised temperatures.

- The strength at elevated temperatures is proportional to the size of the geopolymer paste specimens. Thermal cracking is caused by the substantial temperature gradient between the surface and core of the specimen cross-section. As a result, thermal incompatibility caused by a temperature gradient is most likely the cause of the size impacts. Because of the possibility of less micro cracking in the ITZ of particles in the former, geopolymer concrete using smaller size coarse aggregates displayed slightly greater compressive strength at all raised temperatures than that including bigger coarse aggregates. The rate of aggregate expansion with temperature is an important component in the performance of geopolymer concrete at high temperatures.

- Because coarse particles and fly ash geopolymer paste are thermally incompatible, the compressive strength of geopolymer concretes declined at increased temperatures up to 400°C, which is comparable with OPC concrete. However, the compressive strength of geopolymer concretes was greater at 600°C and 800°C due to the more steady contraction of geopolymer paste at those temperatures.

- The final compressive strength of geopolymers was impacted by porosity, microstructure compactness, internal and external damages, and the development of crystalline phases.

- Based on the findings of this study, geopolymer concrete manufacturing should be encouraged in order to reduce the impact of global warming by successfully using industrial by-products and producing cement-free concrete.

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