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Development Factors in Eco-Friendly Geopolymer Concrete A State of the Art Review

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ABSTRACT
The use of natural resources in different fields increases over time. Governments all over the world encourage all officials to achieve sustainability goals. Therefore, scientists developed geopolymer concrete as an alternative to ordinary cement-based concrete. The production process of one ton of cement is accompanied by emitting approximately one ton of carbon dioxide into the environment. Geopolymer concrete is free of cement and based on by-product materials, which increase the sustainability of structures. Consequently, it has considerable potential to become the future of green building materials due to its advantages in terms of mechanical properties and environmental benefits compared to conventional cement-based concrete. This paper summarizes a review of the development factors of geopolymer concrete and its applications. Moreover, it briefly exhibits the advantages and disadvantages of replacing Ordinary Portland Cement (OPC) concrete with newly developed geopolymer concrete. In addition, it reports a review of the mix design of geopolymer concrete. Furthermore, it helps the reader better understand the properties of fresh and hardened geopolymer concrete. It also outlines and concludes the effect of different components on binder properties through proposed flow charts. Several research studies on different structural elements made of geopolymer concrete are also presented and discussed. Finally, it provides some practical applications for using geopolymer concrete in construction.

Keywords: *geopolymer concrete (GPC); mix design; mechanical properties; sustainability; green buildings*

1. Introduction

In recent decades, the use of Ordinary Portland Cement (OPC) concrete has increased since it is available at a low cost and gives high strength [1]. Every year, the demand for OPC production increases as long as construction practices grow more and more. In a study in 2009, it was reported that OPC production increased from 594 Mt in 1970 to 2613 Mt in 2006 [2]. Furthermore, during the period between 1999 to 2024, it is expected that the demand for cement in the world will be doubled compared to that before this period [3]. In addition, environmental protection and climate change due to global warming have become the concern of many researchers [2], [4]. In general, the emission of carbon dioxide into the atmosphere significantly impacts global warming [5]. In particular, each ton of Portland cement production is accompanied by the emission of one ton of carbon dioxide into the atmosphere [6]. To put it more simply, many researchers reported that carbon dioxide increased during 2020 and reached its peak record of 419.5 ppm, which increased annually at about 3% [4]. It is worth mentioning that these records not only due to cement production but include other carbon dioxide sources, such as fuel combustion and natural-gas processing. Scientists consider this value a critical situation that needs to be avoided in the following years because this level of carbon dioxide affects badly on the environmental conditions [2]. Therefore, scientists put their efforts into developing new eco-friendly materials that can be completely used instead of the OPC in the construction industry or at least decreasing the amount of OPC in the mix. Various mineral admixtures have been used to substitute OPC, such as fly ash (FA), Ground Granulated Blast-furnace Slag (GGBS), metakaolin, Silica Fume, etc. Moreover, Joseph Davidovits, in the last 1970s, developed a material that was synthesized by the reaction of an aluminosilicate powder with an alkaline solution [7]. Using geopolymer concrete leads to significant short- and long-term advantages, especially in achieving sustainability goals, as shown in Figure 1 [8]. It reduces carbon dioxide emission by up to 80% in case of full replacement of OPC in the concrete mix [1]. Moreover, using GPC for construction increases structures' sustainability and durability, increasing their service life. In addition, using industrial waste in GPC production reduces environmental pollution [9]. Even though all of these mentioned benefits of using GPC in construction processes, it still has limited applications. This is because of its relatively higher construction cost, shrinkage, and quick setting. In addition, the standard design codes still do not involve the use of GPC in their new editions **,[10] .[11]**

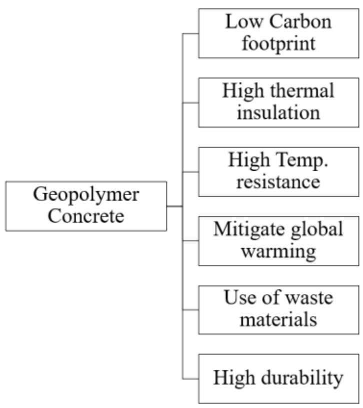


Figure 1: Advantages of geopolymer concrete in sustainable construction

Hence, many studies have been conducted in the same field to enhance this new material's properties and components [12], [13]. It was found that the alkali activator is considered the major component of geopolymer and can be either potassium or sodium hydroxides. In addition, the presence of the precursors, which have low calcium content, such as low calcium fly ash, dramatically affects the properties of geopolymer concrete [7]. In the study by Roy et al. [12], they found that combining the alkali activator with a precursor can enhance the final product. In addition, Hassan et al. reported the durability properties of GPC as well as its characteristics [9]. Likewise, Zhang et al. discussed the mechanical properties of GPC in their study [14], [15]. Also, they showed the microstructural characteristics of geopolymer concrete. According to the literature, it was found that several factors affect the properties of geopolymer concrete. For instance, Jindal's study reported the changes in geopolymer concrete properties along with different mineral additives [16]. In addition, using different oxides compositions in the binder significantly affects GPC compressive strength, which was reported by Reddy et al. [17]. Furthermore, in order to understand the effect of GPC on sustainable development, several researchers analyzed the use of rice husk ash (RHA), fly ash (FA), and foam in the production of GPC under special and ambient curing environments [1]. This article reviews the different components of geopolymer concrete and their development over the decades. In addition, it presents the mechanical and microstructural characteristics of geopolymer concrete mix and binder. Furthermore, the durability properties are discussed in this study.

2. Materials

2.1 Geopolymer components

Geopolymer concrete was first presented in 1970 by Joseph Davidovits [7]. In some situations, it is a construction material that contains a low amount of cement or without cement. The replacement of cement with an eco-friendly material is the main idea of this developed material. Geopolymer is a material that contains some agricultural and industrial waste which have high alumina and silica content, such as Ground-granulated blast-furnace slag (GGBS), Fly Ash (FA), and Rice Husk Ash (RHA). Furthermore, its production is mainly based on a chemical reaction between inorganic molecules [18]. The polymerization process needs an alkaline activator, which is utilized in order to polymerize the contents into molecular chains by activating the bond between mix components to end up with a hardened binder at normal room temperature [19]. This developed material is also called alkali-activated material. This activator should contain either Sodium or Potassium [19]. Moreover, a great conclusion was found in 2017 by Chavan et al. that shows a geopolymer concrete mix with mechanical properties that are very close to those of Ordinary Portland Cement (OPC) [20]. This mix included a ratio between the potassium and sodium hydroxides equal to one to get the same properties. Two main techniques are used in mixing the contents; the first is called one-part and known as "Just Add Water"; the other is called two-part and also known as "Convention Geopolymer Concrete". In the first method, water is added to the dry mixture, and the activators are also added in a solid form [21]. On the other hand, the activators in the second method are added in the liquid state. Figure 2 shows an example of the constituents of geopolymer concrete [22]. In general, the components of geopolymer concrete are mainly the activators and other materials that contain aluminosilicates in the presence of OPC. These materials that contain aluminosilicates are obtained from industrial and agricultural by-products, as mentioned before [23]. In addition, geopolymer concrete may be produced using one of these aluminosilicates-rich materials or a combination between more than one of them. Alkaline activators are mainly used to activate the bond between the contents. Either sodium hydroxide or sodium silicate can be used for this process. However, whenever a mix of both of them is used, this increases the efficiency of the geopolymerization step.

Figure 2: Geopolymer concrete (GPC) contents: (a) Fine aggregates, (b) Coarse aggregates, (c) Sodium Hydroxide, (d) Fly Ash, (e) Sodium Silicate, and (f) OPC

3.1.1 Aluminosilicates

The microstructure of the aluminosilicates is amorphous based on alumina and silica. Several types of aluminosilicates may be used in geopolymer concrete, such as Fly Ash (FA), Ground-granulated blast-furnace slag (GGBS), Rice husk Ash (RHA), and Silica Fume (SF). Usually, the waste materials produced from the industrial and agricultural fields contain high portions of silica and alumina, which can be used to generate energy. This process produces ash as waste material; thus, using it in geopolymer concrete production is one of the best ways to dispose of it in an eco-friendly way [24]. Zain et al. reported in their study the analysis results of X-ray fluorescence (XRF) for different aluminosilicates, as shown in Table 1 [25]. Even though there are different ion concentrations in the tabulated aluminosilicates, the performance of geopolymer concrete is mainly based on the optimum silica and alumina content in the by-product used material, which has a significant effect on the geopolymerization step, especially the chain reaction. Up to this moment, Fly Ash (FA), as well as Ground-granulated blast-furnace slag (GGBS), can be considered the most used binder in the production of geopolymer concrete. FA is a byproduct of coal burning in power plants, which has suitable chemical, physical and microstructural characteristics that enable it to enhance the properties of geopolymer concrete. For example, the particle size and shape help in the geopolymerization process since increasing the surface contact area leads to an increase in the rate of geopolymerization. Furthermore, the porosity of the produced geopolymer concrete depends mainly on the degree of fineness of the used aluminosilicate [26]. Another study by Kamhangrittirong et al. depicts that the increase in the compressive strength of FA-based geopolymer concrete is mainly affected by the ratio of silica to alumina [27]. GGBS comes second after FA as an aluminosilicate that is used in the production of geopolymer concrete. However, geopolymer concrete based on GGBS gives better properties in case of curing at ambient temperature [28]. Furthermore, selecting the concentration of alkaline activators is very important to ensure the superior performance of slag-based geopolymer concrete. In addition, a combination of GGBS and other aluminosilicates can be used to produce geopolymer concrete with relatively superior mechanical properties [29], [30].

Table 1: XRF analysis of several aluminosilicates [25]

Composition	FA	Dolomite	Kaolin
Sources	Coal mining	Oil palm	Nature
SiO_2	52.11	15.37	52.00
Al_2O_3	23.59	1.69	35.00
Fe_2O_3	7.39	0.51	1.00
TiO_2	0.88	0.015	0.90
CaO	2.61	23.00	<0.05
MgO	0.78	17.20	0.70
K_2O	0.80	0.195	2.00
Na_2O	0.42	0.013	0.05
SO_3	0.49	-	-
P_2O_5	1.31	0.019	-
Loss	-	-	-

3.1.2 Activators

The polymerization process of aluminosilicates requires the presence of alkaline activators. There are different types of alkaline activators, such as potassium silicate (K_2SiO_3), sodium silicate (Na_2SiO_3), potassium hydroxide (KOH), and sodium hydroxide (NaOH). In addition, a combination of these activators can be used to dissolve the alumina and silicate atoms [31]. The higher the concentration of activators in the mix, the lower the mechanical strength and the higher the shrinkage effect, which increases the material's porosity. Hence, a good mix design with appropriate portions of activators should be performed and prepared before mixing geopolymer concrete. Based on several studies, it was reported that selecting the appropriate type of alkaline activator as well as using a well-designed portion of it leads to a development in the geopolymer concrete strength. Therefore, the activator-to-binder ratio significantly affects the geopolymerization step and should be precisely determined. Nowadays, silicate sodium and hydroxide sodium are the most commonly used alkaline activators. They give relatively better performance for geopolymer concrete in terms of durability, mechanical, and microstructural characteristics [32]. Furthermore, several researchers reported that the best performance of geopolymer concrete could be achieved by combining silicate- and hydroxide-based activators. On the other hand, using only the hydroxide-based activator gives poor properties with more cracks due to the shrinkage effect. Moreover, Reddy et al. reported that using only silicate-based activators in the mix leads to a delay in the geopolymerization process [33]. However, Deb et al. recommended decreasing the hydroxide/silicate ratio in order to get higher compressive strength and better workability of geopolymer concrete [34].

2.2 Mix design

In general, in order to achieve the desired properties of the mix, a good design should be performed by professionals. However, the geopolymer concrete mix design is not an easy process due to the effect of different variables of the mix, such as the activator ratio, temperature of curing, aluminosilicate type, hydroxide to silicate ratio, etc. Several studies have been performed based on different types of mix design, such as the hit and trial technique, alkaline to binder ratio, strength evaluation, etc. [33], [35]. Some of these methods are discussed in the following subsections.

2.2.1 Hit and trial method

This technique depends mainly on the mechanical properties of the mix [35], [36]. Equation 1, according to the British Standard (BS) [37], is used in this method to get the target strength. Figure 3 demonstrates the procedures of this technique step by step according to the study of Ogheneochuko et al. [38].

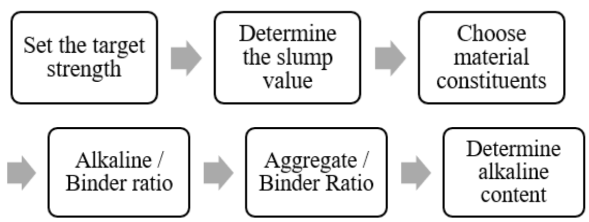


Figure 3: Flow chart describing hit and trial method

One of the most common techniques used in the hit-and-trial method is Taguchi's method. In this technique, the number of variables should be determined in each trial [39]. In addition, this method is used mainly to get high-strength geopolymer concrete. Many trials are performed in this method using different contents, then the optimum mix is determined by getting the response index.

$$f_t = f_{ck} + 1.65\, S_d \quad (1)$$

Where f_t indicates the target compressive strength at 28 days, f_{ck} refers to the characteristic compressive strength at 28 days, and S_d is the standard deviation.

2.2.2 Strength-based method

This method can be considered a modified version of that mentioned in the ACI report ACI 211.4R-93 [37]. It mainly depends on the crucial influencers that affect the strength of the mix, such as the alkaline to binder ratio, degradation of aggregate, and activator content. Multivariate Adaptive Regression Spline (MARS) is one of the most common models used in this method. This model uses a contour plot to develop the mix design using four parameters; alkaline to binder ratio, hydroxides to silicates ratio, activator molarity, and water to binder ratio [40], [41]. More details can be found in Olivia et al [40].

2.3 Geopolymerization

Geopolymerization as a process was discovered first in the 1950s. This process includes numerous internal steps, as shown in Figure 4 [42]. The main idea is to polymerize the aluminosilicates that contain high alumina and silicate by adding an activator. This activator catalyzes the silica and alumina reaction to form a three-dimensional (3D) network. This network converts after that into a 3D chain, forming a polymeric structure.

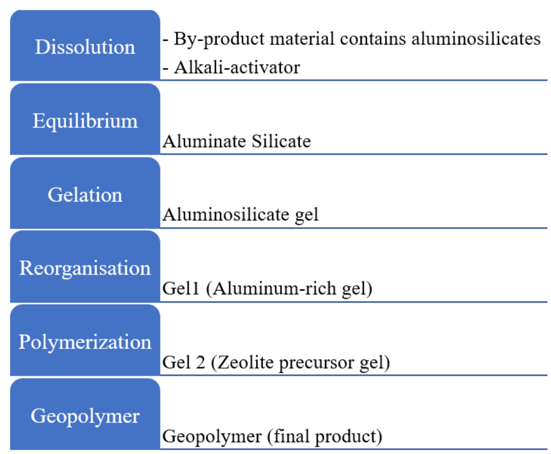


Figure 4: Flow chart showing geopolymerization process

Therefore, the main idea of adding alkaline is to activate the bond between aluminosilicates after the oxidation process occurs [22], [43]. In addition, aluminosilicate oxides are dissolved using a solution of high pH, which converts these oxides into a gel form of polymeric bonds of either Si-O-Al or Si-O-Si. Each of these polymeric bonds or a combination form the geopolymer framework. Finally, the bond between filler materials and other solid particles that have not reacted helps in the hardening process of the framework to end up with the final polymeric structure [44], [45].

3. Geopolymer Concrete properties

Many researchers have studied geopolymer concrete characteristics in terms of construction and mechanical properties. Each of these properties is discussed in detail in the following subsections.

3.1 Workability and Slump behavior

First, it is essential to note that the flowability of geopolymer concrete controls its workability. In addition, many factors significantly affect the workability of geopolymer concrete. Several researchers reported that the higher the molarity of sodium hydroxide, the lower the workability of the mix [46]–[48]. Furthermore, it was reported by Jumrat et al. that the change in the workability of geopolymer concrete affects its hardened characteristics [46]. Also, Mehta et al. discussed the effect of aluminosilicate particle size on workability in their study. They found that the smaller the particle size, the better workability of the geopolymer concrete mix [49]. While in Talukdar et al. study, they found that the production of geopolymer concrete using sodium hydroxide only as an alkaline activator gives a more workable mix than when using a combination of sodium hydroxide and sodium silicate [50]. Moreover, two studies presented the effect of curing temperature as well as selecting the type of activator and its concentration on the slump behavior of geopolymer concrete [51], [52]. They reported a decrease in workability due to an increased sodium silicate to sodium hydroxide ratio in the mix. In addition, the higher molarity of sodium hydroxide, the lower gain in mix workability. Even though using water instead of a naphthalene-based superplasticizer enhances the workability of the geopolymer concrete mix, it gives lower strength results. Al-Majidi et al. mentioned that FA-based geopolymer concrete showed better slump behavior than GGBS-based geopolymer concrete since the GGBS contains relatively larger and nonuniform particles [53]. Another study reported a reduction in the results of the slump in the case of using silica nanoparticles [54].

3.2 Setting time

Numerous factors influence geopolymer concrete's initial and final setting time, such as silicates to hydroxide ratio, plasticizer concentration, binder content, and molarity. These factors have been studied and investigated through several research works. The increase in molarity decreases the setting time since it accelerates the rate of aluminosilicate dissolution, which improves the geopolymerization process. A study by Elyamani et al. reported the effect of molarity on the initial and final setting time for different aluminosilicates of geopolymer concrete. In the case of using Fly Ash (FA)-based geopolymer, the initial setting time decreased along with sing higher molarity [55]. In comparison, the final setting time remains constant for all tested molarity values. On the other hand, the (FAS) mix that contains 50% of FA and 50% of Silica Fume (SF) showed an increase in the final setting time with the molarity of sodium hydroxide. Likewise, the same trend was observed when using a (FASS) mix that includes 50% of FA, 35% of GGBS, and 15% of SF; the higher molarity, the faster the setting time. Many other researchers studied the effect of the alkaline-to-aluminosilicate ratio and silicate-to-hydroxide ratio on the setting time of geopolymer concrete. They reported no significant effect for FA-based geopolymer concrete. Regarding superplasticizer influence on the setting time, Talukdar et al. studied the effect of using slag-based geopolymer concrete along with superplasticizers, including sodium hydroxide and sodium silicate. They confirmed that using sodium hydroxide as an alkaline activator increases the setting time rather than using a combination of sodium hydroxide and sodium silicate [50]. This is because increasing the alkaline leads to an instability of the admixtures [56]. In conclusion, the increase in molarity in the mix leads to a reduction in the setting time of the geopolymer concrete mix.

3.3 Hydartion

It is important to mention that alkaline activators are used to activate the aluminosilicates by the geopolymerization process; this increases the heat of hydration of geopolymer concrete rather than the heat produced from hydration reactions of Ordinary Portland Concrete (OPC). The effect of activator concentration on the released heat was investigated by Singh et al., and no significant increase or decrease was observed for the heat during the mix formation as long as the alkaline concentration was lower than 14M [57]. Likewise, Jiao et al. reported the effect of sodium silicate and sodium hydroxide to fly ash ratio on the heat released from geopolymer concrete formation [58]. The authors found that the higher the ratios, the higher the temperature can be measured, and this may be due to the increased alkaline activator concentration increasing the reactions of geopolymerization, which are considered exothermic. They reported that the silicate-to-FA ratio exhibits a change with a lower slope than the hydroxide-to-FA ratio. However, for both ratios, a linear relation can be observed. Overall, the type and concentration of the alkaline activator significantly affect the heat released from geopolymer concrete formation.

3.4 Compression behavior

Numerous factors significantly affect the compressive strength of geopolymer concrete, such as the type of aluminosilicates, alkaline-to-binder ratio, and type of alkaline activators. Several researchers investigated the use of a different combination of aluminosilicates for the production of geopolymer concrete. They found that when using a binder of 30% FA along with 70% of GGBS, a compressive strength of 66 MPa was achieved.

While, they noticed that the higher the FA content in the mix, the lower the early compressive strength could be achieved. This is due to the increasing ratio of silicate to alumina and FA content increases, leading to a delay in the geopolymerization process [59]. Furthermore, Aguilar et al. discussed the effect of sand type and its ratio in the mix on compressive strength. They concluded that using the limestone sand significantly reduces the compressive strength of geopolymer concrete [60]. Moreover, another study by Kotwal et al. reported an increase in compressive strength with the reduced sand-to-binder ratio from 4 to 2 [61]. The higher fly ash content in geopolymer concrete leads to higher 28 days compressive strength because it forms a relatively denser microstructure, as reported by Ishwarya et al. [62]. In addition, the geopolymer concrete mix achieves higher compressive strength when increasing the curing temperature. A comprehensive study reported the effect of different factors on the compressive strength of the geopolymer concrete mix [63]. The authors concluded that increasing the molarity in the mix increases geopolymer concrete's compressive strength. Likewise, the use of a higher ratio of sodium silicate to sodium hydroxide leads to an increase in compressive strength. In addition, increasing the activator concentration in the mix adversely affects the compressive strength. Also, the mix's compressive strength rises with nanoparticles, as mentioned by Adak et al. [64].

3.5 Flexural and Tensile behavior

According to ASTM C496 [65] and ASTM C293 [66], the flexural behavior and tensile strength can be determined by either performing a splitting tensile test on a standard cylinder or a flexural tension test on a standard prism under three or four-point loadings. Several researchers recognized that almost all variables that affect compressive strength have the same effect on tensile behavior and flexural strength [67]–[70]. For instance, they found that adding 6% of nano-silica to the binder increases the geopolymer concrete mix's tensile, compressive, and flexural strength. Mohammed et al. [71] proposed two power equations (Eqs. 2 and 3) to predict the splitting tensile strength and flexural strength of geopolymer concrete in terms of compressive strength. These equations are based on several previous experimental studies, as mentioned by the authors.

$$f_{sp} = 0.222\ (f_c`)^{0.744} \quad (2)$$

$$f_r = 0.293\ (f_c`)^{0.765} \quad (3)$$

Where, f_{sp}, f_r, and f_c` are the splitting tensile strength, flexural strength, and compressive strength, respectively, measured in MPa.

3.6 Elastic modulus

According to ASTM C469 [72], the modulus of elasticity of different materials can be determined to understand the material's stiffness [69]. Several factors significantly affect the young's modulus of geopolymer concrete, such as aluminosilicate type, aggregate size, and ambient temperature [73]. Several researchers compared the elastic modulus of geopolymer concrete and ordinary Portland concrete at the same compressive strength value. They observed that geopolymer concrete exhibits a lower modulus of elasticity than OPC at the same compressive strength value due to the effect of aluminosilicates on the geopolymerization process. In addition, other researchers investigated the effect of sodium hydroxide on young's modulus of geopolymer concrete. They concluded that using high percentages of sodium hydroxide increases the elastic modulus of geopolymer concrete accordingly [74], [75]. A recent study in 2021 reported a proposed equation to predict the elastic modulus of geopolymer concrete in terms of compressive strength, as follows:

$$E_c = 479.4 + 692.41\ f_c` \quad (4)$$

Where, E_c and f_c` are the modulus of elasticity and compressive strength, respectively, measured in MPa.

3.7 Bonding behavior

It is important to mention that the success of any mix between two components depends mainly on the bond between them. For example, the reinforced concrete structural elements have proved a good performance since experimental tests investigated the high bonding performance between the concrete and the embedded reinforcing bars. Cui et al. conducted a comparison between 12 GPC and 12 OPC beams [76]. They tested the beams according to the ASTM A944 standard [77]. They found no significant difference in the pull-out tests. However, the distribution of bond stresses showed apparent differences during all stages of loading. The maximum bond stress for geopolymer concrete showed higher results than OPC at the final stage of testing. In short, the experimental work proved a high bond stiffness for geopolymer concrete specimens [76].

3.8 Shrinkage

Generally, water evaporation from the surface of concrete causes shrinkage cracks. Several factors control the severity of concrete shrinkages, such as particle size and ambient temperature. Several studies were conducted to determine the difference between geopolymer concrete's shrinkage behavior and OPC. It was reported that geopolymer concrete shows a higher shrinkage than OPC. This may be due to the inclusion of relatively larger pores in the geopolymer concrete paste [78]. In particular, as shown in Figure 5, the measured cracks due to shrinkage in geopolymer concrete show cracks-width exceeding two times that in OPC. Furthermore, Matalkah et al. conducted a Scanning Electron Microscope (SEM) on both types of pastes, OPC and GPC, in order to show the difference in shrinkage crack-width. Figure 6 shows the main components of each paste, in addition to shrinkage cracks, taken by SEM technique .[78]

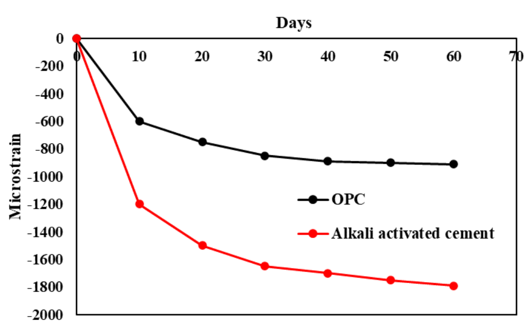
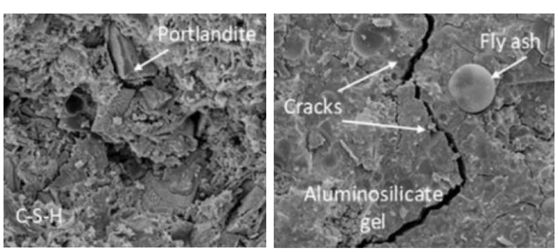


Figure 5: Shrinkage crack width over time [78]



(a) (b)

Figure 6: (a) OPC paste and (b) GPC paste (SEM images) [78]

3.9 Durability

One of the most important features of concrete is durability, which means its ability to avoid any deterioration over time. However, several factors may affect the concrete durability, such as the inclusion of any chemical in its contents and the presence of pores on its surface, which may help in rapidly reinforcing bars corrosion [79]. The durability of geopolymer concrete can be investigated in different ways, such as Rapid Chloride Permeability (RCP) test, absorption test, and water permeability test [80]. More than one research reported that geopolymer concrete generally performs better under aggressive conditions, which means better durability than OPC [80]. Comparing the FA-based geopolymer concrete and slag-based geopolymer concrete in terms of durability; the slag-based mix shows higher durability than the FA-based mix. This is due to that slag-based geopolymer concrete produces a more stable structure. While, FA-based geopolymer concrete exhibits better durability performance than OPC due to the effect of ions in the paste against any chemical attack from the environment. Also, a significant enhancement in the microstructural characteristics of geopolymer concrete was observed when using a combination between rise-husk-ash and GGBS. This might be due to rise-husk-ash reducing the chloride concentration in the mix [81]. Even when using recycled aggregate in geopolymer concrete mixing, it performs better than OPC in terms of durability. In conclusion, geopolymer concrete exhibits much better durability performance than ordinary concrete for several reasons, such as the more stable geopolymer structure, which helps withstand any chemical attacks from the surroundings.

4. Effect of Different Components on Binder Properties

In this section, factors that have a significant effect on geopolymer concrete properties are discussed. The molarity of activators, curing temperature, and alkaline activator to binder ratio affect geopolymer concrete characteristics differently.

4.1 Effect of activators' molarity

As mentioned before, the most critical step in mixing geopolymer concrete is to determine the appropriate concentration of alkaline activator because it has the highest effect on both short- and long-term properties of geopolymer concrete. Several researchers investigated the effect of using different types of alkaline as well as different molarities on geopolymer concrete properties. For instance, Aliabdo et al. studied the effect of molarity on geopolymer concrete compressive strength. The study included three various sodium hydroxide molarities: 10, 12, and 14 M. They found that the higher concentration of sodium hydroxide in the mix results in higher compressive strength [63]. Moreover, using an activator based on silicate rather than hydroxide shows a higher active reaction rate. In addition, the effect of activator types on the geopolymer concrete strength has been studied by Sharayu et al [82]. They concluded that using different types and concentrations of alkaline activators has a significant effect on geopolymer concrete compressive strength. Specifically, the test parameters involved three different molarities (10, 12, and 14 M) along with three various combinations of alkaline activators: $KOH+Na_2SiO_3$, $NaOH+K_2SiO_3$, and $KOH+Na_2SiO_3$. Furthermore, they confirmed that the higher the molarity in the mix, the higher the compressive strength. Figure 7 demonstrates the effect of using different activators on the compressive strength at 7 and 28 days [82].

4.2 Effect of curing temperature

Generally, the rise in curing temperature enables geopolymer concrete to achieve higher compressive strength early; however, it causes rapid water evaporation. This evaporation affects the geopolymerization process and increases the material's porosity, which reduces the compressive strength of geopolymer concrete at later ages.

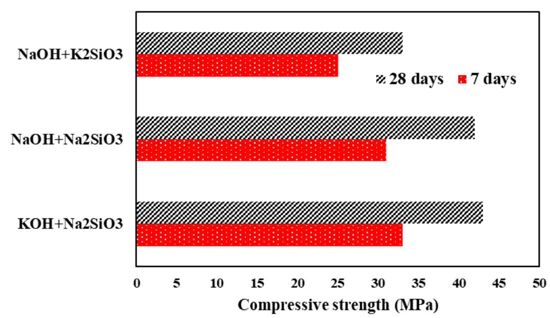
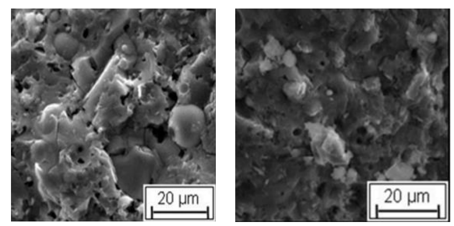


Figure 7: Effect of different alkaline combinations on compressive strength at 7 and 28 days [82]

A comparison study was conducted for a geopolymer concrete mix at two different curing temperatures; ambient temperature (25 ºC) and high temperature (80 ºC). The authors found that the samples cured at ambient temperature give lower compressive strength at seven days. While, at 28 days, the cured samples at room temperature exhibit higher compressive strength than others cured at higher temperatures due to the CSH formation in addition to increasing the porosity in the samples. Figure 8 depicts the main differences between the two samples: one was cured at room temperature (25 ºC), and the second was cured at a higher temperature (80 ºC).

The two images for those two samples were analyzed by SEM technique in order to investigate their microstructure. Figure (8-a) shows the image of the cured sample at a relatively higher temperature, while the other image, Figure (8-b), demonstrates the cured sample at room temperature. The cured sample at ambient temperature exhibits a much softer, smoother microstructure as well as lower voids on the surface than the other sample, which shows a stiffer microstructure with more pores on the surface [62]. Furthermore, many researchers recommended not using heat in the curing process of geopolymer concrete since it significantly affects its properties. However, for FA-based geopolymer, Hardjito et al. reported a significant increase in compressive strength of geopolymer concrete at all ages that was cured under relatively higher temperatures. FA-based geopolymer concrete has different composition compared to slag-based one; hence this may be the reason for different behavior for each one under different curing conditions [83]–[85].



(a) (b)

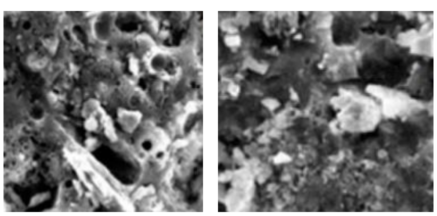
Figure 8: SEM analysis for cured samples at (a) 80 ºC (b) 25 ºC [62]

4.3 Effect of alkaline to binder A/B ratio

Several researchers have studied the effect of the alkaline-to-binder ratio. Aliabdo et al. established a comparison between three different activators to slag ratios (0.40, 0.45, and 0.50). They investigated the effect of activator to slag ratio on the compressive strength and concluded that the higher the ratio of alkaline activator to slag, the lower the compressive strength of slag-based geopolymer concrete [63]. Likewise, but for three various combinations of fly ash to slag ratios (2:1, 3:1, and 4:1), the compressive strength decreased with increasing the fly ash/slag ratios [62]. In general, the use of a lower ratio of alkaline to binder reduces the workability of the mix; however, it exhibits higher compressive strength due to the high silicate and alumina species in the mix. Ozbakkaloglu et al. confirmed that better workability of geopolymer concrete could be achieved with higher ratios of liquid to binder ratio [86]. In short, the appropriately designed ratio between the alkali activator and binder is highly recommended in order to maintain good workability without reducing the compressive strength of geopolymer concrete.

4.4 Effect of OPC in the admixture

Many researchers studied the effect of replacing part of aluminosilicates in a geopolymer concrete mix with OPC. They found significant effects on the microstructure properties of fresh and hardened OPC-GPC mix. First, the presence of OPC and aluminosilicates in the same mix need water for the hydration reactions of cement. However, aluminosilicate reacts firstly with water for a while, then protective layers of calcium ions are formed, which stops the reaction between water and aluminosilicate [87]. After that, the aluminosilicate reacts with calcium hydroxide forming calcium silicate hydrate (CSH), which can be called a pozzolanic reaction due to aluminosilicate pozzolanic characteristics. Aliabdo et al. mentioned three reactions in the OPC-GPC mix; water reacts with cement (Cement hydration), water reacts with aluminosilicate (Aluminosilicate hydration), Ca(OH)2 reacts with aluminosilicate (Pozzolanic reaction) [63]. Siddique et al. studied the effect of partially replacing the aluminosilicate with OPC. They found that combining OPC and fly ash improves the compressive strength because OPC makes the microstructure denser than geopolymer concrete without adding OPC. In addition, this denser microstructure enhances the durability of the concrete. To put it more simply, Figure 9 shows the difference in microstructure between fly ash-based geopolymer concrete and the combination of OPC with fly ash-based geopolymer concrete. These two images were recorded by Chau Khan et al. using the SEM technique [10]. Figure (9-a) demonstrates the fly ash-based geopolymer concrete without adding the OPC, where it shows larger voids. While Figure (9-b) shows the effect of adding OPC to the fly ash-based geopolymer concrete as the microstructure is relatively denser and more compact.



(a) (b)

Figure 9: SEM images of fly ash-based geopolymer (a) without adding OPC (b) with OPC

Furthermore, the inclusion of OPC in the mix also affects workability and setting time. Therefore, Sarker et al. studied that effect and reported a reduction in workability and setting time of geopolymer concrete when adding OPC [29]. Figure 10 depicts the effect of OPC content on the setting time of geopolymer concrete. Contrarily, they observed an improvement in the compressive strength of geopolymer concrete with the inclusion of OPC.

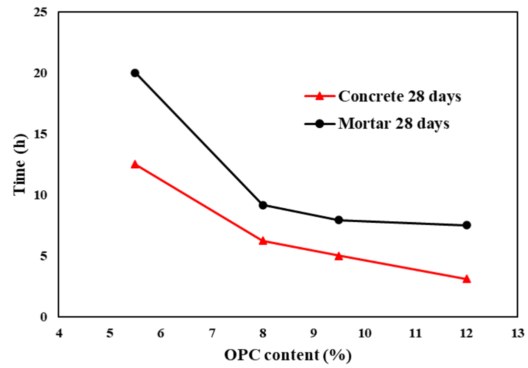


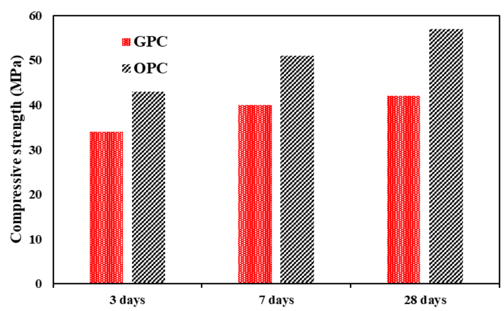
Figure 10: Effect of OPC content on setting time [29]

Likewise, another study conducted by Pangdaeng et al. [88] investigated the partial replacement of the fly ash with different percentages of OPC (0%, 5%, 10%, and 15% Wt.) in geopolymer concrete admixture. The authors concluded that the presence of OPC increases compressive strength at early and later ages. This might be because of the formation of CSH as well as CASH in the structure. Also, Ma et al. replaced the fly ash with different percentages of OPC and reported that the higher content of OPC in the mix, the higher formation of CASH gel, which enhances the microstructure of the mix [89]. Overall, the addition of OPC to the geopolymer concrete mix as a partial replacement of aluminosilicate improves the mechanical and microstructural properties of the mix due to the formation of CASH gel.

5. Comparison between geopolymer concrete and conventional concrete

Understanding the difference between conventional and geopolymer concrete in terms of performance and properties is essential. Geopolymer concrete exhibits superior properties compared to conventional concrete, such as high resistance to chemicals and fire, adjustable setting time, moderate resistance to freezing, less porous, etc. [90]. On the other hand, it shows some drawbacks, such as the high shrinkage of fresh concrete. Nonetheless, most of its drawbacks can be mitigated by adjusting the ratios of the appropriate constituents in the mix, as discussed in more detail in previous sections.

Another study by Hasnaoui et al. showed a comparison between conventional and geopolymer concrete in terms of compressive strength, tensile strength, and modulus of elasticity [91]. Figure (11-a) demonstrates the compressive strength results for both geopolymer and conventional concrete. It can be noticed that OPC overwent its counterpart at 3, 7, and 28 days of standard cube testing. The authors justified the main reason for that might be attributed to the difference in the curing process in addition to the binder water ratio. Another important observation was mentioned in the study regarding the strength evolution from 7 to 28 days. Unlike geopolymer concrete, a significant improvement was recorded for conventional concrete. This is because geopolymer concrete gains its strength earlier than conventional cement-based concrete. Figure (11-b) shows a comparison between both types of concrete in terms of splitting tensile strength. As expected, the observed trend is similar to that of compressive strength. The geopolymer concrete exhibited a very low elastic modulus compared to the conventional, as shown in Figure (11-c). In fact, it was expected that geopolymer concrete would show a lower modulus of elasticity than conventional cement-based concrete, which is attributed to the physical nature of the geopolymer mix itself rather than the porosity.



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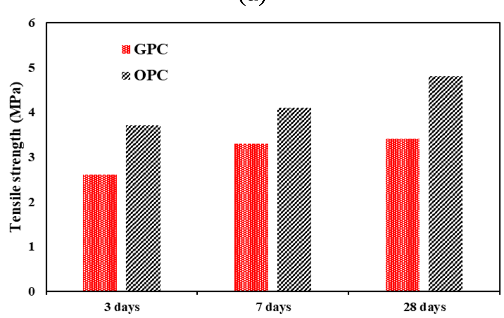

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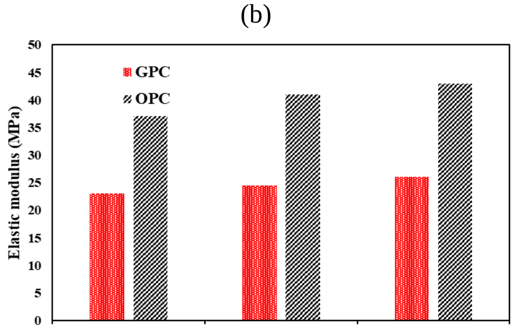


(c)

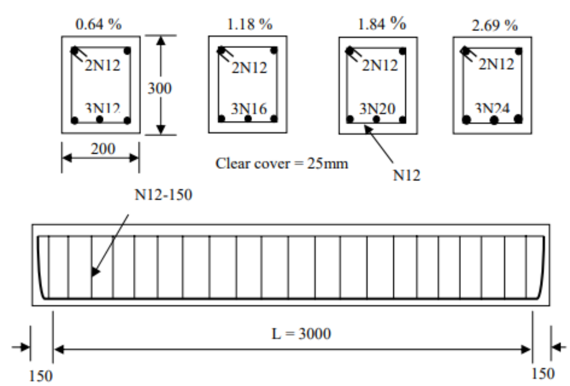
Figure 11: Comparison between geopolymer and conventional concrete in terms of (a) compressive strength, (b) tensile strength, and (c) Elastic modulus [91]

Another study by Rajini et al. in 2020 reported a cost analysis of geopolymer concrete compared to conventional concrete [92]. The scope of their study was on fly ash- and GGBS-based geopolymer concrete. All prices were reported based on the Indian market at that time. For the same compressive strength of 45 MPa, geopolymer concrete exhibited a higher unit cost by 32% than conventional concrete. Nevertheless, the authors stated that consideration of other geopolymer concrete benefits, such as sustainability, low maintenance cost, etc., could allow geopolymer concrete to be comparable to conventional concrete even with a higher initial cost.

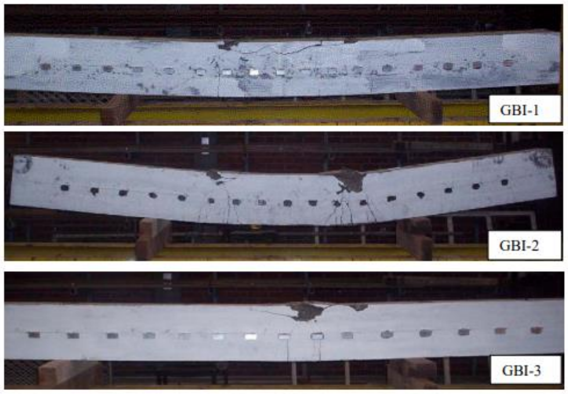
6. Previous Research on GPC Structural Elements

6.1 Geopolymer concrete beams

Geopolymer concrete exhibits outstanding properties compared to conventional cement-based concrete in small-scale experimental tests, as discussed in the previous sections and subsections. The next step is to investigate the structural behavior of different structural members made of geopolymer concrete. An experimental study performed by Sumajouw et al. included 12 beams made of fly ash-based geopolymer concrete [93]. The flexural behavior of all test specimens was investigated. Figure (12-a) depicts the geometry and reinforcement details of test specimens. The test parameters were the longitudinal reinforcement ratio at the tension side and the compressive strength of the concrete. Figure (12-b) demonstrates the cracking pattern of some specimens after the test. The authors reported that the geopolymer concrete beams experienced comparable load-deflection results to conventional cement-based concrete beams. Moreover, they evaluated the results according to the equations mentioned in the existing design standard codes for conventional concrete beams and found a good match.



(a)



(b)

Figure 12: (a) Test specimens geometry and reinforcement details, (b) Cracking pattern of test beams [93]

Ferdous et al. studied the flexural behavior of geopolymer concrete beams and compared the results to OPC concrete beams [94]. They used two types of binder in the mix; fly ash and ground granulated blast-furnace slag (GGBS). Figure 13 describes the test setup and the dimensions of the test specimens. The authors mentioned that slag-based geopolymer concrete beams exhibited better performance, which is close to the conventional concrete beams, unlike the fly ash-based geopolymer concrete beams. Figure 14 shows the load-deflection behavior. Furthermore, it was reported that the number of cracks, crack width, and spacing between cracks was similar between slag-based geopolymer concrete and conventional concrete beams. Additionally, the authors carried out a nonlinear FE analysis, and the numerical results agreed with the experimental tests. Also, an analytical method to predict the failure load was performed and showed promising results compared to the recorded experimental results [94].

Madheswaran and Philip experimentally studied the shear behavior of deep beams made of geopolymer concrete beams with a span-to-depth ratio of 1.9 [95]. They found that the failure of beams without stirrups was controlled by the diagonal compression that led to web crushing. In contrast, beams with stirrups failed due to diagonal compression or shear tension based on the spacing between stirrups. Another study by Aldemir et al. in 2022 investigated the shear behavior of geopolymer concrete beams [96]. They used recycled aggregates instead of natural aggregates in order to validate the possibility of increasing the sustainability of geopolymer concrete beams. Moreover, they investigated different shear span-to-depth ratios as a test parameter. Figure 15 shows the reinforcement details of test specimens.

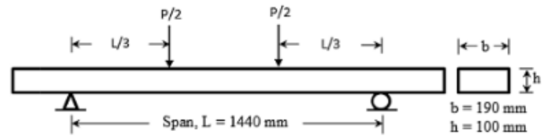


Figure 13: Specimens geometry and test setup [94]

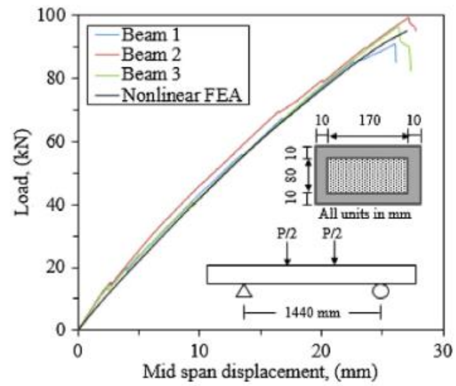


Figure 14: Load-deflection behavior [94]

The authors reported that geopolymer concrete beams with natural aggregates exhibited similar behavior to conventional concrete. When replacing the natural aggregates with recycled ones, the failure mode changed from flexural dominated to shear dominated. It is worth mentioning that the authors reported a significant effect, due to replacing the natural aggregates with recycled ones, on load-deflection behavior, specifically before yielding [96]. Figure 16 demonstrates the moment-curvature relationship for specimens with a span-to-depth ratio of 1.0. Furthermore, they investigated the validation of capacity formulas mentioned in the ACI 318 [97] standard and found an average error of 55% between the experimental results and standard code predictions. This significant error could be attributed to the lower shear span-to-depth ratio in the experiment compared to the basis of the ACI equation. In other words, the formula in the standard is based on shear span-to-depth ratios exceed 2.0, whereas the measured value in the experiment was less than 2.0.

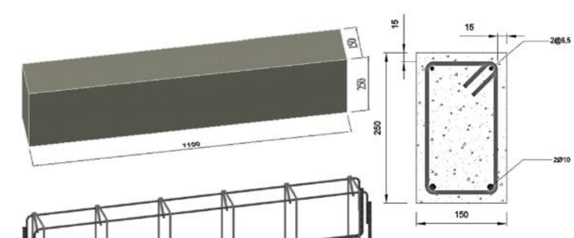


Figure 15: Details of reinforcement of test specimens [96]

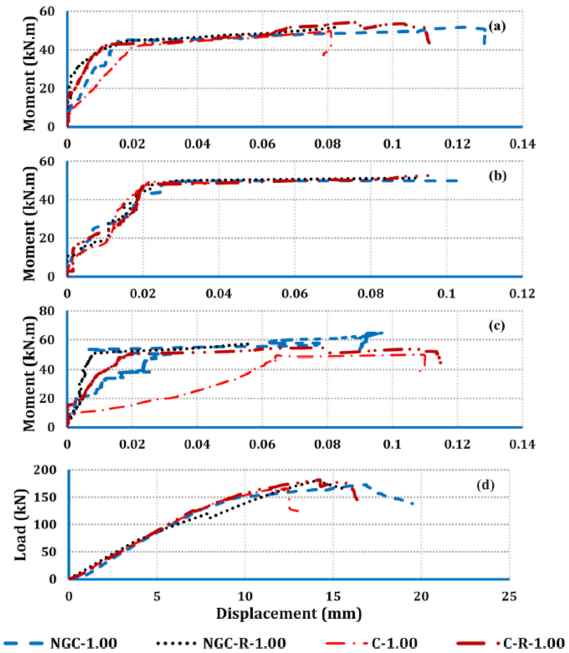
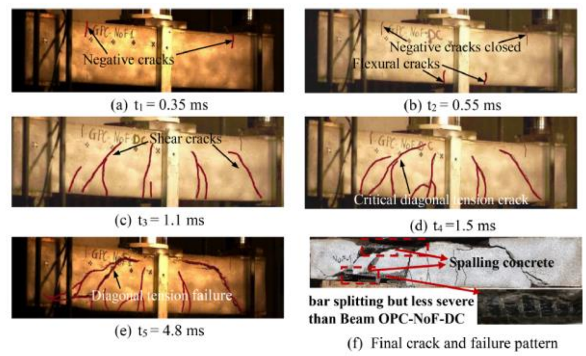


Figure 16: Moment-curvature relations at different LVDT positions [96]

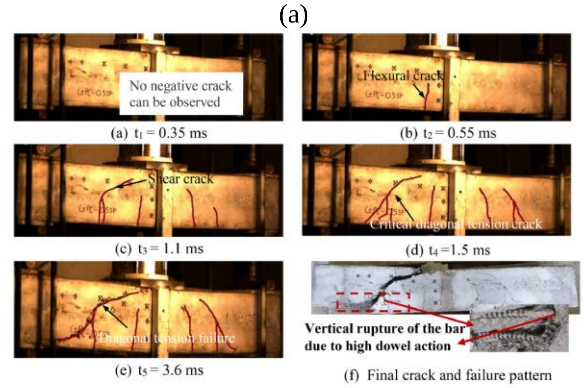
Several research studies have investigated geopolymer concrete beams analytically and numerically using nonlinear FE analysis software [98]–[102]. The results showed an excellent agreement with the experimental results. Tran et al. investigated the shear capacity of geopolymer concrete beams subjected to impact loads [103]. The concrete mix was reinforced with fibers in order to enhance the tensile properties. Two conventional concrete beams were tested as a reference. The authors mentioned that including fibers in the mix significantly improves the post-peak behavior. Figure (17-a) depicts the cracking pattern and failure mode of test specimens without fibers. While Figure (17-b) shows the same but for beams with fibers inside. It can be noticed that test specimens with fibers exhibited better crack distribution as at crack location, the fibers act as a bridge, which mitigates the crack growth by the so-called bridging action. They also investigated using a rubber pad under the load location, which led to shifting the failure from pure shear to flexural-shear dominated.

6.2 Geopolymer concrete slabs

To the best of the authors' knowledge, there is a lack of research in the available literature regarding the use of geopolymer concrete in RC slabs. Eren studied ten RC two-way flat slab specimens made of geopolymer concrete, and half of them were reinforced with steel fibers under center point loading in order to investigate their punching shear capacities [104]. Two different types of hook-ends of steel fibers were used. Figure 18 depicts the test setup used in the experimental test. The experimental results exhibited that adding the nano-silica (NS) and steel fibers (SFs) enhanced the absorption energy capacity. Moreover, it is worth mentioning that the combination of NS and SFs in geopolymer concrete flat slabs performed better than the individual utilization of each in terms of punching shear and deflection capacities. Specifically, the flat slab with NS and NFs achieved ~130% higher load-carrying capacity than their counterparts, as shown in Figure 19. Additionally, flat slabs with longer SFs exhibited better energy absorption capacity than slabs with shorter SFs.



(a)



(b)

Figure 17: Crack propagation and failure mode for geopolymer concrete (a) without and (b)with fibers [103]

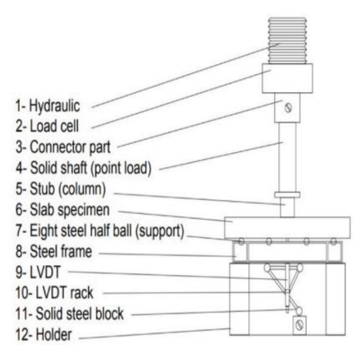
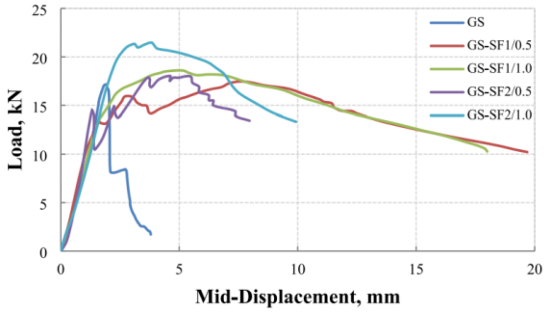
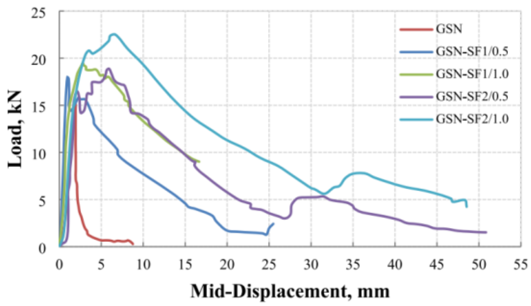


Figure 18: Test setup [104]



(a)



(b)

Figure 19: Punching shear test results of geopolymer concrete slabs [104]

Another study carried out by Meng et al. investigated the effect of gas explosion on geopolymer concrete slabs reinforced with steel fibers (SFs) [105]. The utilized binders in the geopolymer concrete mixture are fly ash (FA) and ground granulated blast-furnace slag powder (GGBS). Experimental tests were carried out on full-scale specimens with dimensions of 1800 cm x 400 cm x 90 cm. The findings showed that geopolymer concrete slabs reinforced with SFs were able to withstand the natural explosion of methane gas better than slabs without SFs.

6.3 Geopolymer concrete columns

Saranya et al. carried out an experimental investigation on four geopolymer concrete square columns reinforced with different steel fiber volume ratios (0%, 0.25%, 0.5%, and 0.75%) [106]. Moreover, one control beam made of ordinary concrete was tested. All columns were cast with a length of 1100 mm and a cross-section of 200 mm x 200 mm. Test setup and reinforcement details are shown in Figure 20. The experimental results showed that the GPC column without steel fibers behaved similar to the ordinary concrete column with an increase in ultimate load of 28%, as shown in Figure 21. Moreover, the early age strength of geopolymer concrete is much higher than ordinary concrete, which in turn helps save time in construction steps. Regarding the economic perspective, the authors mentioned that geopolymer concrete has less cost than ordinary concrete, making it a valid alternative to ordinary concrete in practical applications.

Figure 20: Test setup and specimen details [106]

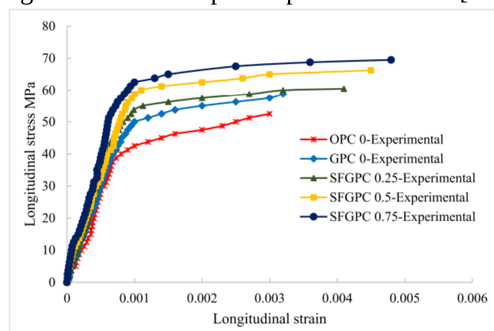


Figure 21: Stress-strain results [106]

An analytical study conducted by Ali et al. was to establish different interaction diagrams (IDs) of geopolymer concrete columns with a circular cross-section and reinforced with glass fiber-reinforced polymer (GFRP) [107]. First, the analytical model was validated with an experimental published data test. The verification showed good agreement. The authors then carried out a parametric study in order to investigate different parameters such as concrete compressive strength and longitudinal and transverse reinforcement ratios. The findings exhibited that the increase in longitudinal reinforcement ratio has more effect on raising the load-carrying capacity of geopolymer concrete circular columns reinforced with GFRP bars and helices than the increase in transverse reinforcement. Furthermore, the compressive strength of geopolymer concrete significantly affects the axially-loaded columns rather than eccentric-loaded ones.

7. Applications

Due to its significant advantages, there are several applications of geopolymer concrete in most structural members. Practically, the first multi-story building that was built in 2013 using geopolymer concrete is the Global Change Institute at Queensland University. The geopolymer concrete was used in casting the precast beams in this building [108]. Figure 22 shows a real photo of the building that was taken after the completion of the construction process.

Figure 22: Stress-strain results [108]

Furthermore, geopolymer can remarkably resist chemical attacks; hence it is also utilized as a protective layer for different structural members to improve their durability [109]. The microstructural properties of geopolymer concrete and its chemical composition make it suitable for acid-resistance applications. For instance, it is recommended by many researchers to be used in marine structures for durability reasons [110]. In addition, the inclusion of alkali activator solutions enhances the microstructure's stability, increasing the density of the geopolymer concrete's microstructure and making it much more compact. The higher the density of geopolymer concrete microstructure, the higher the resistance to chemical attacks [111].

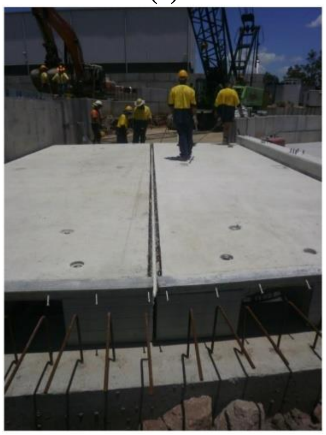
Furthermore, geopolymer concrete can also be used in repairing applications of existing structures due to its ability to prevent reinforcing bars from corrosion [112]. Ichimiya et al. reported the high bonding performance of geopolymer concrete with the addition of fibers; hence, it is used with fiber for bonding between structural members such as bridge elements [113]. In addition, geopolymer concrete can be used as a strengthening material for different structural members, especially those subjected to repeated loads or seismic effects. Due to the high abrasion resistance of geopolymer concrete mix, especially when adding steel slag, it is recommended to be used in the airport or factory ground areas. Moreover, the microstructure characteristics of geopolymer concrete increase the practical application of using it as the primary material in structural members or a secondary one. Emadadi et al. discussed a new application of geopolymer concrete in cooling and evaporative systems [114].

Moreover, geopolymer concrete is efficient as a fire-resistant material due to its microstructure's stability and increasing compressive strength at high temperatures. Overall, several researchers concluded that using geopolymer concrete as an alternative selection for ordinary concrete has many advantages since it increases building sustainability which makes the environment cleaner. Figure 23 shows some examples for geopolymer concrete applications [108].

(a)

(b)

(c)



(d)

Figure 23: Geopolymer concrete applications (a) Pavement placing, (b) water tank, (c) precast boat ramp, and (d) Precast bridge

8. Conclusion

The use of geopolymer concrete can solve several problems as an eco-friendly construction material, such as decreasing the emission of carbon dioxide as well as saving natural energy. However, from the market point of view, it may need some time to replace ordinary concrete based on OPC entirely. Therefore, this paper reviews the recent research related to geopolymer concrete and tries to combine their conclusion marks in terms of mix compositions, curing temperature, and microstructural properties in order to get the full image of this newly developed material and its characteristics. It is found that geopolymer concrete, as an eco-friendly material, can be the alternative solution to ordinary concrete in different construction fields. This is due to its sustainable nature along with the comparable structural behavior to conventional concrete. As mentioned in this article, geopolymer concrete shows better durable properties, making it one of the best options for marine structures and structures that are usually under acid attacks. The durability of geopolymer concrete is due to the stability of the microstructure, which reduces the pores inside the material, preventing any pass of external fluids. Furthermore, geopolymer concrete exhibits better mechanical properties compared to ordinary OPC concrete. Hence, it can replace ordinary concrete in many structural members. In addition, several researchers investigated the performance of different aluminosilicates such as fly ash, ground granulated blast-furnace slag, rise-husk-ash, etc. They reported that fly ash-based geopolymer concrete gives better characteristics than others. They also compared different alkaline activators and concluded that the best activators are based on sodium hydroxide and sodium silicate. Moreover, they also mentioned many factors that significantly affect the geopolymerization process, such as the molarity, percentage, and reactivity of alkaline solutions. Regarding the mix design, researchers recommended that an appropriate dosage of alkaline activator should be used in the mix in order to achieve the desired properties of geopolymer concrete. Furthermore, they found that a faster geopolymerization reaction occurs when using silicates as the alkaline solution in the mix compared to the hydroxide-based alkaline activator. Also, all factors that affect the mix design should be considered in order to get better mechanical characteristics of the produced geopolymer concrete. These factors include the molarity and concentration of activators, type and dosage of the used superplasticizer, aggregate type, type of sand type and content, water-to-binder ratio, activator-to-binder ratio, and hydroxide-to-silicate ratio.

Adding OPC to geopolymer concrete enhances the microstructure by forming CSH products that fill the voids in the mix to have a relatively denser and more compact microstructure than fly ash or slag-based geopolymer concrete. Consequently, the denser microstructure reduces the porosity and shrinkage of geopolymer concrete. Several researchers have studied and investigated the ratios of different geopolymer concrete contents and concluded the activator-to-binder ratio, curing temperature, alkaline molarity, OPC presence, curing age, etc. Those studies will help in determining the optimum ratios and optimum conditions for the production of geopolymer concrete that has superior characteristics. According to the aforementioned research from the available literature, different researchers have paid great attention to geopolymer concrete to investigate its behavior in several structural elements, such as beams, slabs, and columns, under different conditions. It exhibited good results compared to ordinary concrete. Additionally, geopolymer concrete is used in several applications, some of which were mentioned in this review. For future research, the long-term behavior of geopolymer concrete should be investigated in more detail to ensure its ability to replace OPC-based concrete entirely.

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