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MECHANICAL AND DURABILITY PROPERTIES OF FLY ASH GEOPOLYMER CONCRETE – A REVIEW

Ali Shebli
Faculty of Engineering, Beirut Arab University, Debbieh, Lebanon, aas018@student.bau.edu.lb

Jamal Khatib
Faculty of Engineering, Beirut Arab University, Debbieh, Lebanon, j.khatib@bau.edu.lb

Adel Elkordi
Faculty of Engineering, Beirut Arab University, Debbieh, Lebanon, a.elkordi@bau.edu.lb

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1. INTRODUCTION

Concrete has been recognized as one of the most extensively produced materials on the planet (Machaka et al., 2019), with a mean consumption amounting to millions of tons (Soomro et al., 2023). The environmental impact of concrete production is a well-documented issue, particularly when it comes to the emission of CO_2 throughout the construction process (Machaka & Elkordi, 2017). The principal binder for a concrete mixture, which is extensively used for many sorts of constructions, is ordinary portland cement (OPC). However, producing OPC necessitates the use of several natural resources (Khatib et al., 2020) and significantly increases emissions of CO_2 (Payá et al., 2019). According to various studies, including (Gastaldini et al., 2015; Hills et al., 2016) around 0.6 to 0.8 kilograms of CO_2 are produced for every 1 kilogram of OPC. Moreover, Hanifa et al. (2023) highlighted that global CO_2 emissions are influenced by cement plants, which contribute to around 7% of the overall emissions.

Over the past 20 years, there have been considerable studies on substituting cement with an eco-friendlier binder to minimize the harmful environmental effects of OPC. Geopolymer binders have been identified as a promising alternative to OPC, they are formed by reacting aluminosilicate precursors with alkaline solutions (ElKhatib et al., 2022). The aluminosilicate sources need to have a high concentration of silicate and aluminates and can include fly ash, metakaolin, red mud, or silica fume (Kishore, 2020). While alkaline activators (AA), which might be sodium hydroxide (NaOH) or sodium silicate (Na_2SiO_3), are often utilized in the manufacturing process of geopolymer materials. These geopolymers have been presented as a more ecologically friendly and sustainable alternative to OPC (Shobeiri et al., 2021). Pacheco-Torgal.(2015) reported that the utilization of geopolymers leads to a reduction of 80% in CO_2 emissions as compared to OPC.

Besides being environmentally friendly, geopolymer concrete (GPC) offers a host of advantages over OPC concrete. Many studies have found that GPC has superior durability as well as mechanical properties over OPC concrete (Al Bakri et al., 2013; Bellum et al., 2020; Castel & Foster, 2015; korditib & Clay, 2004; Mangat & Khatib, 1993). Fly ash, which is abundant and readily available, is among the most widely utilized raw materials in GPC. It contains essential components for the synthesis of GPC, such as SiO_2 and Al_2O_3. For decades, fly ash was used as a partial replacement for OPC in concrete production (García-Taengua et al., 2015). Fly ash characteristics are shaped by a range of factors, such as coal type, combustion conditions, and collection method (McCarthy & Dhir, 2005). The discovery of fly ash pozzolanic properties and potential for reaction dates back to 1914, but it was not until 1937 that a comprehensive examination of its use in concrete was conducted in the US (Halstead, 1986; McCarthy & Dhir, 2005).

The purpose of this study is to review various types of aluminosilicate precursors employed in the creation of GPC. It also intends to explore the impact of several aspects on the fresh, mechanical, and durability properties of fly ash GPC, such as curing conditions, activator types, and mix proportions.

2. GEOPOLYMER COMPOSITIONS:

Inorganic polymeric materials known as geopolymers are created by combining an aluminosilicate precursor with an AA (Cong & Cheng, 2021). The aluminosilicate material used must have a high content of silicon and aluminum, and it could be obtained from natural sources like red mud or industrial by-products like fly ash and silica fume. The alkaline solution used in the process can be derived from substances like sodium silicate or hydroxide, potassium hydroxide, or potassium silicate.

2.1 Aluminosilicate Precursors:

Geopolymers rely heavily on aluminosilicate precursors, which may not react with water but instead react slowly (Habert, 2014). However, if these materials are placed in an alkaline solution, they will undergo hydrolysis and condensation, leading to the formation of new inorganic polymers. The chemical composition of a precursor is crucial in geopolymerization, with most precursors consisting of silicate and aluminate that dissolve in alkaline or acidic solutions to form a hardening gel. Many of these precursors are waste materials resulting from various procedures. The most utilized mineral materials for this purpose are fly ash, silica fume, ground granulated blast furnace, and limestone powder (El-Kurdi et al., 2014) . This section gives a short review of a few of the primary precursors utilized in geopolymer production.

2.1.1. Fly ash:

Fly ash is a residual material that arises as a result of the incineration of pulverized coal in power plants (Alterary & Marei, 2021). During the burning process, flue gases carry unburned waste away from the combustion zone, which is then collected using electrostatic or mechanical separators to form fly ash. In numerous countries, it's common to employ fly ash as a substitute for cement at a rate of up to 40% (Siddique & Khatib, 2010). Nevertheless, a significant amount of fly ash remains unused, leading to significant environmental concerns and exorbitant disposal expenses. ASTM C618 categorizes fly ash as either Class C nor F depending on the chemical composition, as shown in Table 1. Additionally, fly ash contains small spherical particles with a specific gravity ranging between 1.6 and 3.1 (Bhatt et al., 2019) and has a considerable specific surface area as well as a low bulk density (Ram & Masto, 2014), making it a popular material for various construction applications.

Table 1. ASTM Specification for Fly Ash (ASTM C618, 2019)

Class	Definition	Chemical prerequisites
C	Fly ash produced by the combustion of anthracite and bituminous coal, possessing pozzolanic properties, and meeting the applicable conditions specified herein.	$SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$
F	Fly ash derived from sub-bituminous coal or lignite, with cementitious and pozzolanic properties, and meeting the applicable conditions specified herein. Some Class C fly ashes may contain more than 10% lime.	$SiO_2+Al_2O_3+Fe_2O_3 \geq 50\%$

2.1.2. Metakaolin:

To produce metakaolin, kaolinitic clay is calcined at high temperatures, typically ranging from 800°C to 1000°C (Khatib et al., 2014). Unlike other aluminosilicate precursors that are mostly derived from industrial by-products, metakaolin is completely natural (Khatib et al., 2018). The main constituent required for metakaolin synthesis is kaolin, and the resulting chemical formula of metakaolin is Al2Si2O7. Metakaolin was found to have an average particle size around 3 µm, and almost all of its particles, 99.9%, were smaller than 16 µm (Farhan & Gul, 2017). The composition of metakaolin, as presented in

Table **2**, predominantly comprises of silica. When combined with calcium hydroxide, that is generated during cement hydration, silica reacts to create more C-S-H gel, thereby aiding in the strength and durability of the final product (Hou et al., 2004). The effectiveness of metakaolin in cement-based systems as a pozzolan is determined by its degree of purity. When utilized, it can promote increased strength, reduced drying shrinkage, and improved durability (Khatib et al., 2018).

Table 2. Chemical Composition of Metakaolin (Khatib et al., 2010)

Components	Content (%)
SiO_2	52.10
Al_2O_3	41
Fe_2O_3	4.32
MgO	0.19
CaO	0.07
Na_2O	0.26
K_2O	0.63
TiO_2	0.36
LOI	0.6

2.1.3. Ground granulated blast furnace slag:

Blast furnace slag (BFS) is a by-product derived from heating a mixture of limestone, iron ore, and coke in a furnace at a temperature of roughly 1500°C in industrial processes (Vivek & Dhinakaran, 2022). Granulated BFS is produced by grinding BFS to a fine powder after rapidly quenching the molten slag extracted from blast furnaces (Manjunath & Narasimhan, 2020). It possesses both cementitious and pozzolanic properties, and it's been utilized as a primary supplementary cementing product for almost a century (Yuksel, 2018). It is mostly composed of calcium oxide (CaO), silica (SiO2), magnesia (MgO), and alumina (Al2O3), with minor oxides present in trace amounts. Table 3 shows different physical properties of GGBS. It has a specific gravity between 2.54 and 2.9, and this is comparable to that of cement. While its bulk density varies between 1165 and 1668 kg/m3, it is approximately equal to the cement density (1440 kg/m3). However, GGBS possesses a much larger surface area, ranging from 3900 to 4700 cm2/g, compared to the cement surface area of 3310 cm2/g. Because of the larger surface area of GGBS, more mortar is required for covering, reducing the quantity of paste available for lubricating. As a result, when GGBS is used as a partial substitution for cement, the flowability of the GPC may be reduced.

Table 3. GGBS Physical Properties

Physical Properties	Value Range	References
Specific Gravity	2.54-2.9	(Majhi et al., 2018; Siddique & Bennacer, 2012; Vignesh et al., 2015)
Fineness Modulus (cm^2/g)	4000-5000	(Majhi et al., 2018; Ramakrishnan et al., 2017)
Bulk Density (kg/m^3)	1165-1668	(Rathod et al., 2017; Siddique & Bennacer, 2012; Vignesh et al., 2015)
Surface area (cm^2/g)	3900–4700	(Khatib & Hibbert, 2005; Siddique & Bennacer, 2012)
Unit Weight (kg/m^3)	1555	(Siddique & Bennacer, 2012)

2.1.4. Silica fume:

Silica fume, a substance that goes by various names such as micro silica, volatilized silica, or nano silica, is an industrial by-product generated from the manufacturing of ferrosilicon and silicon through smelting (El-Kurdi, 2014). It is composed of micro crystalline particles having a surface area varying from 13000 m2/kg to 30,000 m2/kg (Shanmugapriya et al., 2013). Its particle size is about 1/100th that of the standard cement particle size (Khan & Siddique, 2011), which makes it an incredibly fine material. The high silica content combined with the extremely fine nature of silica fume makes it an effective pozzolanic material with significant scientific and industrial applications. It plays three fundamental roles in concrete: (i) refining the pore size and densifying the matrix (Khatib & Mangat, 2003), (ii) reacting with free-lime, and (iii) refining the cement paste-aggregate interface. Table 4 displays the chemical components of silica fume, revealing that most of its components consist of SiO2, which accounts for more than 95% of the material's composition.

Table 4. Chemical Composition of Silica Fume (Hooton & Bentz, 2010)

Components	Content (%)
SiO_2	96.65
Al_2O_3	0.23
Fe_2O_3	0.07
MgO	0.04
CaO	0.31
Na_2O	0.15
K_2O	0.56
SO_3	0.17
LOI	2.27

2.2 Alkaline Activators (AA)

During the early stages of geopolymerization, AA plays a crucial role. The content of the activator, including its type, concentration, and activator-to-binder ratio, has such a massive influence on the resultant geopolymer properties (Alhawat et al., 2022). The chemical constituents of alkali-activators are characterized by notable variations across different categories and are intrinsically linked to the specific chemical agents employed in their synthesis (Elkhatib et al., 2021). The most widely utilized activators in geopolymerization are sodium silicate (Na2SiO3), sodium hydroxide (NaOH), either alone or in combination, as well as potassium hydroxide (KOH), and potassium silicate (K2SiO3) (Pacheco-Torgal et al., 2008).

3. PROPERTIES OF FRESH CONCRETE:

3.1 Workability

Concrete workability refers to its ease of mixing, transportation, setting, and compaction, is a crucial property. However, because of the elevated viscosity of sodium hydroxide, GPC is less workable than OPC concrete (Deb et al., 2014). Unlike OPC concrete, water is not added to GPC to improve its workability because the formation of geopolymer results from an aluminosilicate reaction that produces a gel that hardens. Shinde et al. (2017) examined how the alkaline ratio affected the workability of fly ash GPC. Their study showed that increasing the Na2SiO3/NaOH ratio enhanced the mix's workability, as shown in Fig.1. In another study by Aliabdo et al.(2016), examined the effect of NaOH solution molarity on fly ash GPC slump value. As depicted in Fig.1, increasing NaOH molarity resulted in a decrease in slump. In comparison with the control mix having a NaOH molarity of 12M, slump was reduced by 10.5% for the solution of 16 M and by 20.0% for the 18 M solution.

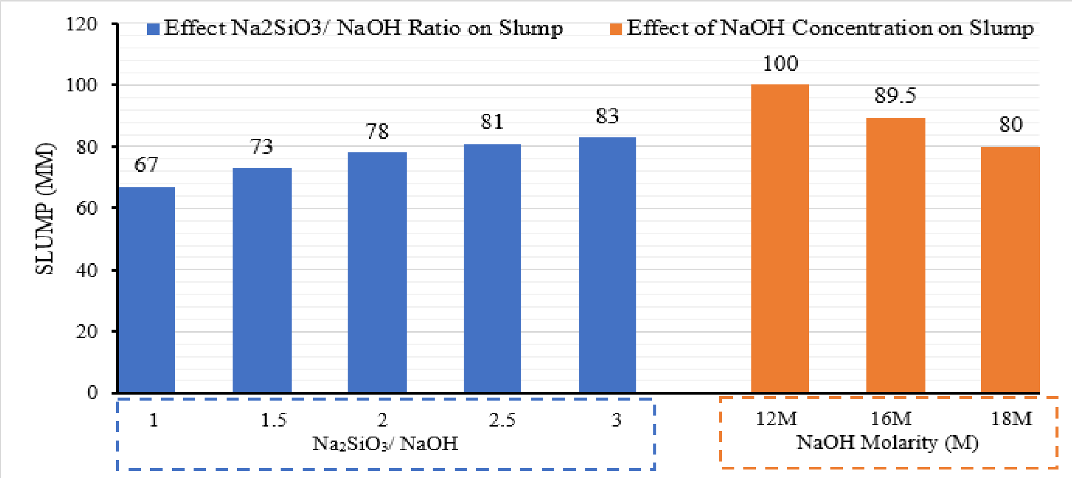

Fig.1: Impact of NaOH Molarity and Na_2SiO_3/NaOH on the Workability of Fly Ash GPC (Aliabdo et al., 2016; Shinde et al., 2017)

3.2 Setting Time:

The time taken for GPC to set is a critical consideration in the building sector (Won et al., 2009). The setting process has two distinct stages: initial and final setting times, with the former taking a relatively longer time and the latter taking a relatively shorter time. Leonard Wijaya et al. (2017) studied the effect of various types of fly ash, sourced from different places and with varying chemical compositions, on the paste setting time. The findings demonstrated that the CaO level in the fly ash impacted the setting time, with those with a CaO content of less than 10% taking a longer time to set, while those with more than 10% CaO content exhibited a similar setting time to the OPC control mix. As shown in Fig.2, as the amount of CaO in fly ash increases, both the intial and final setting decrease. Mohamed et al. (2019), examined the effect of the solid/liquid ratio on the fly ash GPC setting time. The results found that increasing the ratio resulted in a quicker setting time for the GPC. This is because a higher ratio accelerates the gelation process, resulting in faster bonding. The highest ratio tested produced the fastest setting time. However, it is important to note that a fast-setting time may not always be beneficial as it can lead to improper geopolymer bonding, low networking, and ultimately, low compressive strength (Abdul Rahim et al., 2014). Therefore, it is important to change the setting time to suit the specific application in construction. The results emphasize the significance of determining the optimal solid-to-liquid ratio that balances the advantages of a faster setting time with the necessity of proper geopolymer bonding.

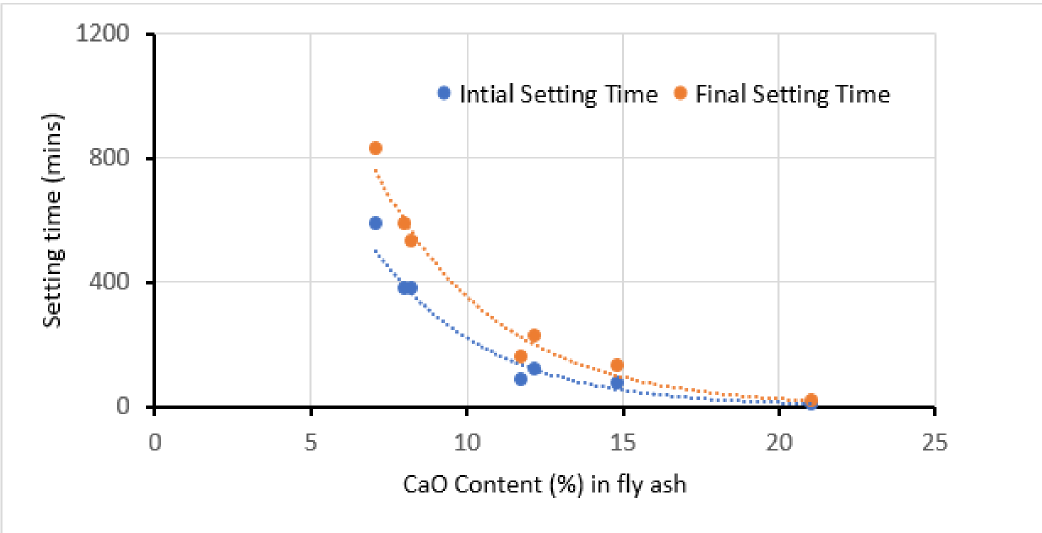

Fig.2: Effect of CaO Level in Fly Ash on Setting Time (Leonard Wijaya et al., 2017)

4. MECHANICAL PROPERTIES:

4.1 Compressive Strength:

When it comes to designing and analyzing concrete, compressive strength takes the lead in terms of importance. However, there are several factors that might affect GPC's compressive strength. As highlighted by Luhar & Luhar (2022) , the AA/binder ratio, the curing duration and temperature, and Na2SiO3/NaOH are among the elements that influence the GPC compressive strength. These factors are essential for achieving the optimum degree of strength in GPC, making them a crucial aspect of the design and analysis process. Ryu et al. (2013a), examined fly ash GPC compressive strength with varying concentrations of NaOH, including 6M, 9M, and 12M. The rise in molar concentration of NaOH resulted in an increase of compressive strength, especially during the initial stages, as depicted in Fig.3. This increase is due to the activation of internal Si and Al components, which results from the greater breakdown of the fly ash's glassy chain. The heightened alkalinity that results from the increased NaOH molarity causes this breakdown, leading to a higher compressive strength.

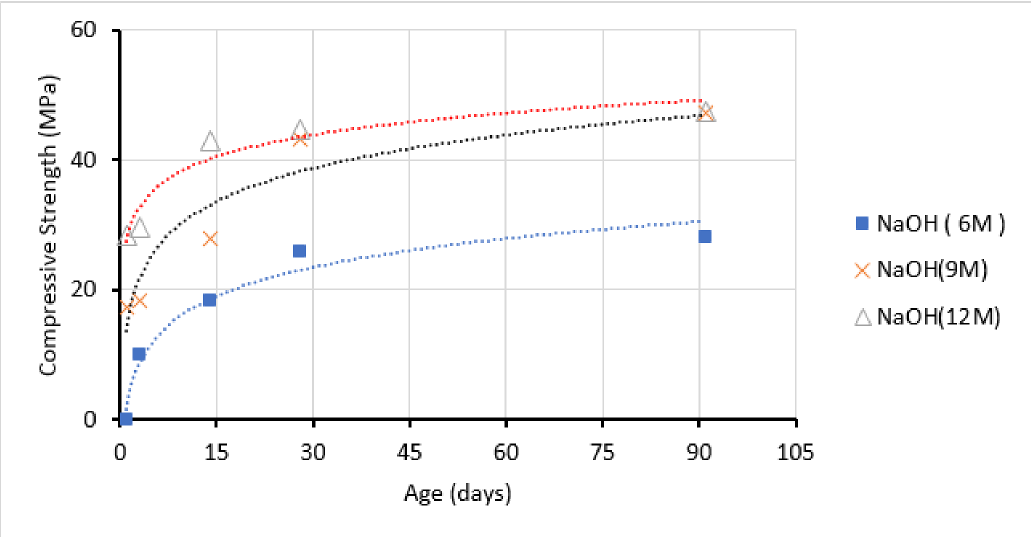

Fig.3: Compressive Strength of Fly Ash GPC with Respect to NaOH Molarity (Ryu et al., 2013a)

Manesh et al. (2012) examine the impact of curing temperature and duration on fly ash GPC compressive strength. Results showed that specimens cured at higher temperatures (60°C, 90°C, and 120°C) for 6 hours displayed greater compressive strength, with the highest being 56.44 MPa for those cured at 120°C, and 39.26 MPa for those cured at 60°C. Furthermore, samples cured at the same temperature (60°C) for a longer duration (24 hours) showed a gain in compressive strength from 39.26 to 46.52 MPa, as shown in Fig.4. Therefore, higher curing temperatures for longer durations yield optimal results in compressive strength in GPC. High temperatures have already been proven to promote and accelerate the geopolymerization kinetics, ultimately reducing the duration of both the setting and hardening phases of concrete. Moreover, the application of higher temperatures during curing was found to significantly increase the production of N-A-S-H gels in concrete compared to ambient temperature curing (H. Zhang et al., 2018). These N-A-S-H gels are paramount in enhancing the compressive strength of concrete, highlighting the invaluable role that thermal curing can play in the optimization of concrete performance.

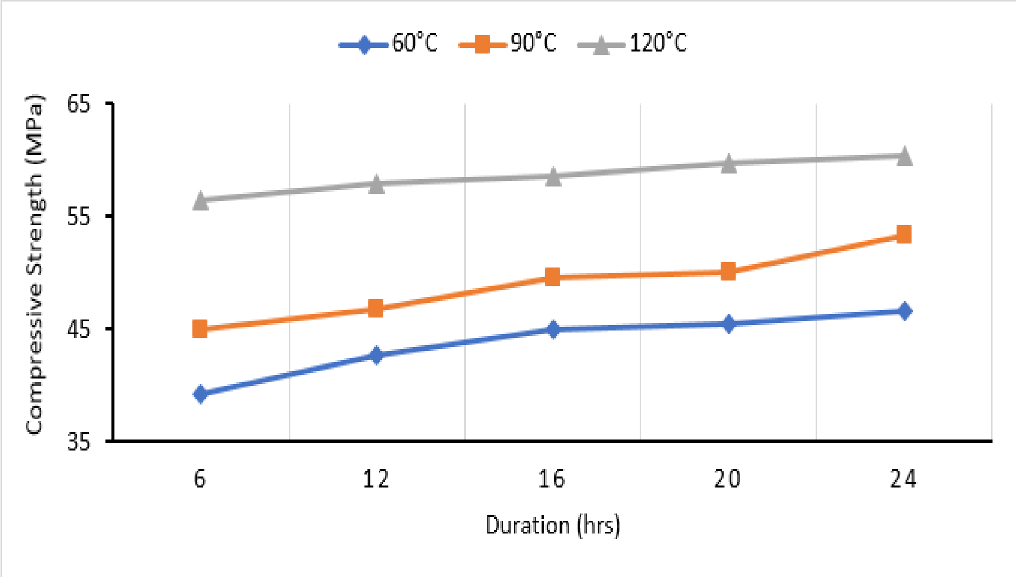

Fig.4: The Impact of Curing Temperature and Duration on Compressive Strength of Fly GPC (Manesh et al., 2012)

4.2 Flexural Strength:

Flexural strength is the ability of a concrete beam to resist deformation and fracture when subjected to bending stress (P. Zhang et al., 2020). Ghafoor et al. (2021) examined the impact of NaOH concentration and the AA/fly ash ratio on fly ash GPC flexural strength. It was found that increasing NaOH concentration led to improved flexural strength of GPC. Fig.5 displayed the highest flexural strength at 16 M NaOH molarity, which was the optimum value.

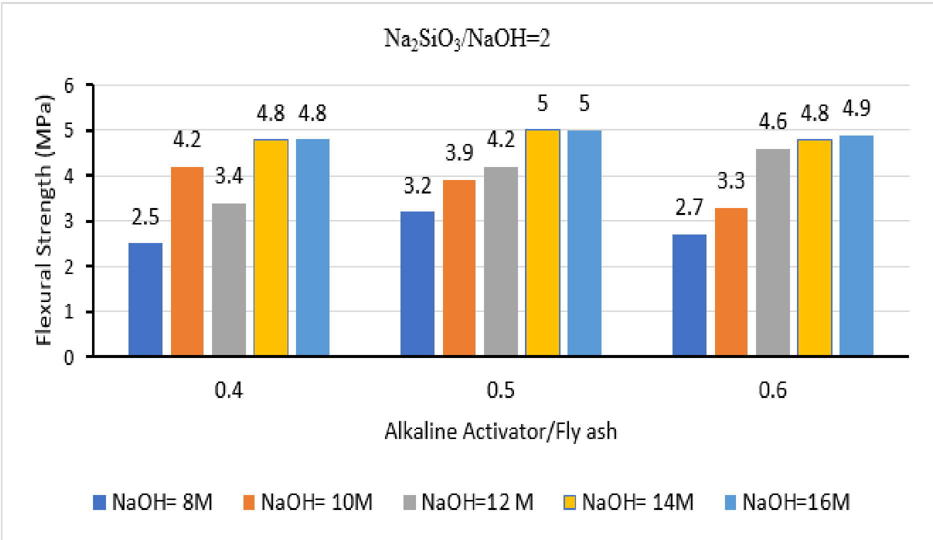

Fig.5: Effect of AA/FA and NaOH Molarity on Flexural Strength (Ghafoor et al., 2021a)

The reported rise in NaOH molarity resulted in a corresponding enhancement in the extraction efficiency of alumina and silica species from the fly ash particulates within the mixture (Nath et al., 2017). As a result, more alumina and silica ions were present in the mix, resulting in the production of N-A-S-H gel. This, in turn, resulted in the creation of a strong and durable geopolymer matrix, ultimately increasing GPC flexural strength. Furthermore, the findings showed that raising the AA/binder ratio to 0.5 resulted in a growth in GPC's flexural strength. Nonetheless, raising the ratio from 0.5 to 0.6 resulted in a drop in strength. This decrease is caused by the deposition of soluble aluminum and silicon ions prior to the initiation of the geopolymerization reaction (Komljenović et al., 2010). The maximum flexural strength for GPC was found to be obtained with an ideal AA/FA ratio of 0.5. Additionally, the water content was identified as a crucial factor during the dissolution phase of the geopolymerization process (Hu et al., 2017). Compared to OPC concrete, GPC exhibits significantly greater flexural strength when compressive strength is similar (Ghafoor et al., 2021b).

4.3 Split Tensile Strength:

The splitting tensile strength of concrete is a significant mechanical property that has a broad range of applications in design and analysis of structures. It is particularly relevant for determining the potential for cracking, shear resistance, and the ability of reinforcing steel to be anchored within concrete (Deb & Nath Sarker, 2014). Parveen et al. (2018) investigated the influence of fly ash and sodium hydroxide concentration on the concrete tensile strength . The study involved using concrete samples with varying fly ash contents of 350, 375, and 400 kg/m3, with different NaOH molarities of 8, 12, and 16 M. The results showed that raising both fly ash level and molarity of the NaOH solution led in a considerable rise in concrete tensile strength, as shown in Fig.6. Another study by Wongsa et al. (2016) , tested the split tensile strength of fly ash GPC with varying Na2SiO3/NaOH ratios of 0.5,1 and 1.5 and the AA/fly ash ratios to 0.70, 0.75, and 0.80. The results showed that as the Na2SiO3/NaOH ratio increased, the split tensile strength of the GPC decreased. However, when the AA/fly ash ratio was 0.7, the GPC exhibited impressive mechanical properties.

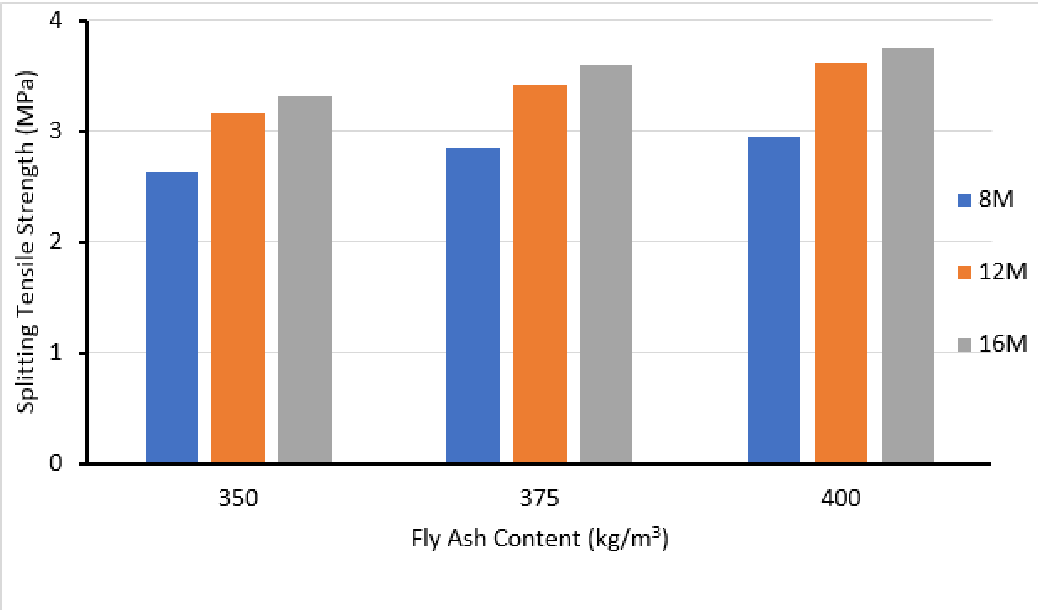

Fig.6: Impact of Fly ash Level and NaOH Molarity on Split Tensile Strength at 28 Days of 27°C Cured Concrete (Parveen et al., 2018)

4.4 Modulus of Elasticity:

Modulus of elasticity is a crucial factor in structural design, as it indicates a substance's ability to withstand elastic deformation when subjected to external force. This parameter is particularly significant for concrete, as it influences its ability to bear loads and maintain its shape under stress. Noushini et al. (2016) evaluated the correlation between the concrete strength and modulus of elasticity of both OPC concrete and GPC, the results were presented in Fig.7. The results showed that fly ash GPC with the same compressive strength as OPC concrete exhibited a lower modulus of elasticity. This difference was attributable to the GP paste's lower modulus of elasticity in compared to the OPC paste (Pan et al., 2011). These results align with the findings of another study conducted by Fernandez-Jimenez et al.(2006), which demonstrated that the elastic modulus

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of GPC is around 50% lower than that of OPC concrete with similar strength. While Olivia & Nikraz (2012) showed that GPC exhibits a lower modulus of elasticity by 14.9 to 28.8 % than those of OPC concrete.

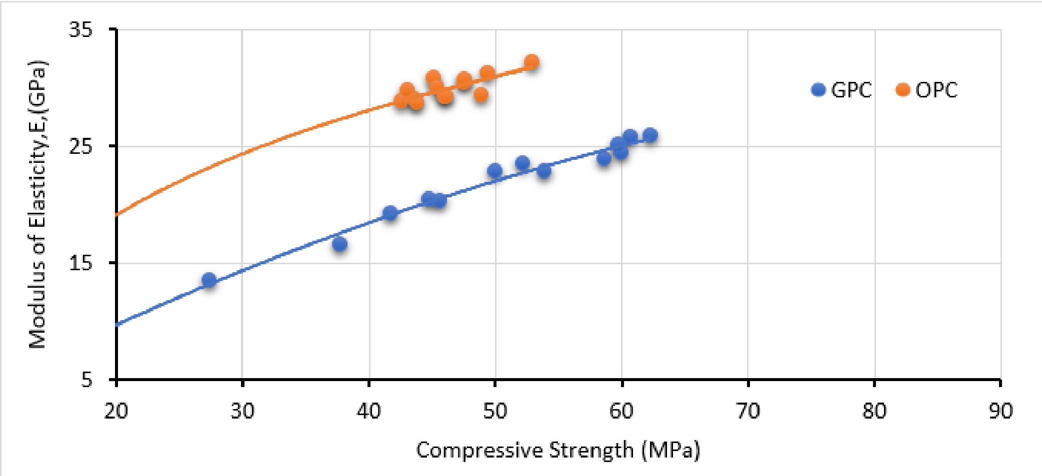

Fig.7.Comparison of Modulus of Elasticity and Compressive Strength for GPC and OPCC (Noushini et al., 2016)

4.5 Ultrasonic Pulse Velocity:

Ultrasonic Pulse Velocity (UPV) test is used to analyze the quality of concrete and identify any defects present within it, by transmitting electronic waves through the concrete. Rao et al. (2016) conducted a study aimed to investigate the quality of roller compacted concrete (RCC) having varying levels of fly ash by measuring its UPV. Results demonstrated that UPV of concrete that contains fly ash regularly exhibited lower values than that of the control sample with no-fly ash, regardless of the age or replacement level of the concrete, as shown in Fig.8. The reason for the drop in UPV of fly ash GPC is that the strength provided by fly ash in RCC is less than that of cement, even after a 90-day curing period, leading to lower UPV values.

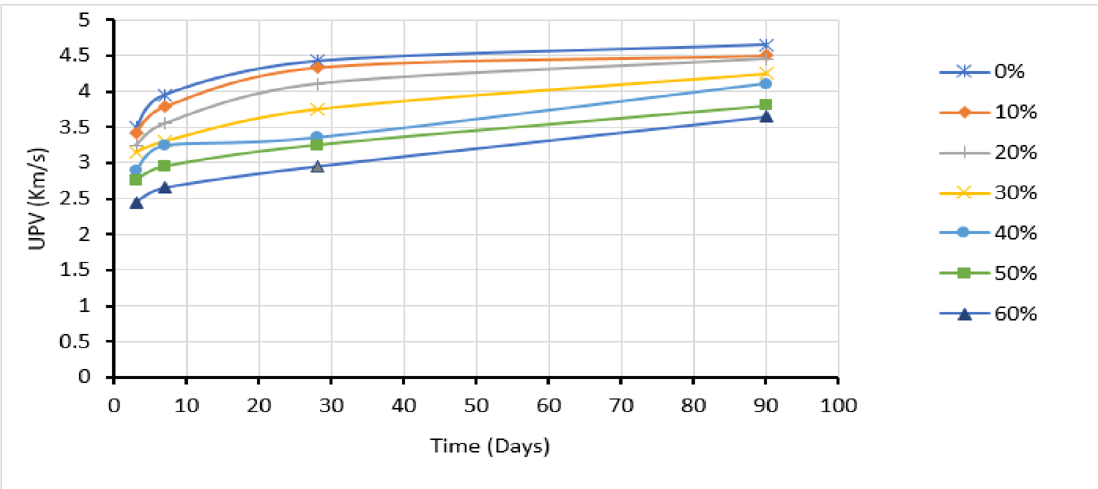

Fig.8: UPV of Concrete at Different Ages with Different Levels of Fly Ash (Rao et al., 2016)

Another study by M Liu. (2010), showed that using fly ash as a replacement for cement till 40% in self-consolidating concrete (SCC) did not significantly affect the UPV compared to that of the control SCC. Subsequently, upon elevating the fly ash replacement levels to 60% and 80%, a reduction in UPV values by 8% and 12%, respectively, was observed following a 28-day curing period. Similar outcomes were noted in the investigation for the UPV values after a 90-day curing duration.

5. DURABILITY PROPERTIES

5.1 Sulfate Resistance:

Sulfate attack is among the reasons that may cause significant damage to concrete and should be considered carefully in design requirements in certain situations (Al-Jabari, 2022). Sulfate has the potential to decrease concrete compressive strength, in addition to causing fractures and expansion (Rasheeduzzafar et al., 1994). When Na+ ions migrate from fly ash-based geopolymer into sulfate solutions, it can lead to the development of vertical cracks and a subsequent decrease in strength (Baščarević et al., 2014). Additionally, the sulfate solution can cause the breakdown of -Si-O-Si- bonds in the geopolymer gel and the leaching of silicon, which contributes to its deterioration. There are various aspects that can influence the sulfate resistance of fly ash GPC, including the presence of calcium in fly ash and the type and level of concentration of the AA utilized. Generally, fly ash GPC exhibits superior sulfate resistance when compared to OPC concrete (Fu et al., 2021). Bhutta et al. (2014) found that fly ash GPC emerged unscathed even after being submerged in a 5% Na2SO4 solution for 540 days, whereas OPC concrete experienced visible cracks, loss of mass, and reduction in compressive strength. Moreover, EDX analysis of OPC concrete confirmed the existence of gypsum crystals due to the high concentration of Ca, O, and S. Conversely, SEM images of fly ash GPC revealed negligible new stage formation, with the EDX spectrum primarily consisting of O, Si, Na, and Al. These findings suggest that fly ash GPC offers superior sulfate resistance when compared to OPC concrete. Another study by Hussain & Arifa (2017) examined the impact of sulfate on OPC concrete and fly ash GPC. The initial set of samples underwent a 7-day curing process, following which compressive strength measurements were conducted on both types of concrete, serving as the control. Subsequently, the remaining set of samples were immersed in a 5% sulfate solution for a duration of 28 days, after which the decline in compressive strength was measured as a percentage. The results presented in Fig.9 demonstrate that the decline in compressive strength was more notable in the case of OPC concrete when compared to the fly ash GPC, suggesting that fly ash GPC is more resistant to sulfate. Another study conducted by Pasupathy et al. (Pasupathy et al., 2021) on the sulphate content profile of GPC and OPC concrete after 10 years of severe exposure.

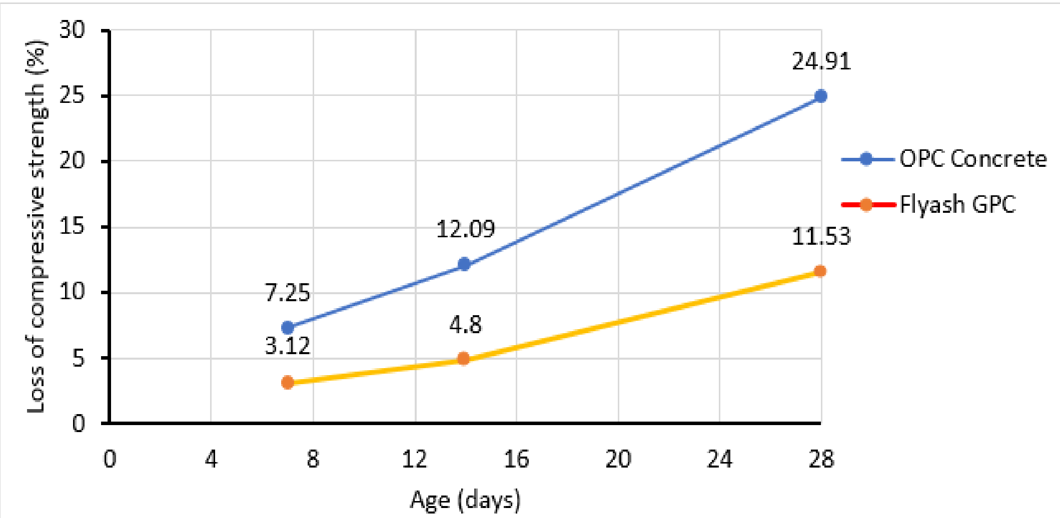

Fig.9: % Loss in Compressive Strength of OPC Concrete and Fly ash GPC with Sulfate Immersion (Hussain & Arifa, 2017)

The results indicated that GPC had a higher sulphate content compared to OPC concrete after the 10-year exposure period. The mechanism of deterioration in OPC concrete in sulphate media is attributed to the reaction of C3A and C-S-H components with sulphate ions (Neville, 2004). This reaction leads to an increase in the volume of the concrete matrix, resulting in cracking and spalling of the concrete structures due to the formation of gypsum and ettringite (Babu et al., 1990). On the other hand, the mechanism of sulphate attack in geopolymer binders is different from that of OPC binders due to the formation of different geopolymer reaction products compared to the hydration components in OPC concrete.

5.2 Chloride Penetration:

Reinforced concrete structures in harsh environments such as harbors, offshore locations, and pavements are known to undergo long-term deterioration (Ghanem et al., 2008, 2019). This deterioration is often attributed to the infiltration of chloride ions inside concrete (Liu et al., 2014). The ingress of chloride ions promotes the corrosion of the embedded steel bars that serve as reinforcing elements for concrete structures (Mengxiao et al., 2015). In a study conducted by Kupwade-Patil & Allouche. (2013), the chloride diffusion behavior was investigated in GPC specimens prepared using fly ash of Type F and Type C, as well as OPC concrete. The findings, presented in Fig.10, revealed that after an intermittent exposure to saltwater for 352 days, the GPC specimens made with fly ash of Type F exhibited a smaller chloride diffusion coefficient of 9.8x10 -12 m2/s compared to the GPC specimens formed from fly ash of Type C, which showed a diffusion coefficient of 1.87x10-11 m2/s, and OPC concrete with a value of 7.13x10-13 m2/s. Fly ash Type C is known to have a higher Ca content in comparison to Class F fly ash. This chemical composition provides more reactive sites for chloride to interact with calcium, leading to the formation of calcium chloride. Chindaprasirt & Chalee. (2014) studied the impact of varying concentrations of NaOH on the ingress of chloride and corrosion of steel in fly ash GPC under conditions similar to those found in a marine environment. The findings indicated that a higher concentration of NaOH in GPC led to a notable decrease in the rate of chloride ingress. An increased concentration of NaOH in fly ash GPC facilitates the leaching of silicon and aluminum from the fly ash. This process results in a higher level of geopolymerization compared to concrete with lower NaOH concentrations. Therefore, the GPC exhibits a denser matrix with enhanced resistance to chloride ions' penetration (Ryu et al., 2013b).

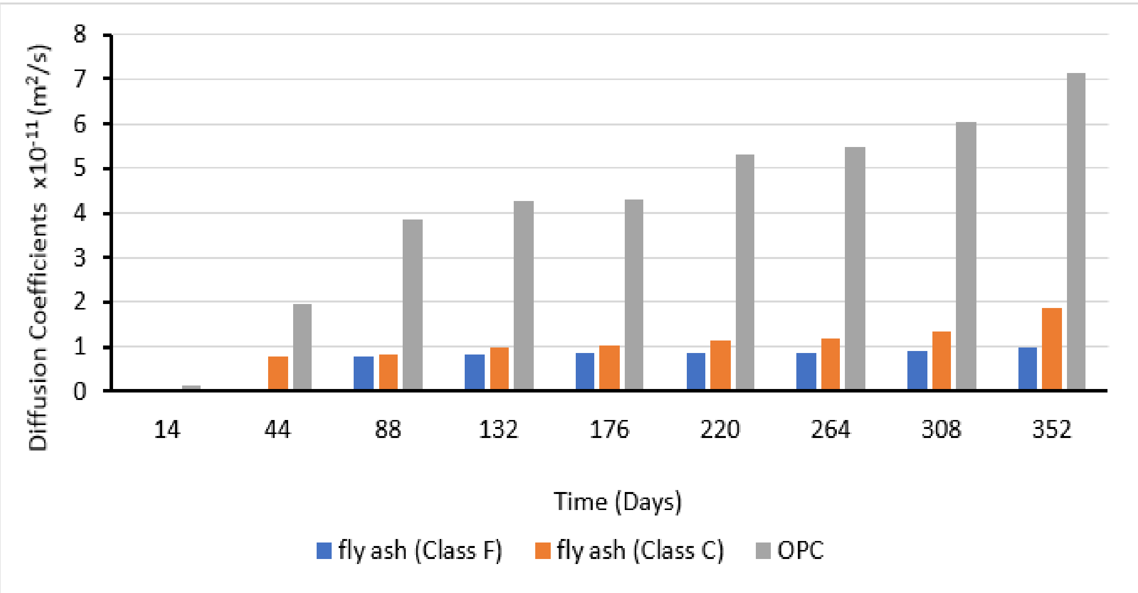

Fig.10:Chloride Diffusion Coefficients in Fly Ash C and F GPC and OPC Specimens over Time (Kupwade-Patil & Allouche, 2013)

5.3 Water Absorption:

Water absorption refers to the process by which water moves through the small voids within the concrete. To determine water absorption, the specimen is subjected to a standardized process wherein it is first dried until it reaches a consistent weight. It is subsequently immersed in water for a predetermined time period, and the percentage increase in weight with respect to the initial dry weight is measured to ascertain its water absorption capacity (Khatib, 2014). Concrete's water absorption could be useful as an initial point for its durability properties (Pradhan et al., 2022). Adak & Mandal (2019) investigated the water absorption capacity of fly ash GPC. The specimens underwent complete immersion in water for a duration of 24 hours before being subjected to a drying process in an oven set at 110°C. Their findings revealed that GPC specimens, which were cured under ambient conditions, had a lower water absorption rate compared to GPC and OPC cured at a higher temperature. Khatib. (2008) conducted a study to assess the influence of fly ash content on the performance of self-compacting concrete (SCC). According to the results depicted in Fig.11, the absorption rate after 1, 28, and 56 days of curing was observed to rise proportionally with the increase in fly ash content from 0 to 80%. Nevertheless, at the 56-day mark, all concrete mixes, including those containing 80% fly ash, demonstrated below 2% absorption, indicating low water absorption (LH McCurrich, 1987).

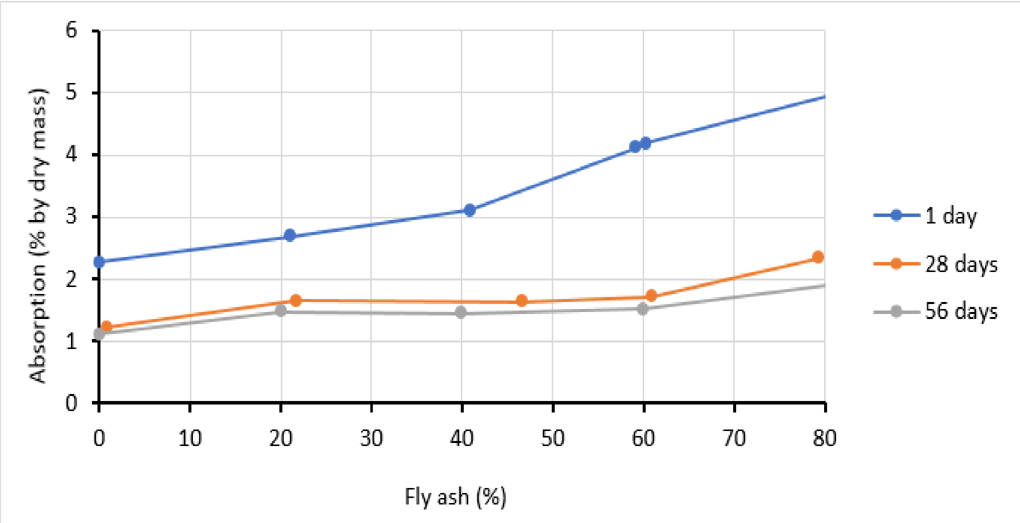

Fig.11: Impact of Fly Ash Content on Water Absorption of SCC (Khatib, 2008)

5.4 Efflorescence Resistance:

The term efflorescence refers to the appearance of noticeable white salt deposits on or near the surface of concrete (Bai, 2009). This phenomenon occurs as an effect of a chemical reaction that occurs between the alkali found in concrete, water, and CO2 in the atmosphere (Larosche, 2009). In general, GPC has a higher concentration of soluble alkali metal compared to OPC concrete. As a result, GPC is more susceptible to efflorescence. The formation of efflorescence is recognized as a significant durability concern for GPC, leading to its deterioration over time (Wang et al., 2018). A study conducted by Wang et al. (2020) on the impact of different Si/Al ratios on the occurrence of efflorescence in GPC. The study examined several ratios, including 0.5, 1, 1.5, 2, and 2.5, which were achieved by incorporating bauxite into fly ash. The findings revealed that raising the Si/Al ratio to 1.5 reduced the level of efflorescence. However, when the ratio was increased beyond 1.5, the efflorescence levels began to rise again. The optimal resistance to efflorescence was observed at a Si/Al ratio of 1.5, where the concrete exhibited the smallest pore volume of 0.017 cm3/g, smallest pore size of 6.21 nm, and the highest level of aluminum tetrahedra. These parameters were crucial in regulating the migration of alkalis, resulting in a reduction in the degree of efflorescence.

5.5 Carbonation:

Concrete structures are susceptible to a chemical process known as carbonation, in which Ca $(OH)2$ found in the cement matrix reacts with CO2 found in the atmosphere (Talukdar et al., 2012). This process causes the pH levels to decrease, which leads the reinforcing steel within the concrete to undergo corrosion (Parrott, 1987). According to Zhuguo et al.(2018), fly ash GPC has a lower carbonation rate than OPC concrete. Kellouche et al.(2019) investigated the effect of fly ash level on carbonation depth at various ages. Results showed that at early ages, substituting cement with fly ash had little effect on carbonation depth, but a weak increase was observed with more than 20 % fly ash, as shown in Fig.12 . However, as compared to control concrete, higher fly-ash percentages resulted in a rise in carbonation depth at older times. When the fly ash percentage was more than 25%, the carbonation level increased at a faster rate, which is related to the consumption of Ca (OH)2 by higher fly ash contents. Badar et al. (2014) studied the impact of fly ash's calcium content on the carbonization resistance of fly ash GPC. The research found that fly ash GPC with a lesser calcium content exhibited better carbonization resistance than those with a higher calcium content. This was related to reduced porosity, a smaller CO2 cumulative intrusion volume, and a smaller fall in pH during carbonization in FABGC samples with lower calcium content.

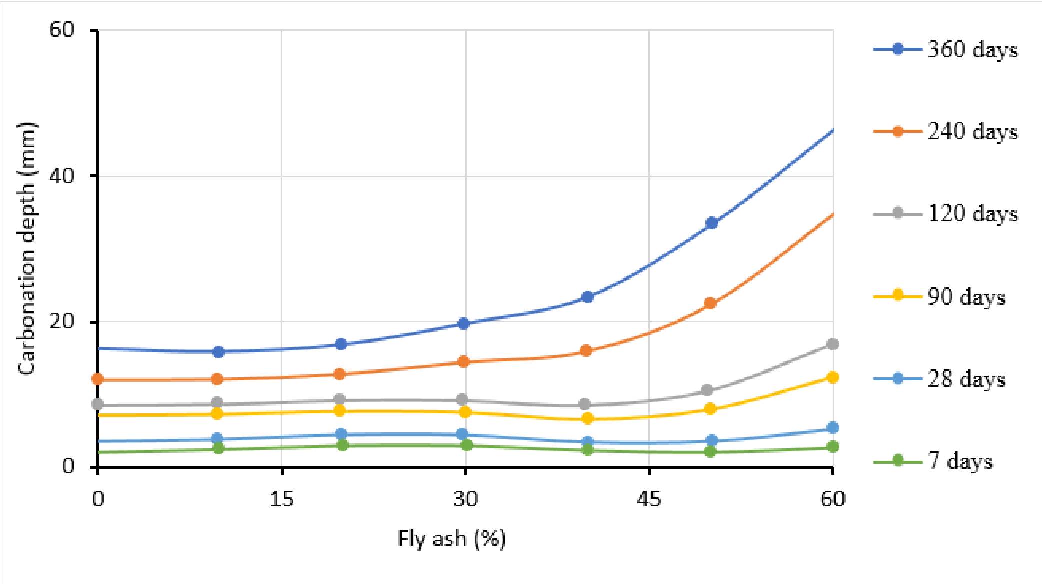

Fig.12: Carbonation Depth at Different Ages as Affected by Fly-Ash Content (Kellouche et al., 2019)

6. CONCLUSIONS:

To minimize the environmental impact of the construction industry, it is critical to identify sustainable alternatives to traditional construction materials. GPC is a promising solution as it is made from waste materials like fly ash, which reduces the carbon footprint of construction activities.

Fly ash properties can vary widely based on their source and processing conditions. Therefore, careful material testing is necessary to determine its suitability for use in GPC. The characteristics and properties of the fly ash can affect the mechanical and durability properties of the GPC, along with its workability and setting time.

The production of fly ash GPC requires the use of an alkaline solution to initiate the geopolymerization reaction. The type and concentration of the alkaline solution can affect the properties of the GPC. NaOH and KOH are commonly used as alkaline solutions, but their corrosive nature can cause handling and safety issues.

Furthermore, the curing temperature of fly ash GPC is an important factor that can affect its properties. The curing temperature can range from ambient temperatures to high temperatures, depending on the specific application. The curing temperature can also affect the energy consumption and production time of the GPC.

Based on the conclusions drawn above, the following recommendations can be made for future research and development in the use of fly ash GPC:

- Continued material testing: While fly ash GPC has shown promise as a potential eco-friendly alternative to OPC concrete, further material testing is needed to establish its long-term durability, strength, and resistance to corrosion.
- Optimization of production processes: To ensure the consistency and quality of fly ash GPC, there is a need for further research and development of production processes. This includes optimization of the alkaline solution and curing temperature to achieve the desired properties of the concrete.
- Establishment of guidelines and codes: To encourage the use of fly ash GPC in construction, clear guidelines and codes need to be established to ensure the quality and safety of structures built using this material.
- Reinforced concrete research: Since fly ash GPC contains alkaline solutions, further research is necessary to study its response to corrosion in reinforced concrete structures. This will help establish the feasibility and safety of using fly ash GPC in such applications.

Overall, continued research and development are necessary to establish the full potential of fly ash GPC as an eco-friendly alternative to OPC concrete. By addressing the above recommendations, it will be possible to increase the use of this material in construction, leading to more sustainable and environmentally friendly building practices.

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