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Elevated Temperature Effects on Geo-Polymer Concrete: An Experimental and Numerical-Review Study

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ABSTRACT

The manufacture of cement plays a substantial role in the emission of carbon dioxide (CO_2) into the atmosphere, hence exacerbating the adverse impacts of global warming. Consequently, the emergence of Geo-Polymer concrete has presented itself as a potentially feasible substitute owing to its commendable environmental sustainability. This manuscript provides a comprehensive analysis of prominent studies investigating the effects of increased temperatures and fire exposure on concrete across its entire operating duration. This study examines the significant impacts on the fundamental physical and mechanical characteristics of concrete, as revealed by laboratory experiments. Furthermore, this review comprehensively examines previous research endeavors that have used machine learning methodologies to predict tangible actions, aiming to optimize resource allocation, time efficiency, and cost-effectiveness in laboratory inquiries. Geo-Polymer concretes have exhibited remarkable resistance to elevated temperatures and severe fires, as evidenced by laboratory and field assessments of cracking, spalling, and strength degradation. Prior studies have demonstrated that both the aggregate type and temperature have a substantial impact on the degradation of compressive strength. Moreover, previous research has indicated that Geo-Polymeric concrete, which is comprised of fly ash, exhibits superior heat resistance compared to conventional concrete using Portland cement, withstanding temperatures of up to 400 degrees Celsius. This research also highlights the widespread adoption of the Artificial Neural Network (ANN) technique in forecasting the compressive strength of conventional concrete. Conversely, alternative approaches such as the Genetic Weighted Pyramid Operation Tree (GWPOT) are preferred for high-performance concrete. The primary objective of this extensive investigation is to establish a fundamental basis for future studies on sustainable alternatives to concrete and approaches for predictive modeling.

1. INTRODUCTION

Concrete is an essential material in construction due to its affordability, durability, accessibility of raw materials, and versatility in size and shape [1, 2]. However, the production of cement, a key component of concrete, is a significant contributor to CO_2 emissions, causing a substantial increase in global greenhouse gas levels [3]. Regular Portland cement, commonly used in civil engineering projects, releases a significant amount of CO_2 [4]. In fact, concrete is responsible for approximately 7% of atmospheric carbon dioxide emissions [5], exacerbating the issue of greenhouse gas accumulation. Consumption-based emissions frameworks hold consumers accountable for their carbon dioxide emissions [6]. Fortunately, there are various measures available to mitigate carbon dioxide emissions, and several indicators can be used to assess their effectiveness. The Carbon Monitor near-real-time CO_2 emission dataset reveals an 8.8% reduction in global CO_2 emissions from January 1 to June 30, 2020, compared to the same period in 2019. However, the dataset also indicates a subsequent increase in CO_2 emissions by late April, primarily attributed to the recovery of economic activity in China and the partial easing of restrictions in other countries. This daily-updated CO_2 emission dataset offers valuable opportunities for scientific research and policy development. It is projected that these emissions will contribute to 12% of the global CO_2 emissions by 2020 [7]. The production of electric energy from gases and solids is a pressing global pollution issue, and addressing it necessitates significant efforts and funding. Hence, the concept of recycling these wastes in various industries, particularly the construction sector, offers promising prospects for pollution reduction and decreased reliance on natural resources. Fly ash, widely recognized as one of the most prevalent solid waste materials globally, presents a significant environmental concern, particularly regarding its disposal from thermal power plants [8]. In order to meet the requirements of low carbon emissions and environmental sustainability in the construction industry, it becomes imperative to explore viable alternatives for structures that consume fewer energy and resources [9].

Based on the previously mentioned results, it has been determined that conventional concrete exerts a negative impact on the environment, including with regards to the emission of carbon dioxide and its contribution to the phenomenon of global warming. In this paper, reviewed alternatives to ordinary Portland cement, especially Geo-Polymer concrete, and its environmental impact, in addition to the issue of concrete durability, as well as the effect of high temperatures and fires on the physical and mechanical properties of its type of concrete from both the laboratory and numerical sides.

Davidovits introduced the term 'Geo-Polymer' in 1978 to describe a cementitious material possessing ceramic-like properties [10]. Geo-Polymers are considered sustainable cementitious binders [11] and can be produced from various precursors rich in alumina and silica. They are globally accessible, reactive, and cost-effective. The adoption of modern eco-friendly binders has grown significantly [12]. Due to their ceramic-like characteristics, Geo-Polymers exhibit excellent heat and fire resistance [13]. The process of Geo-Polymerization requires 60% less energy compared to the synthesis of ordinary Portland cement (OPC) [14]. Furthermore, the reaction kinetics of Geo-Polymers occur at low temperatures and atmospheric pressure conditions. Since fly ash is already a byproduct, the production of fly ash-based Geo-Polymers does not require substantial energy inputs, unlike OPC. With the implementation of the Geo-Polymer technique, emissions have the potential to be reduced by up to 80% [15]. Geo-Polymer represents the advancement of cement technology, classified as the third generation of cement [16]. Geo-Polymer concrete (GPC) serves as an environmentally friendly alternative to traditional cement. By 2050, significant reductions in gas emissions, particularly carbon dioxide, ranging from 50% to 80%, are anticipated [17]. Geo-Polymers undergo a reactive process that results in the formation of synthetic alkali alumina silicate, commonly, Geo-Polymers are produced using materials such as meta-kaolin, fly ash (FA), slag, or rice husk ash [18].

Wu and Sun [19] employed silica-alumina resources such as fly ash (FA) and meta-kaolin (MK) to activate a gel formation using an alkali activator solution consisting of Na_2SiO_3 and NaOH. In 2011, David Easton invented Geo-Polymer concrete through the utilization of burnt watershed resources. Poly-condensed alumina is derived from various sources including fly ash, red mud, rice husk ashes, silica fume, and palm oil fuel ashes. Silica exhibits polymer-like behavior below 100°C. Chemical reactions between alumina-silicate oxides and alkali poly-silicates lead to the formation of polymeric Si-O-Al linkages, resulting in three-dimensional silica-aluminates that can be amorphous or semi-crystalline. In 1991, Davidovits described three fundamental forms: a-Poly (Sialite) (-Si-O-Al-O-), b-Poly (Sialate-Siloxo) (-Si-O-Al-O-Si-O-), and c-Poly (Sialate-Disiloxo) (-Si-O-Al-O-Si-O-Si-O-). Construction composites must possess high-temperature strength endurance to meet the demands of the construction industry. Reinforced concrete (RC) buildings are prone to fire damage throughout their lifespans. The molecular structures of concrete are only stable within specific temperature ranges, and their stability can fluctuate with temperature variations. Factors such as temperature, exposure time, and heating rates can lead to changes in the molecular structure and degradation of concrete. Consequently, concrete experiences a loss of strength under severe temperature conditions [20]. This loss of strength can result in the development of cracks in concrete structures, making them porous and increasing the risk of corrosion, rendering them unusable [21]. The reduction in concrete stiffness and mechanical properties is attributed to the strength loss and dihydroxylation of $Ca(OH)_2$ that occurs between 400 and 500°C, leading to significant crack formation. The gradient of ordinary Portland cement (OPC) thermal concrete makes it perform poorly at high temperatures. Geo-Polymer concrete has garnered significant attention for its remarkable thermal, fire, and spalling resistance at high temperatures. The inorganic structure of Geo-Polymers is fortunately thermally stable and fire resistant, with only a minimal loss of the gel structure observed up to 700-800°C [22]. Compared to composites based on ordinary Portland cement (OPC), Geo-Polymers exhibit slower dehydration. They maintain their chemical stability even at elevated temperatures [23]. In OPC-cement concrete, the concrete matrix undergoes dehydration of Calcium-Silica-Hydrate (C-S-H) at 105°C. Figure 1 illustrates the primary advantages of Geo-Polymer concrete. An exemplary benefit is the reduction in the demand for natural raw materials, such as clay and limestone, which are traditionally used in the cement industry. Instead, waste materials harmful to the environment can be utilized in the production of Geo-Polymer concrete, thereby minimizing their impact and preserving nature.

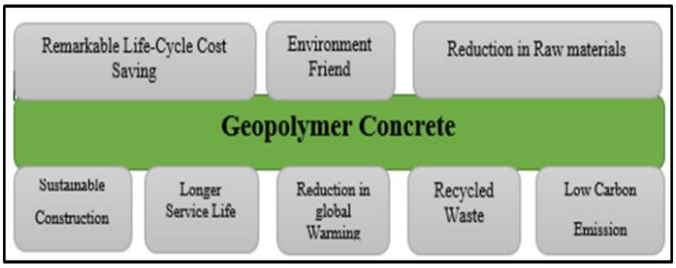

Figure 1. The main benefits of Geo-Polymer concrete

2. GEO-POLYMER CONCRETE (GPC)

Geo-Polymer represents the third type of binder, following Portland cement and lime. In 1978, Daidovits coined the term 'Geo-Polymer' to describe materials composed of chains or networks of inorganic molecules. Concrete made with Geo-Polymer cement is produced utilizing waste materials such as fly ash, ground granulated blast furnace slag (GGBS), among others. These 'Geo-Polymers' are amorphous alkali alumina-silicates. Despite the name, these substances share similar chemistry [24]. Alumina-silicate minerals such as kaolinite, feldspar, fly ash, metallurgical slag, and mining refuse are employed in the production of Geo-Polymers. The reactions of these alumina-silicate materials are influenced by their mineralogy, glassy phase composition, and fineness. In traditional Geo-Polymer systems, alkali activators such as NaOH, KOH, Na_2SiO_3, and KOH (K_2SiO_3) are utilized. KOH exhibits higher alkalinity compared to NaOH, while NaOH facilitates the dissolution of silicate and aluminate monomers in alumina-silicate precursors [24]. The characteristics of Geo-Polymers can be enhanced for specific purposes through the selection of raw components, upgrading processes, and refining techniques. The growing interest in Geo-Polymer concrete is evident from the abundance of research and studies exploring various scientific aspects, as well as the mechanical and durability effects of concrete the table below presents titles of recent research and studies that provide valuable insights for researchers engaged in the investigation and application of Geo-Polymer concrete. Table 1 below showcases Geo-Polymer concrete research conducted between 2021 and 2022. As mentioned earlier, Geo-Polymer concrete comprises two primary components: the alumina-silica source and the alkali activator solution. These materials react to form the binder material for the Geo-Polymeric paste, which binds the aggregate granules, both fine and coarse, to create Geo-Polymer concrete. The following section provides an explanation of the commonly used materials in the production of Geo-Polymer concrete, serving as sources of alumina-silica, along with the alkali activator solution.

Table 1. Some research on Geo-Polymer concrete for the years, 2021 and 2022

Source	Year	Title
[25]	2021	A scientometric review of Geo-Polymer concrete
[26]	2022	Ultra-high-performance Geo-Polymer concrete: A review
[27]	2022	Durability Performance of Geo-Polymer concrete: A Review
[28]	2022	A Study on the Properties of Geo-Polymer concrete Modified with Nano Graphene Oxide
[29]	2022	Geo-Polymer concrete as a cleaner construction material: An overview on materials and structural performances
[30]	2022	The role of nanomaterials in Geo-Polymer concrete composites: A state-of-the-art review
[31]	2022	Geo-Polymer concrete incorporating recycled aggregates: A comprehensive review
[32]	2022	Production of Geo-Polymer concrete by utilizing volcanic pumice dust
[33]	2022	Durability performance evaluation of green Geo-Polymer concrete
[34]	2022	Review on the Relationship between Nano Modifications of Geo-Polymer Concrete and Their Structural Characteristics
[35]	2022	Sustainability benefits and commercialization challenges and strategies of Geo-Polymer concrete: A review
[36]	2022	Compressive strength prediction of fly ash-based Geo-Polymer concrete via advanced machine learning techniques
[37]	2022	Effect of air agent on mechanical properties and microstructure of lightweight Geo-Polymer concrete under high temperature
[38]	2022	Factors affecting production and properties of self-compacting Geo-Polymer concrete – A review
[39]	2022	Analyzing the mechanical performance of fly ash-based Geo-Polymer concrete with different machine learning techniques
[40]	2022	The roles of cenosphere in ultra-lightweight foamed Geo-Polymer concrete (UFGC)

2.1 Alumina-silicate precursors

Geo-Polymer paste consists mainly of precursors derived from alumina silicate. The polymer chains are formed through their reaction with the activated base solution. In the presence of a significant amorphous component, these materials will undergo decomposition and condensation, resulting in the formation of carrier inorganic polymers under alkaline circumstances. The chemistry of precursors has a significant impact on the process of Geo-Polymerization. Silicate and aluminate precursor particle size impacts monomer solubility. These reactions utilize the system's natural alkalinity Potent bases activate alumina-silicates. Several studies addressed this. GC can be polymerized from alumina-silicates like fly ash, slag, meta-kaolin, rice husk ash, and HCWA. Alkaline solutions activate Geo-Polymer-binding pozzolanic materials rich in SiO_2 and alumina, Alumina-silicate availability impacts Geo-Polymer concrete quality. Fly ash dominates Geo-Polymer concrete. Fly ash is Class F or C per ASTM C618-03 [41, 42]. Class-C fly ashes have more CaO than Class-F. Ash's calcium, silica, alumina, and iron concentration distinguishes these classes. Geo-Polymer composites are made from alumina-silicate low-calcium fly ash [43, 44]. This section briefly reviews Geo-Polymer precursors:

2.1.1 Fly ash (FA)

Geo-Polymers can be produced using fly ash from coal power plants [45]. Fly ash, also known as 'pulverized fuel ash' or FA, is a byproduct of coal combustion that includes fine particles generated from power plant boilers and flue gases [46]. In typical concrete, FA is frequently used as a substitute for Portland cement [47]. In ordinary concrete, Portland cement is partially replaced with FA due to its pozzolanic reaction, which enhances mechanical properties and durability [48, 49].

2.1.2 Ground granulated blast slag (GGBS)

GGBS, a byproduct of blast furnace in metal production, is utilized [50]. The molten slag consists of approximately 40% calcium oxide and 30% to 40% silicon dioxide [51]. To produce GGBS, the molten slag is rapidly quenched by water after being tapped off [52]. GGBS enhances porosity in conventional OPC concrete and improves resistance against alkali silica and sulfate reactions. Moreover, GGBS reduces hydration heat and enhances the long-term performance of OPC [53].

2.1.3 Meta-kaolin (MK)

The optimal conversion of kaolin to meta-kaolin is typically achieved during the calcination process. Mehsas et al. [54] examined the results of calcining two types of kaolin used for meta-kaolin production. The target temperature (ranging from 500 to 1000℃) and holding duration were varied to create different thermal cycles for the raw ground materials (2, 3, and 5 hours). The investigations consistently demonstrated that calcination improved the pozzolanic reactivity of the materials, with the temperature of 800℃ and a holding duration of 5 hours resulting in the highest level of pozzolanicity. This indicates the significant value of these materials as supplementary cementitious materials (SCMs) and their potential for use in environmentally friendly cement.

2.1.4 Red mud (RM)

Red mud (RM), a by-product of the Bayer process, is involved in the refinement of 55-65% of bauxite into alumina [55]. A typical alumina mill produces RM in quantities 1-2 times greater than alumina. The red color of RM is attributed to its iron oxide content, which ranges from 30 to 60%. Additionally, RM exhibits alkalinity with a pH level ranging from 10 to 13 [56]. The annual usage of RM in OPC manufacturing amounts to 2-3 million tons. As mentioned earlier, RM solids contain toxic heavy metals, alumina, and primarily hematite, which is an iron oxide [57].

2.1.5 Rice husk ash (RHA)

Milling rice necessitates the application of heat in order to boil it. In most rice mills, heat energy is obtained from a boiler. The boiler directly combusts or gasifies rice husks (hulls), which are generated during the milling process, to produce energy [58, 59]. Rice husk ash (RHA), an inorganic waste, contains highly reactive silica. The properties of RHA can be influenced by the burning temperature and holding time [60]. Higher temperatures result in the production of more crystalline silica and less unburned carbon in the RHA [61].

2.1.6 Glass powder (GP)

Glass powder serves as another precursor for Geo-Polymers. Geo-Polymers can be produced using glass powder. Sustainable roof tiles utilize glass polishing powder. Additional research indicates that Geo-Polymers can be created using glass powder and other precursors. One advantage of incorporating crushed glass in concrete is its minimal water absorption, rendering it an exceptionally durable material [62].

2.1.7 Palm oil fuel ash (POFA)

Palm oil is widely used in kitchens [63]. The production of palm oil serves as a significant economic driver in Malaysia and Thailand. In addition to crude palm oil, substantial quantities of kernels, fibers, and dried fruit bunches are generated. Approximately four kilograms of dry biomass are required to produce one kilogram of palm oil [64]. These byproducts are burned in boilers at palm oil factories to reduce the energy demand. The waste product known as Palm Oil Fuel Ash (POFA) contains 5% fiber and ash from shells, this type of ash is described in the literature [65-67].

2.1.8 Silica-Fume (SF)

Silica-Fume (SF), similar to FA, is used as a partial replacement for Portland cement in concrete [68]. SF is produced from a ferrosilicon alloy with silicon metal. According to Amran et al. [69], the silica in pozzolana reinforces the portlandite formed during OPC hydration. The interaction of SF provides a binder that enhances the strength, impermeability, and durability of concrete [70]. Silica Fume Geo-Polymers contribute to increased compressive strength. Silica fume-based Geo-Polymers enable the production of environmentally friendly high-strength or ultra-high-performance concrete [71].

SF can be utilized in the construction of concrete without the need for cement. It also offers a sustainable solution for disposing of silica fume [72]. Table 2 provides a list of typical product materials [72-74]. Figures 2, 3, 4, and 5 depict the scanning electron microscopy (SEM) images of fly ash, glass powder, GGBS, and Red Mud particles, respectively. Table 3 showed FA, SF, GGBS, RHA, and GP chemical composition.

Table 2. Typical properties of by product materials

Property/Element	FA	RHA	GGBS	SFA	POFA
Fineness (m^2/kg)	450	~450m^2/kg	350 to 550	15,000 to 35,000	4900e5200cm^2/g
Bulk density (kg/m^3)	1300	96e160kg/m^3	1200	1350e1510	2.40e2.50g/cm^3
Specific gravity	2.2	2.11	2.9	2.2	2.14

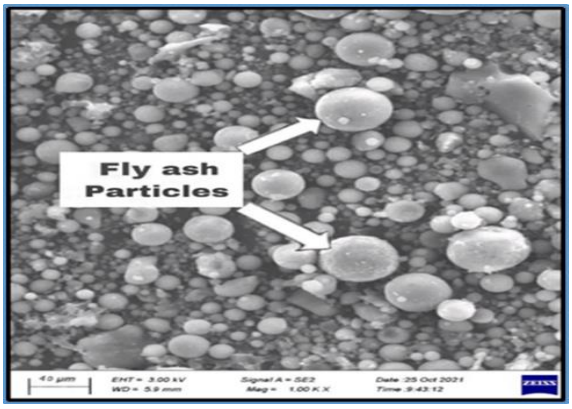

Figure 2. (SEM)-Fly ash particles [72]

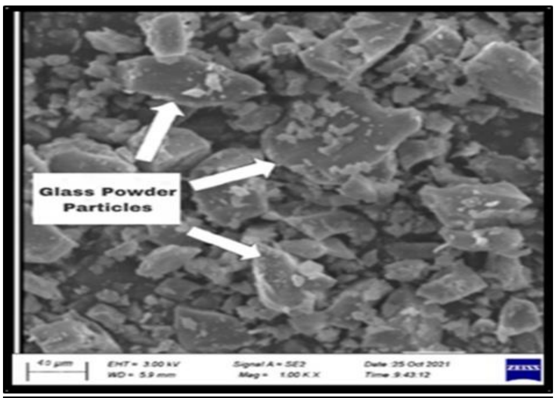

Figure 3. (SEM) -Glass powder particles [72]

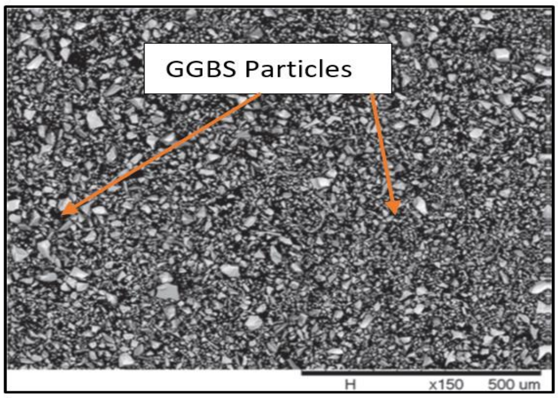

Figure 4. (SEM)-GGBS particles [73]

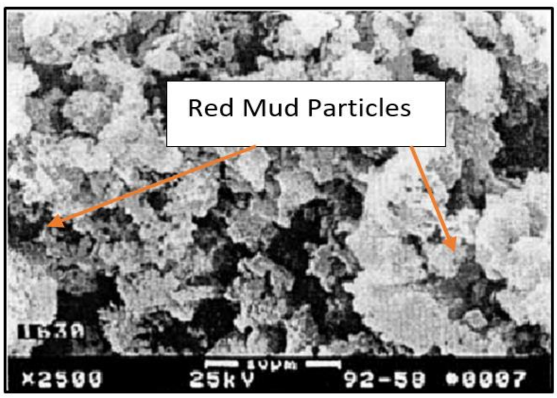

Figure 5. (SEM)-Red mud particles [74]

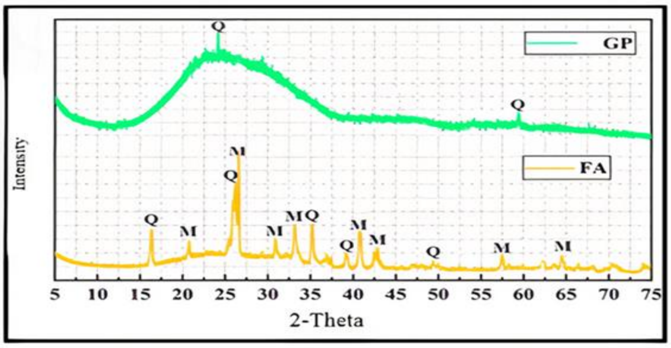

Figure 6. Raw material XRD patterns. mullite, quartz-FA, and GP [72]

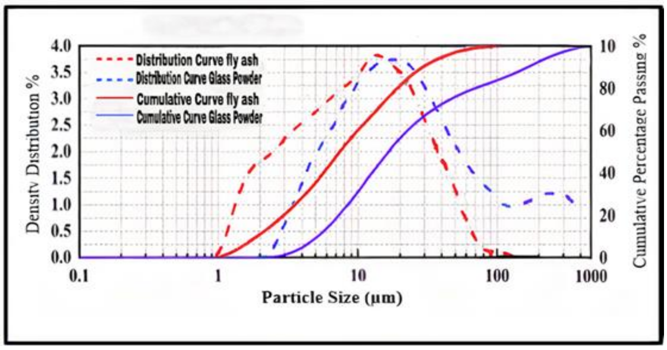

Figure 7. FA and GP particle distribution [72]

Table 3. FA, SF, GGBS, RHA, and GP chemical composition

Precursor	Oxide										Source
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3	MgO	TiO_2	LOI	
FA	61.86	-	-	-	-	-	0.28	0.86	-	0.83	[75]
	63.13	24.58	3.07	2.58	0.71	2.01	0.18	0.61	0.96	1.45	[76]
	66.56	22.47	3.54	1.64	0.58	1.75	0.1	0.65	0.88	1.66	[77]
	64.97	26.64	5.69	0.33	0.49	0.25	0.33	0.85	-	0.45	[78]
SF	92.39	1.41	0.15	0.54	-	0.85	-	-	-	2.59	[79]
	94	1.2	1.6	0.95	0.7	1.2	-	1.8	-	3.5	[80]
	93.67	0.83	1.3	0.31	0.4	1.1	0.16	0.84	-	2.1	[81]
RHA	96.23	0.281	1.36	0.57	0.05	0.45	0.2	0.27	-	-	[82]
	93.46	0.58	0.52	1.03	0.08	-	0.6	0.51	-	7.76	[83]
	89.17	-	0.41	0.61	7.29	1.12	-	1.22	0.03	0.15	[84]
	89.47	0.83	0.53	0.68	0.22	0.17	0.12	0.37	-	7.61	[85]
GGBS	35.8	13.21	1.97	35.68	0.48	0.57	0.21	9.76	-	2.32	[85]
	32.9	-	0.7	41.3	0.45	-	0.21	5.9	-	2.1	[75]
	34.51	10.3	0.6	42.84	0.4	0.52	1.95	7.41	0.67	0.45	[86]
	33.54	1.17	12.52	37.93	-	-	2.51	9.29	0.95	1.25	[87]
GP	71.20	1.71	0.24	10.02	13.17	0.19	0.25	3.01	0.07	-	[88]
	70.01	1.8	0.45	10.15	12.95	0.45	0.25	2.75	-	-	[89]
	71.19	2.81	-	10.26	14.31	0.52	0.07	0.9	0.11	-	[90]
	72.38	1.49	0.29	11.26	13.52	0.27	0.07	0.54	0.04	-	[91]

Figure 6 shows the XRD traces of mullite, quartz-fly ash, and glass powder. Most of the trial setting is made up of amorphous glass powder. X-ray diffraction research was used to figure out what glass powder and fly ash were made of. SiO_2 contains quartz. Figure 7 shows the particle distribution (PD) of glass powder and fly ash that are used in commercial goods.

2.2 Alkali-activator solution

The alkali activator solution is typically composed of two main types: sodium or potassium silicate and hydroxide. These solutions interact with the silica-alumina present in the Geo-Polymer source to form the binder. The strength of Geo-Polymer concrete depends on the ratio of the binder to alkali during curing at either oven or room temperature [92]. The most commonly used alkaline solutions for Geo-Polymerization are NaOH or KOH, along with Na_2SiO_3 [93]. Among these, NaOH solution is the most widely employed alkali hydroxide activator for Geo-Polymerization due to its availability and cost-effectiveness [94]. Figure 8 illustrates the main components of Geo-Polymer cement as follows:

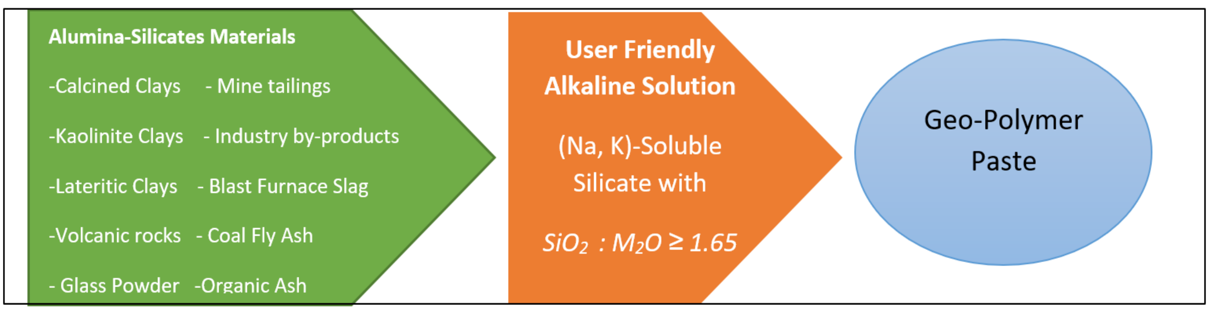

Figure 8. Main compounds of Geo-Polymer cement

Thus, sodium silicate and hydroxide bring about two alterations in Geo-Polymeric concrete. Firstly, they affect the alkaline activator solution in terms of its molarity (NaOH) and weight ratio to the alumina-silica resource. Molarity concentration represents the percentage of a chemical in a solution. The optimal NaOH concentration for Geo-Polymer samples reached its peak value and gradually decreased as the NaOH concentration was further increased. Consequently, an ideal NaOH concentration resulted in increased compressive strength [95]. Eq. (1) below shows the Molarity

$$M = MOF/\text{LOS} \quad (1)$$

where, M is Molarity, MOF is mole of solute, and LOS is liter of solution.

The strengths mentioned above largely depend on changes in various parameters, such as the (Na_2SiO_3/NaOH) ratio and the molarity of the alkaline solution, while keeping the curing temperature constant at 80°C. Geo-Polymer concrete offers the advantage of rapid strength development, as its compressive strength can improve significantly within the first 24 hours, this enables faster construction processes [96].

3. HIGH TEMPERATURE IMPACT

Concrete is frequently exposed to elevated temperatures due to fires or other extreme conditions, which can have a profound impact on its structural characteristics. The specific type of aggregate chosen, as well as the primary constituents of the concrete, are key factors that determine how it responds under such circumstances. In environments characterized by extremely high temperatures, the binder-alkali ratio becomes an indispensable factor in achieving the optimum performance of Geo-Polymer concrete (GPC) [96-98]. This ratio, given its dominant presence in both Geo-Polymer and conventional concrete compositions, exerts a substantial influence over the overall concrete properties and behavior.

3.1 Compressive strength (CS)

Numerous factors influence the compressive strength of Geo-Polymer concrete after exposure to high temperatures. Internal factors include the proportions of materials used in the concrete industry, such as the Geo-Polymeric paste created from aluminates-silicates, the alkaline activated solution, the molarity of sodium hydroxide, and the solution-to-source weight ratio as well as another internal factor is the type and quantity of aggregate used as mentioned above [72]. The following are key research studies investigating the effects of internal and external factors on Geo-Polymer concrete after exposure to high temperatures. A Geo-Polymer mortar, composed of two types of Class-F fly ash, was subjected to testing after exposure to temperatures of 800°C [99, 100]. All specimens experienced a decrease in strength up to 300°C, with Si/Al ratios of 2.2, 1.9, and 1.7 exhibiting strength losses of 50%, 58%, and 63% at 900°C, respectively [101]. Palm oil and powdered fuel ashes demonstrated higher heat resistance compared to other alumina-silicate materials [102]. The combination was weakened between 200 and 800°C. The three Geo-Polymer concrete samples, consisting of 60% fly ash Class-F and an activator solution with NaOH concentration of 12M, exhibited a moderate to significant improvement in strength between 200 and 400°C, but all samples were weakened at 800°C [103]. The compressive strength of the GM specimens showed some improvement after 100°C before declining between 300 and 700°C [104]. Another study examined the performance of Geo-Polymer concrete containing Fly Ash Class-F and GGBS at temperatures of 200, 400, 600, and 800°C. The compressive strength increased by 40% at 200°C [98]. Geo-Polymeric concrete, utilizing Fly Ash Class-C and Class-F paste, was tested up to 1200 degrees. At 1200°C, Class-C exhibited a residual compressive strength of 2.65%, while Class-F showed 0% residual compressive strength [105]. In Fly Ash-based Class-F Geo-Polymer concrete, utilizing an activator solution with NaOH concentration of 10M and typical particles, lower compressive strength was observed at 200, 400, 600, and 800°C compared to ambient temperature [106]. Using a mixture of FA Class-F and GGBFS, along with a 10M NaOH solution, tests revealed a decrease in compressive strength with losses of 42.46%, 66.60%, and 84.43% at temperatures of 300, 500, and 700°C, respectively [107]. Fly ash Class-F Geo-Polymer concrete was used to compare the residual strength after high temperatures under ambient and heated curing conditions. The Geo-Polymer concrete (GPC) specimens retained 82.24%, 64.61%, 55.78%, and 49.91% of their strength after exposure to temperatures of 400, 600, and 800°C, while ambient curing retained 133.29%, 118.15%, 81.79%, and 72.71% [108].

3.2 Volume stability and mass loss

The alteration in mass has a profound impact on the cross-sectional morphology of materials when subjected to elevated temperatures. This thermal exposure induces the processes of dehydration and de-hydroxylation within the Geo-Polymer gel, resulting in a discernible loss of both mass and bulk density in the concrete. In their comprehensive study, Abdulkareem et al. [109] meticulously examined the behavior of hardened Geo-Polymer materials under these conditions and identified three distinct forms of water trapped within the material that can escape during heating. Vapor pressure continues to rise above 100°C, resulting in mass loss when water adsorbed to the binder's surface is removed between room temperature and 100°C, and when pore water is eliminated between 100°C and 1000°C. The loss of water within the paste reduces the mass because Geo-Polymers act as solvents, containing more free water that is displaced at temperatures below 400°C [110]. Low calcium fly ash, granite aggregate, and river sand all experience weight loss when heated to 800°C [111]. In a previous study the mass weight of Fly Ash Class-C Geo-Polymer paste was measured at various temperatures: 20°C, 100°C, 300°C, 500°C, 800°C, 1000°C, and 1200°C, the average weight loss for Geo-Polymer concrete, containing combinations of fly ash and GGBS, at 800°C heat exposure was 4.64%, and conducted an evaluation of the volume effects at high temperatures using waste glass as a fine aggregate substitute for sand in a mixed fly ash Class-F and GGBFS Geo-Polymer mortar. After exposure to 800°C, the mortar based on sand experienced expansion, leading to longitudinal and transverse fractures. Cement exhibits greater expansion than Geo-Polymer concrete at higher temperatures [112]. Additionally, the figures showcase the alterations in color observed in four distinct types of Lightweight Geo-Polymer concrete after being exposed to a range of temperatures, namely 35°C, 200°C, 400°C, 550°C, and 800°C, respectively.

Figure 9. The Cracks on the Surface of Geo-Polymer after exposed to 800°C (Own source)

Khan and Sarker [112] conducted an evaluation of the volume effects at high temperatures using waste glass as a fine aggregate substitute for sand in a mixed fly ash Class-F and GGBFS Geo-Polymer mortar. After exposure to 800°C, the mortar based on sand experienced expansion, leading to longitudinal and transverse fractures. Cement exhibits greater expansion than Geo-Polymer concrete at higher temperatures. Hussin et al. [113] discovered that Geo-Polymer concrete utilizing agro-industrial waste ashes exhibited greater stability compared to cement concrete within the temperature range of 200-800°C. GPC demonstrates higher stability than OPC due to the melting of fly ash particles at 600°C. X-ray investigations comparing GPC to regular concrete at 700°C revealed that OPC concrete experiences more spalling than GPC [114]. Geo-Polymers without calcium fly ash display significant volumetric strain at 600°C, with the most significant weight loss occurring at 300°C [115]. Figure 9 illustrates the surface of Geo-Polymer concrete after exposure to a temperature of 800°C.

3.3 Chemical stability

Lahoti et al. [116] investigated the chemical stability of the core mechanisms through microstructure studies and characterization methods before and after exposure to excessive temperatures. The findings of this study indicate that the binders subjected to high-temperature exposure exhibit chemical stability and form distinct crystal phases.

3.4 Flexural behavior

Mathew and Joseph [117] suggest that the strain compatibility approach can predict the curvature of GPC (Geo-Polymer concrete) beams at ambient atmospheric temperature, as well as OPC (Ordinary Portland Cement) reinforced concrete beams. However, stress compatibility underestimates the load curvature at the formation of initial cracks in GPC beams subjected to higher temperatures. The ductility of Geo-Polymerized beams reduces rapidly with increasing temperature. As the exposure temperature rises, the peak curvature of the Geo-Polymer concrete beam decreases. For instance, at 800°C, a Geo-Polymer concrete beam experienced a loss of 64% in flexibility.

3.5 Color change

After reaching a temperature of 500 degrees Celsius, Geo-Polymer concrete undergoes a color transformation from gray to yellow and pink. Four types of lightweight Geo-Polymer concrete, namely Porcelanite aggregate (PA), Recycled Clay Bricks Aggregate (RBA), Lightweight Expanded Clay Aggregate (Leca), and Recycled Foam Concrete Aggregate (RFA), exhibited color changes after one hour of exposure to temperatures of 35, 200, 400, 550, and 800°C. In calcined fly ashes at 500 and 800°C, the crystallization of hematite results in the transformation of gray fly ash to a red-brown color, indicating increased crystallization [118]. The occurrence of hematite crystallization can cause fly ash to change from gray to red-brown. Figure 10 illustrates the color changes observed in the four types of lightweight Geo-Polymer concrete after exposure to temperatures of 35, 200, 400, 550, and 800°C.

Figure 10. The color change in four types of lightweight Geo-Polymer concrete after exposed to (35, 200, 400, 550, 800°C) (Own source)

3.6 Water absorption

High temperature significantly affects the density and water absorption of concrete. The average results from three lightweight Geo-Polymer concrete specimens revealed variations in density and water absorption under high temperature conditions. The elevated temperatures induce evaporation, fractures, and promote fungal growth, thereby accelerating water penetration into the concrete [119, 120].

3.7 Shrinkage and expansion

Shrinkage occurs in concrete when moisture is lost. The extent of shrinkage shows little dependence on the applied load weight, as reported by Mane and Jadhav [121]. Geo-Polymer specimens exhibit some expansion up to 100°C, which ceases around 200°C. However, a significant shrinkage is observed in the temperature range of 200-300 degrees Celsius. This thermal shrinkage leads to thermal incompatibility damage, which is the most prominent factor. Heating the Geo-Polymer results in shrinkage, and between 300-500°C, both shrinkage and expansion come to a halt. The expansion of aggregates plays a role in the strain of the Geo-Polymer/aggregate composite since aggregates contribute to 75-80% of the concrete composition. At temperatures ranging from 220°C to 320°C, aggregates undergo more expansion than the Geo-Polymer paste, leading to overall concrete expansion [122]. Table 4 displays the residual strengths obtained from the high-temperature study.

Table 4. Previous studies on the effect of high temperatures, type and proportions of materials on compressive strength

N.	Alumina-Silicate Resource	Type of Aggregate	Temp. ℃	M	Activator/Ash Ratio	Residual Comp. Strength %	Ref.
2	Fly ash class-F Types	1- Basalt aggregates+River sand 2- Granite aggregates+crushed sand	500	14	0.35	1- 66.65% 2- 70.99 %	[123]
1	Fly ash class-C	Paste Mortar (river sand) LWA (clay aggregate) (LECA)	800	12	0.6	0% 47.7% 61%	[124]
3	Fly ash class F Types (A,B)	River Sand	800	10	0.605	A=41.86% B=28.83%	[125]
4	Fly ash class F (Si/Al=2.2, 1.9, and 1.7)	None	900	-	0.32	50%, 58%. and 63%	[126]
5	Fly Ash, palm oil fuel ash, and pulverized fuel ash	Normal	800	14	0.4	84%	[127]
6	Fly ash class-F	Basalt natural aggregates and non-pelletized lightweight Fly Ash (Flash-Ag) aggregate	800	12	0.6	55%	[128]
7	Fly Ash class-C and 50% met kaolin	River sand	700	15.8	0.45	66.8%	[129]
8	Fly ash class-F and GGBS	River sand & Crushed granite	800	8	0.55	35%	[130]
9	Fly ash class-C and class-F	None	1200	10	0.45	Class-C=2.65% Class-F=0%	[131]

3.8 Microstructure of Geo-Polymer concrete

The morphology of Geo-Polymer concrete (GPC) is analyzed using field emission scanning electron microscopy (FESEM) to examine its microstructure [122]. The choice of precursors employed in the Geo-Polymerization process influences the microstructure of Geo-Polymers, as highlighted by Myers et al. [132]. The majority of the studies indicate the formation of cross-linked structures through Geo-Polymerization according to the study the type of precursors used plays a significant role in the micro-structuring of Geo-Polymers, with Geo-Polymerization resulting in the formation of cross-linked structures. Figure 11 illustrates different types of Geo-Polymer concrete after exposure to high temperatures of around 800℃.

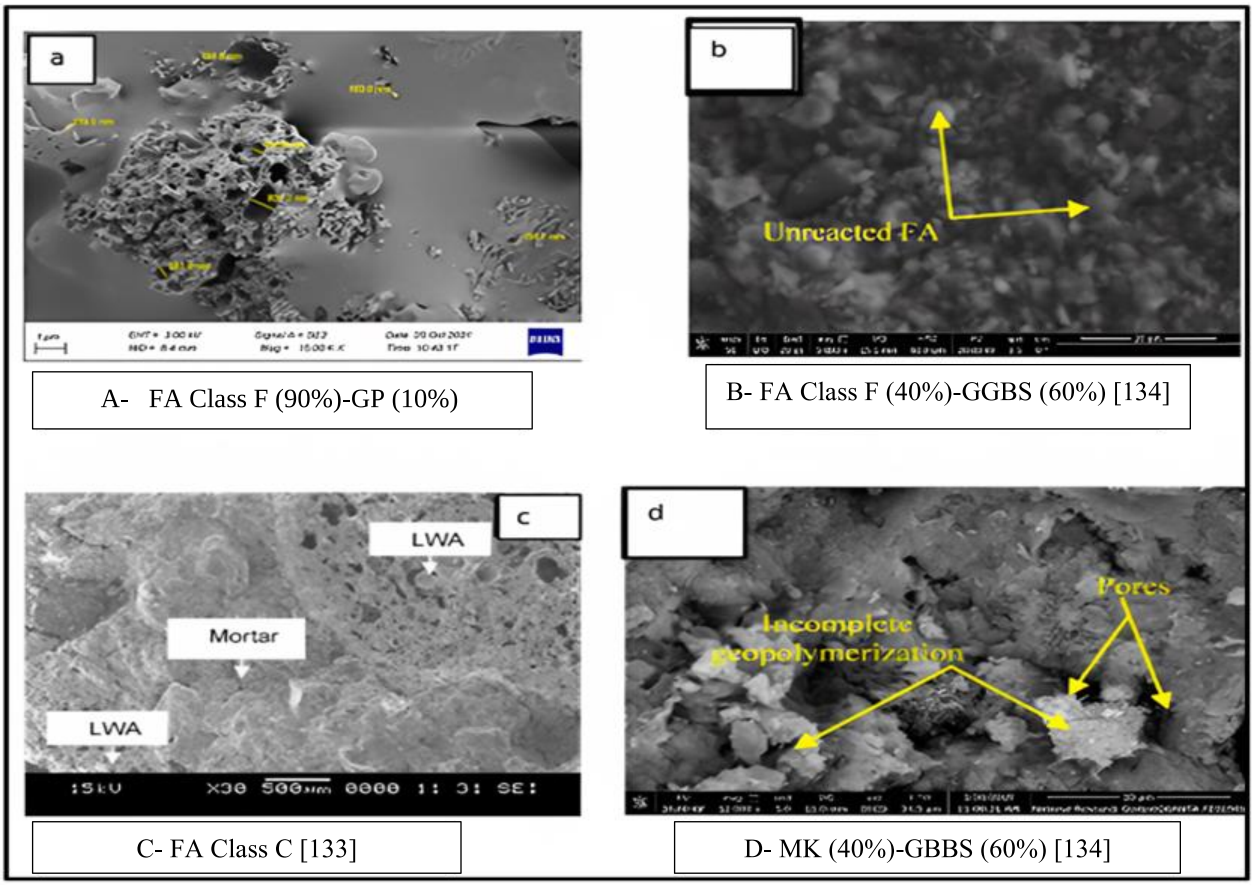

Figure 11. Multi-types of Geo-Polymer concrete after exposed to 800℃

4. NUMERICAL PREDICATED

To mitigate the labor, time, and financial resources expended on laboratory testing aimed at understanding the characteristics of concrete under diverse external and internal factors, including temperature impacts, certain measures need to be implemented. In this section, a comprehensive evaluation is conducted on significant prior studies and research regarding the influence of temperature on mechanical properties, with a particular emphasis on investigations related to compressive strength using various methodologies.

Machine learning, a computational approach that leverages experiential knowledge to enhance system performance, offers a diverse range of techniques. Compressive strength is commonly used as a metric to assess the effectiveness of concrete in structural applications, as it takes into account other qualities such as density and durability. By employing machine learning, the time and effort required for determining concrete strength can be reduced. Traditionally, compressive strength is assessed after a curing period of 28 days. However, utilizing the proposed Artificial Neural Network (ANN) model, which is inspired by the structural organization of the human brain, serves as a basis for machine learning models. The ANN system consists of interconnected nodes, known as neurons, arranged in layers. These nodes facilitate the flow of data, and the weights of connections are dynamically adjusted to acquire knowledge of patterns and provide predictions. By utilizing the ANN model, the results can be predicted in a shorter time frame [135, 136].

In recent studies, researchers have focused on utilizing machine learning (ML) algorithms to estimate the compressive strength of Geo-Polymer concrete (GPC). Dao et al. [137] conducted a study using Fly ash-based Geo-Polymer concrete (GPC) that incorporated fine and coarse aggregates made from scrap steel slag. They predicted the 28-day compressive strength of 210 specimens using Artificial Neural Network (ANN) neural network is a machine learning algorithm based on the model of a human neuron. The human brain consists of millions of neurons, and Adaptive Neuro-Fuzzy Inference System (ANFIS) An adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a kind of artificial neural network that is based on Takagi-Sugeno fuzzy inference system techniques, both models demonstrated a high level of accuracy as evaluated by various metrics. ANFIS showed superior performance with a correlation coefficient (R^2) of 0.879, surpassing the correlation coefficient R^2 of 0.851 achieved by ANN. Furthermore, the stability of each method was assessed over 100 iterations, and the findings confirmed the previous observation that ANFIS outperforms ANN.

Conventional methods are disregarded in this investigation due to their inefficiency and slow performance. The publication employs widely used and reliable techniques to ensure accurate predictions. Kandiri et al. [138] utilized a modified Artificial Neural Network (ANN) to assess the compressive strength of recycled aggregates. By incorporating the Salp Swarm Algorithm (SSA) is a recent metaheuristic inspired by the swarming behavior of salps in oceans. SSA has demonstrated its efficiency in various applications since its proposal [139], Genetic Algorithm (GA) Genetic algorithm (GA) is a well-known algorithm, which is inspired from biological evolution process, and GA mimics the Darwinian theory of survival of fittest in nature [140], and Grasshopper Optimization Algorithm (GOA) is a recent swarm intelligence algorithm inspired by the foraging and swarming behavior of grasshoppers in nature [141], the ANN model's outputs were improved. Among the models, SSA-ANN demonstrated superior accuracy. Kaperkiewicz et al. [142] employed a fuzzy-ARTMAP network (A Neural Network Architecture for Incremental Supervised Learning of Analog Multidimensional Maps) to estimate compressive strength (CS) with limited information and input parameters. While predicting the compressive strength of high-performance concrete (HPC) remains challenging, reasonable precision can be achieved using models. Yeh [143, 144] advocated the use of machine learning in high-performance concretes and suggested that ANN can effectively predict HPC-CS. Tayfur et al. [145] studied the predictive ability of Fuzzy Logic (FL) and ANN for HPC-CS, reporting that ANN outperformed FL by 15% in terms of effectiveness.

Among the different models, the Genetic Weighted Pyramid Operation Tree (GWPOT) The Global Weighted Prediction Operation Tree (GWPOT) model combines the Weighted Operation Structure (WOS) and Pyramid Operation Tree (POT) models in order to improve both prediction accuracy and alignment with empirical data. demonstrated the best performance in solving the problem of predicting high-performance concrete compressive strength when compared to other methods such as ANN, SVM, and GOT, as indicated by the study results [146]. Nehdi et al. [147] claim to be the first to utilize machine learning (ML) for predicting self-consolidating concrete compressive strength (SCC). The authors argued that ANN could accurately forecast the compressive strength as well as other factors of SCC, such as segregation, droop, and filling capacity.

Uysal and Tanyildzi [148] compared the learning algorithms Fletcher conjugate power and Levenberg-Marquardt back-propagation. They found that while the Fletcher method achieved an R^2 of 0.95, the Levenberg-Marquardt method achieved an R^2 of 0.92. Topcu and Saridemir [149, 150] discovered that both Fuzzy Logic (FL) is a method of reasoning that resembles human reasoning, this approach is similar to how humans perform decision making and ANN models accurately predicted the compressive strength (CS) of fly ash and recycled aggregate concrete (RAC) with minimal data. In both cases, ANN outperformed FL. Naderpour et al. [151] employed an ANN model to determine the compressive strength (CS) of Fiber-reinforced polymer (FRP) reinforced concrete samples. By iteratively determining model parameters that enhance the findings, they were able to uncover 11 previously hidden neurons.

Jalal and Ramezanianpour [152] utilized Artificial Neural Network (ANN), Linear Regression (LR), and Non-Linear Regression Analysis (NLR) to calculate the compressive strength (CS) of Functional Reactive Programming (FRP)-confined concrete. The ANN model exhibited the highest performance among the three. Nehdi et al. [153] predicted the compressive strength (CS) of cellular concrete using an ANN model. Their algorithms accurately anticipated the CS with a prediction error that was 47% smaller than the real data.

Ashrafian et al. [154] determined the compressive strength (CS) of cellular concrete by comparing Linear Regression (LR) models, Artificial Neural Network (ANN), standard Multivariate Adaptive Regression Splines (MARS), is an algorithm for complex non-linear regression problems. The algorithm involves finding a set of simple linear functions that in aggregate result in the best predictive performance, Support Vector Machine (SVM), and the combination of MARS with the Water Cycle Algorithm (MARS-WCA). MARS-WCA outperformed the competing methods, showing a 25% higher effectiveness. The Mat Lab program can be utilized to predict the behavior of materials under the influence of external factors [155]. For the testing dataset, the ensemble boosted model demonstrated the highest levels of reliability and accuracy, achieving an R^2 of 0.97, an RMSE of 71.963 kN, and a mean absolute error of 43.452 kN.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on reviews of previous studies and research, Geo-Polymer concrete is regarded as the future alternative to traditional concrete currently in use. This is due to the environmental impact associated with traditional concrete, as explained in the research paper and summarized below. Additionally, Geo-Polymer concrete addresses certain weaknesses of traditional concrete, including its high-water absorption capacity, susceptibility to sulfates and chlorides attacks, and deterioration in compressive strength when exposed to high temperatures.

Geo-Polymer concrete is a viable alternative to conventional Portland cement due to its environmental and economic advantages. The micro-structure of Geo-Polymers is influenced by the choice of precursors, which leads to the formation of cross-linked structures during Geo-Polymerization. Although Geo-Polymer concrete is susceptible to damage from high temperatures, the rate of deterioration is 15 to 25% lower compared to Portland cement-based concrete, particularly at temperatures exceeding 500 degrees Celsius. Additionally, Geo-Polymer concrete exhibits reduced volumetric changes and water absorption compared to Portland cement-based concrete, owing to the different reaction products. Employing machine learning techniques enables efficient prediction of the impact of high temperatures on Geo-Polymer concrete, resulting in significant time, effort, and cost savings by minimizing the need for extensive laboratory testing. Previous studies have shown that the Artificial Neural Network (ANN) method is commonly used for predicting the compressive strength of conventional concrete, while for high-performance concrete, alternative methods such as the Genetic Weighted Pyramid Operation Tree (GWPOT) are preferred. Based on the obtained findings, it is recommended that researchers should perform comprehensive laboratory tests on construction waste generated during demolition processes, alongside the development and evaluation of numerical models. These models should aim to predict the behavior of the resulting demolition materials when incorporated into Geo-Polymer concrete, in order to enhance our understanding of the effects of high temperatures on Geo-Polymer concrete. Such investigations are crucial, particularly in regions prone to fire or elevated temperatures, such as factory walls. By gaining insights into the behavior of these materials under extreme thermal conditions, they can potentially serve as viable replacements for existing construction materials.

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