Durability of Fly Ash Geopolymer Hybrid Concrete in Seawater, Sulfuric Acid, and Fire Resistant – A Review

Niko Rizaldi¹, Habib Abdurrahman², Miguel Felix Wijaya², Gunawan Wibisono², Monita Olivia*³

¹ Dept. of Civil Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Indonesia
² Dept. of Civil Engineering, Faculty of Engineering, Universitas Riau, Indonesia
* Jl. Ganesa No. 10, Lb. Siliwangi, Bandung, 40132, Indonesia
² Jl. HR. Soebrantas, Km. 12.5, Pekanbaru, 28293, Indonesia

monita.olivia@lecturer.unri.ac.id

Abstract. Fly ash is a hazardous and toxic waste material from burning coal. However, it can be used as a material of geopolymer concrete because it contains high amounts of silica and alumina. Recent research on geopolymer concrete is still being conducted because it is part of green building material. This review aims to determine and analyzed the durability of fly ash geopolymer hybrid concrete in aggressive environments. The environment studied included seawater, sulfuric acid, and elevated temperature. OPC concrete is a high calcium material; therefore it is susceptible to aggressive environments compared with OPC concrete, geopolymer concrete contains aluminosilicate and low calcium material, which is not reactive with aggressive environment. The method used in this study is a literature review of several relevant research sources, and data were collected and analyzed. The results showed that fly ash geopolymer hybrid concrete had increased compressive strength compared to OPC concrete. In the seawater environment, the compressive strength of geopolymer concrete increases from 10%-15%. The compressive strength of geopolymer concrete also increases in a sulfuric acid environment up to 360 days of test age, and it is resistant to fire up until 800 °C. Likewise, the porosity of the geopolymer fly ash concrete decreased while the OPC concrete increased. According to the analysis and discussion results, it was resumed that fly ash geopolymer concrete is more environmentally friendly and durable than OPC concrete, especially in seawater, sulfuric acid, and post-fire environments.

1. Introduction
Coal production increased annually, for example in 2019, coal production was recorded at 616,154,054 tons, rising 10.4% from the previous year [1]. The availability of coal and operational costs are efficient compared to other fuels, thus encouraging the industry to use coal as an energy source. The method used involves burning coal, for example, coal-fired power plants (PLTU), paper mills, and palm oil mills. However, in addition to producing energy, coal combustion produces residues that cause environmental pollution, such as fly ash. In addition, instead of producing energy, coal combustion also produces residues that cause environmental pollution, such as fly ash [2]. Fly ash is classified as hazardous and toxic because it contains heavy metals [3]. Although it contains...
hazardous elements, fly ash contains a lot of alumina and silica. Both elements can be used as cement substitute materials with solidification methods such as concrete [4].

Geopolymer is a binder that utilises alumina and silica content in fly ash by a solidification system [5]. Geopolymer bonding is formed with the help of an activator liquid hence sodium silicate and sodium hydroxide. The functions of these two solutions support each other in the formation of bond activation. Therefore, the suitable composition of the mixture can form a stronger geopolymer bond of the cement bond [6]. Geopolymer concrete strength is influenced by the composition of a material, concentration of NaOH and modulus silicate, quality of fly ash, and rest period in early age [7-9].

Concrete is the most commonly used development material, and it is the second most burned-through material after water. Fly ash geopolymer concrete has the same physical and mechanical strength as conventional concrete (ordinary Portland cement concrete), and is durable for aggressive environments, has good performance and sustainability [10]. This paper will review the durability of geopolymer concrete under three aggressive environmental conditions: seawater, sulfuric acid, and elevated temperature (fire). The geopolymer used was hybrid concrete with an OPC mixture. Additional OPC on geopolymer concrete aims to accelerate the setting time without elevated temperatures for rest and curing periods [11]. Olivia and Nikraz [12], Pasupathy et al. [13], Jun et al. [14], and Ge et al. [15] showed durable fly ash geopolymer concrete under seawater environmental conditions. In addition, based on research by Sata et al. [16], Ariffin et al. [17], Mehta and Siddique [18] and Saavedra [19]. Geopolymer concrete can withstand the environmental conditions of sulfuric acid and resistant to elevated temperatures (fire burn), based on research by Abdulkareem et al. [20], Hussin et al. [21] and Zhang et al. [22]. In this review, durability of fly ash geopolymer hybrid concrete was assessed by compressive strength test and porosity values in aggressive environments.

2. Methodology

![Flowchart of study method](image)
The study method used was a literature review using data from the amount of research. Data is collected and analyzed to become the result of the discussion and finally concluded into a theory or idea. Figure 1 shows the flow chart of review methodology in this paper.

The methodology used consisted of several phases. First, the literature review searches for information and data relevant to the study using keywords. It is geopolymer concrete, seawater, sulfuric acid, fire-resistance, compressive strength, and porosity. The database used in the listing was Google Scholar, ScienceDirect, and Research Gate from 2010 to 2021. Many papers and data are found, then selected into 30-40 text articles that are more relevant to the topic of study. Furthermore, reducing and summarizing data have been collected and focused on several environmental and testing conditions. The environmental conditions reviewed were seawater, sulfuric acid, and fire-resistance. Meanwhile, parameter studies for durability fly ash geopolymer concrete consist of testing the compressive strength tests and porosity. The data obtained were tabulated, mapped, analyzed, and compared. The data results are presented in the form of narrative text, tables, images, and graphics that are easy to understand. Finally, a conclusion is drawn from the existing data, becoming a theoretical idea and recommendations for application.

3. Results and Discussion

3.1 Fly Ash Geopolymer Hybrid

The term geopolymer was first coined by Davidovits, a construction material expert from France, in the 1990s. Geopolymer materials were developed as alternatives to cement derived from industrial waste containing alumina and silica, such as palm ash, fly ash, bottom ash, and rice husk ash. Based on Davidovit's research [5], the production of 1 ton of OPC produces CO$_2$ gas emissions of 1 ton. In addition, reducing CO$_2$ emission gas by up to 80% compared to OPC, geopolymers also have several other benefits as shown in Figure 2 [23].

![Figure 2. Schematic of geopolymer benefits as a construction material.](image-url)
Geopolymers are designed in a mortar or concrete product as one of the construction materials. The use of concrete due to its saplings, strong and from the price, is also cheap, generally used for rigid roads, stakes, column-beam buildings, and waterways. Hybrid fly ash geopolymer concrete mixture consists of gravel, sand, fly ash, water, sodium silicate, sodium hydroxide, additional OPC, and superplasticiser. Concrete fly ash geopolymers have a long connective reaction at the beginning of the concrete life and still react until 90 days [24]. Therefore, it takes a catalyst to speed up the time setting, and one of the solutions offered by Nath & Sarker [11] and Wattanachai & Suwan [25] is to use OPC. In addition, concrete fly ash geopolymer does not yet have a standardised mixed planning design, so its manufacture still uses a performance-based and required trial mix [24].

3.2 Compressive Strength Test of Fly Ash Geopolymer Hybrid

The compressive strength test aims to know the maximum force (P) per unit working area (A) on cylindrical concrete samples. The concrete press strength in MPa units and formulated as follows,

\[ f'c = \frac{P}{A} \]

Compressive strength test is generally done based on the test age of 28 days [26]. Furthermore, after 28 days, the sample was placed in an extreme environment to determine its durability against chloride (seawater), sulfuric acid, and fire (heat temperature). Then the compressive strength test was carried out again for several days exposed to an aggressive environment.

3.2.1 Seawater

Fly ash geopolymer concrete in seawater. According to several studies, the marine environment is not friendly to conventional reinforced concrete. This is due to high salinity and chloride content that can attack reinforced concrete. Every year piers, bridges, and other concrete constructions located at sea will require costs for maintenance due to damage [27]. Chloride is the leading cause of this damage, leading to corrosion of concrete and steel, thereby reducing the strength and stability of the structure [28].

In contrast to OPC concrete, several studies have proven that geopolymer concrete is environmentally friendly in seawater (Table 1). The increasing compressive strength value evidence this, and the change in stable strength is not in the negative range (Figure 3). The difference in the compressive strength value (S) is taken from the compressive strength value on the test day \((C_1)\), minus the previous day \((C_0)\), and divided by the previous compressive strength \((C_0)\), can be formulated as follows,

\[ S = \left( \frac{C_1 - C_0}{C_0} \right) \times 100\% \]

Table 1. Summary of compressive strength studies in seawater

| Ref. | Findings |
|------|----------|
| [12] | Geopolymer concrete performs better than OPC concrete on exposure to seawater. Based on changes in the compressive strength of geopolymer concrete, there is no negative range from the test age of 0 to 200 days. |
| [23] | OPC concrete is less durable and less resistant to carbonation and chloride than geopolymer concrete. Geopolymer concrete is denser and the bond between aggregates is better than OPC concrete. Thus, fly ash geopolymer concrete is more resilience and durable to corrosion in seawater. |
| [29] | Geopolymer concrete in seawater has a higher compressive strength than geopolymer |
concrete in ordinary water. This proves that geopolymer concrete is durable in the marine environment due to the availability of Na\(^+\) in seawater which helps improve the performance of geopolymer concrete.

The SiO\(_2\) (silica) element in fly ash will enhance the strength of geopolymer concrete. Silica will increase the Si/Al ratio to prevent zeolite formation. The presence of zeolite will interfere with the polymerization process of concrete so that the compressive strength becomes low.

Figure 3. Change in compressive strength of geopolymer (GP) and OPC in seawater

A change in compressive strength data to 200 days was determined exposed to seawater. After 28 days, both geopolymer concrete and OPC concrete experienced an increase in strength. At that time, the carbonation or chloride reaction was not too strong against the concrete, so there was still an increase in strength. However, after reaching 90 days, 129 days, and 200 days, there is a big gap between geopolymer concrete and OPC concrete. OPC concrete experienced a drastic decrease in performance up to 25% on the 200th day of exposure to seawater. This indicates that the chloride attack has been strong at 90 days and enters the concrete, disrupting the concrete binding structure, resulting in a performance degradation until the 200th day [12].

The availability of Na\(^+\) in the marine environment helps the geopolymer concrete perform better. Na\(^+\) is one of the essential components for the activator solution, useful for activating the silica element in fly ash and increasing the polymer binding gel [30]. According to Figure 3, until the 200th day in the marine environment, geopolymer concrete still has an increase in strength of 5%-15%.

3.2.2 Sulfuric Acid

A sewer environment is one area that has a high sulfuric acid content due to factory and mining activities. In addition, sulfuric acid is also found in acid rain and sulfuric soil [32]. Extreme environments such as sulfuric acid will damage the concrete and harm the surrounding concrete structure. The sulphate attack comes from sulfuric acid ions, which are reactive to calcium hydroxide (C-H). The results of the two reactions of these compounds form gypsum, which is easy to segregate from concrete. In addition to gypsum, the reaction will continue to become ettringite. Thus, the two compounds resulting from the reaction with acid will expand and become the main trigger for cracks to spalling in concrete [33]. In contrast to OPC concrete, geopolymer concrete exhibits excellent resistance in sulfuric acid environments. Visually, a comparison of the conditions of the two concretes in a sulfuric acid environment is shown in Figure 4.
Fly ash geopolymer concrete does not suffer significant damage such as cracking or spalling in a sulfuric acid environment. This is because geopolymer concrete is a category of low calcium concrete. The strength of geopolymer concrete prefers aluminosilicate (A-S-H) bonds over calcium bonds [34]. This concrete is classified as a stable material. Its performance is still increasing up to 90 days. Its compressive strength value continues to increase even though it is in a sulfuric acid environment. Several studies have proven that geopolymer concrete is more resistant to sulfuric acid than OPC concrete, a summary of which is described in Table 2. Compressive strength data is also collected based on this series, and the change in concrete strength is calculated, as shown in Figure 5.

**Table 2. Summary of compressive strength studies in sulfuric acid**

| Ref. | Findings |
|------|----------|
| [34] | Geopolymer concrete has better resistant to sulfuric acid attack after 90 days with strength loss of 9.67%, while OPC concrete as control got strength loss of 33.57%. |
| [18] | Concrete damage will increase along with the amount of calcium (Ca) in the concrete. It was attributed to the formation of gypsum, ettringite which interfered with the cement bond. |
| [35] | Resistance of fly ash geopolymer concrete di sulfuric acid was significantly higher than that of the control (OPC concrete). |
| [36] | Sulfuric acid has a more detrimental impact on OPC Concrete with a strength loss of 26% compared to geopolymer concrete with only a strength loss of 7.3%. |
| [17] | The overall performance of geopolymer concrete in sulfuric acid for greater than 12 months became advanced to OPC concrete that is attributed to a greater solid cross-connected aluminosilicate polymer shape formed withinside the geopolymer concrete. |
The data collected from the research summary reached 360 days of testing; for approximately a year, the pattern of changes in the compressive strength of OPC concrete with fly ash geopolymer concrete can be seen in Figure 5. Of the five geopolymer concrete data, 4 of them are GP[36], GP[35], GP[18], and GP[17], showed an increase in strength at 28 and 90 days. This indication shows that the polymerization process is still ongoing, so that the strength is still increasing. Even at a specimen age of 360 days, geopolymer concrete still increases strength by up to 5%. In addition to the long polymerization process, the geopolymer concrete's resistance performance is not compromised by the presence of sulfuric acid [17]. On the other hand, conventional concrete undergoes a sharp degradation of up to 40%, calcium-binding factor (C-S-H) is the main cause of decreased compressive strength performance [36].

3.2.3 Fire Resistant

Fire accidents can destroy buildings and result in economic losses. After the fire, a debate arose about the residual strength of the structure used as a condition for decision making, namely repair or rebuilding [37]. Concrete buildings are generally resistant to fire, but more than 400 °C will affect dehydration in very elevated temperatures and destroy the concrete binding gel (C-S-H). In addition, a fire forms a high-temperature gradient, and the hot layer can crack and spall the concrete [38]. Therefore, the post-fire performance of concrete will decrease.

The bond is made of aluminosilicate, which acts like crystal-ceramic that is resistant to the effects of elevated temperatures [5] which is slightly different from fly ash geopolymer concrete with inorganic polymer bonds. Several studies have shown that geopolymer concrete has excellent fire resistance compared to conventional concrete (OPC). In addition, aluminosilicate in geopolymer concrete is an alkaline mineral, is not susceptible to temperature changes, and has a three-dimensional connective tissue [39], [21]. In detail, the research summary is detailed in Table 3.

| Ref. | Findings |
|------|----------|
| [21] | Geopolymer concrete shows better strength and stability after exposure to elevated temperatures due to its aluminum silicate polymer structure. OPC concrete has cracked at 200 °C but geopolymer concrete still survives up to 800 °C. |
| [40] | Fly ash geopolymer concrete with low calcium for 2 hours at 600 °C does not lose strength. |
| [41] | Geopolymer shows better flexural and compressive strength than OPC cement mixtures especially after exposure to elevated temperatures. |
Better performance is shown by geopolymer concrete compared to OPCC. Among 72 geopolymer concrete specimens with elevated temperatures reaching 800 °C, only one specimen experienced spalling at 500 °C.

Temperatures of 300 °C and above will reduce the strength of the geopolymer. However, the bond strength of geopolymer concrete is better than that of OPC concrete. OPC concrete has reached spalling when it is at a temperature of 300 °C.

Data from the research summary are collected and plotted in a graph of changes in compressive strength, as shown in Figure 6. In general, geopolymer concrete and OPC concrete have decreased performance due to the influence of elevated temperatures. Of the 5 geopolymer concrete data, 4 data namely GP[40], GP[41], GP[42] and GP[22] experienced a decrease in strength at temperatures reaching 400 °C. While the first data, GP[21] can increase its strength up to a temperature of 600 °C. The good fire resistance of geopolymer concrete is due to highly distributed nanopores in the microstructure, such as ceramics. These small pores will become a container for water to migrate and to evaporate without effect the aluminosilicate system [38]. Regarding the porosity of concrete, it is explained in section 3.3.

Similar to geopolymer concrete, OPC concrete also experiences a decrease in strength. However, the reduction in the strength of OPC concrete was more significant, reaching 55%. The effect of a very high-temperature gradient between hot and cold reduces the performance of concrete, and segregation occurs because the impact of shrinkage also affects the strength of the concrete. OPC concrete has undergone performance degradation starting from 100 °C, showing low fire resistance.

3.3 Porosity Test of Fly Ash Geopolymer Hybrid

Porosity is the percentage of pores or space in the concrete to the volume of concrete. Porosity can be caused by relatively large concrete constituent particles so that the density is not optimal. The air voids in the concrete depend on several factors, such as the size distribution of the fine aggregate, consistency of the concrete, and duration of mixing. The resulting value indicates the level of density of pore grains in concrete. The formula used to calculate porosity is:

$$\text{Porosity} = \frac{W_2 - W_1}{W_2 - W_3} \times 100\%$$

where, \(W_1\) = weight of specimen after the oven
\(W_2\) = weight of specimen after immersion/saturation weighed in air

**Figure 6.** Compressive strength test geopolymer and OPC concrete in elevated temperature
$W_1 = \text{weight of specimen after soaking/saturated weighed in water}$

The purpose of this test is to determine the value or percentage of empty pores of the material to the volume of concrete, with the reference standard ASTM C 642. After a curing period of 28 days, the test is carried out and placed in aggressive environmental conditions to determine its durability. Generally, the porosity results relate to the compressive strength of concrete; the lower the porosity, the greater the strength of the concrete.

### 3.3.1 Seawater

Several studies related to the porosity of OPC concrete and geopolymer concrete in seawater are presented in Table 4. The total porosity of OPC concrete is lower than that of geopolymer concrete, but what makes geopolymer porosity is fine crystalline pores which are generally 1.25 nm - 25 nm in diameter [43]. Despite the initial high porosity, after undergoing a test period of up to 90 days, geopolymer concrete has a decrease in porosity of 6% - 12%, so this also causes the compressive strength to increase [45]. Fly ash geopolymer concrete is concrete that polymerizes long enough so that after 90 days, the strength will continue to increase, and the tiny pores will slowly close. Noshini [45], in his research, reported that geopolymer concrete is more durable in high salinity environments than OPC concrete and is proposed to last up to a service life of 50 years.

**Table 4. Summary of porosity studies in seawater**

| Ref. | Findings |
|------|----------|
| [43] | The porosity of GPC is 12.6% greater than OPC 9.5%. Although the total porosity of geopolymer concrete is higher than OPC, most of the pores are fine pores with the diameter of 1.25 nm - 25 nm. Meanwhile OPC concrete has larger pores in the range of 25 nm - 50000 nm. The porosity data seems to be consistent with the compressive strength of geopolymer concrete. If the compressive strength increases, the porosity of geopolymer concrete will decrease. |
| [44] | The average porosity of GPC is 23.5%. Based on porosity testing, chloride penetration, and other tests GPC is proposed for marine environments with a service life of 50 years. |
| [45] | The GPC mixture has a decreased effective porosity change value compared to OPC concrete for up to 90 days. |

**Figure 7.** Change in porosity test geopolymer and OPC concrete in seawater.
3.3.2 Sulfuric Acid

Sulfuric acid is a strong acid that is reactive with bases, one of the essential elements found in concrete is calcium (Ca). For conventional concrete, calcium is the main element in cement bonding; 65% - 80% of the cement content is Ca, and the rest is silica, aluminium, iron, and other minor components. Together with silica and water, calcium forms a strong binding gel called calcium silicate hydrate (C-S-H). With this gel, concrete can be designed with a particular strength and become a construction material. However, the reactive sulfuric acid environment with calcium will break and disrupt the cement binding gel. As a result, concrete is no longer dense but porous, spalling, and its compressive strength decreases [47].

Table 5. Summary of porosity studies in sulfuric acid

| Ref. | Findings |
|------|----------|
| [47] | Sulfate attack increases the porosity of OPC and geopolymer concrete. However, because the polymerization process is still ongoing, the porosity of geopolymer concrete is decreasing day by day, while the OPC concrete is otherwise damaged. The effectiveness of geopolymer concrete porosity 20.5% Geopolymer fly ash showed a decreased total porosity (14% to 11%), so the permeability resistance to sulfuric acid was better. While OPC concrete porosity increased (16% to 19%) higher than geopolymer, this resulted in acid attack can enter through the OPC pores and spalling. |
| [48] | At the beginning of the age, the geopolymer concrete had a porosity of 17%, after 24 months of exposure to sulfuric acid the porosity did not increase significantly, only 20%. This is because it is influenced by the low calcium content and does not react with sulfate anions. |
| [49] | Silica in geopolymer concrete plays an important role in residual strength because it produces a dense structure and reduces porosity in sulfuric acid environments. |
| [50] | Gel C-A-S-H, because there is not too much addition of C, provides microstructure and helps accelerate the activation of aluminosilicate. The pore capacity is filled better with the microstructure of C-A-S-H so that the porosity value decreases and the compressive strength increases. The porosity values of hybrid-OPC geopolymer concrete at 28, 56, and 90 days in the sulfuric acid environment were 16%, 14%, and 12%, respectively. |
| [51] | Several studies (in Table 5) show an increase in OPC concrete porosity still occurs at the age of 90 days exposed to sulfuric acid by 20% [48]. You can imagine when the concrete reaches the age of 1-year, structural damage will occur. Researchers then began to develop geopolymer concrete as a construction material that is environmentally friendly with sulfuric acid. However, geopolymer concrete has a high initial porosity value; until the age of 90 days exposed to sulfuric acid, the porosity decreases. The research of Duan [48] and Negahban [51] showed that the porosity of geopolymer concrete decreased with a change value of 10%-15%. The porosity value of geopolymer concrete relates to its compressive strength value; the lower the porosity, the higher the strength of the concrete (in Figure 8). Vice versa with OPC concrete, the greater the porosity value so that the performance of the concrete strength decreases. |
3.3.3 Fire Resistant

Both OPC concrete and fly ash geopolymer concrete porosity values increase with increasing temperature. Several studies, which have been summarized in Table 6, show that the porosity of OPC concrete increases due to micron-sized pores, while the porosity of geopolymer concrete is due to nano-sized and large pores [52], [53]. In Figure 9, the increase in porosity of OPC concrete reaches 33%, a significant change in porosity harms the stability of the structure, and it can be predicted that if the temperature is more than 800 °C, the OPC concrete will crumble and the structure collapses. Positive changes in porosity also occur in geopolymer concrete, but it is still in the low range of 8% to 18% and has not experienced severe damage. Based on Chen's research [55], the average mass loss of OPC concrete is 90%, while geopolymer concrete is only 5% after the fire.

Table 6. Summary of porosity studies in fire-resistant

| Ref. | Findings |
|------|----------|
| [52] | Geopolymer concrete has many small pores so that the porosity value is high. The porosity of geopolymer concrete increased from 25% to 28% after the fire occurred at the age of 7 days. This is because the silica is still reacting, expanding, and creating small pores. On the other hand, the presence of these pores is advantageous, because it reduces thermal conductivity. |
| [53] | The porosity of geopolymer concrete before the elevated temperature is 16% after reaching a temperature of 800 °C to 23%. While the OPC concrete from 15% to 31% after reaching a elevated temperature. The compressive strength of geopolymer concrete and OPC decreased, but OPCC decreased significantly more than geopolymer concrete. |
| [54] | The small pores of the geopolymer can remove water quickly, and the heating in the concrete will be evenly distributed. OPC concrete exposed to elevated temperatures has a significant temperature gradient, which has the potential to cause spalling. Geopolymer fly ash loses weight on average 5% while OPC averages 90% post-fire. |
| [55] | Compared to OPC concrete, geopolymer concrete is more spalling resistant to exposure to elevated temperatures. This is due to the small pore structure making it easier to release the internal vapor pressure during heating. |
| [42] | |
Figure 9. Change in porosity test geopolymer and OPC concrete in elevated temperature

OPC concrete pores are formed due to water and air trapped in the concrete; when exposed to a combustion temperature of 400 °C, it will make it difficult for heat distribution. Uneven heat distribution and excessive area of the outer layer while the inner layer is cold will trigger the occurrence of shrinkage cracks. The higher the temperature, the larger the crack, resulting in increased porosity and spalling of the outer layer [54].

Geopolymer has great fire resistance of the raised temperature because of the presence of profoundly appropriated nano-pores in the ceramic microstructure that permits actually and synthetically reinforced water to move and dissipate without harming the aluminosilicate system [38]. Nevertheless, during fire, a few occasions, for example, dissipation of water adsorbed by aluminosilicate gel, development of anhydrous items, crystallization of stable anhydrous stages, and liquefying prompting obliteration by and significant happened. The stage change of geopolymers during a fire is portrayed in Figure 10.

Figure 10. Phase transformation of geopolymers during fire
4. Conclusion
This study investigated the durability of OPC concrete and geopolymer fly ash hybrid concrete by testing compressive strength and porosity. In addition, durability is reviewed with aggressive environmental conditions, namely seawater, sulfuric acid, and elevated temperature. Based on the results and discussion, geopolymer concrete has a higher compressive strength than OPC concrete in seawater and sulfuric acid environments. While both concrete experienced a decrease in performance at elevated temperatures, OPC concrete decreased significantly than fly ash geopolymer concrete. Similar to compressive strength test, porosity test decreased in seawater and sulfuric acid environments. While at elevated temperatures the porosity of concrete increases, but the increase in porosity of geopolymer fly ash concrete is not as sharp as OPC concrete. Thus, it can be concluded that geopolymer concrete with aluminosilicate gel that is low in calcium can survive in a high chloride environment, is resistant to sulfuric acid, and is resistant to fire compared to OPC concrete.

References
[1] [BPS] Badan Pusat Statistik 2019 Produksi barang tambang mineral Wwww.Bps.Go.Id
[2] Xu G and Shi X 2017 Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review Resour. Conserv. Recycl 136 95–109
[3] Peraturan Pemerintah Indonesia 2014 PP No. 101 Tahun 2014 - Pengelolaan Limbah Bahan Berbahaya dan Beracun
[4] Liu X, Zhao X, Yin H, Chen J and Zhang N 2018 Intermediate-calcium based cementitious materials prepared by MSWI fly ash and other solid wastes: hydration characteristics and heavy metals solidification behavior J. Hazard. Mater 349 262–271
[5] Davidovits J 1994 Properties of Geopolymer Cements First Int. Conf. Alkaline Cem. Concr 131–149
[6] Adak D and Mandal S 2019 Strength and Durability Performance of Fly Ash–Based Process–Modified Geopolymer Concrete J. Mater. Civ. Eng 31(9) 04019174
[7] Rizaldi N, Rusadi A I, Wibisono G, Saputra E and Olivia M 2020 Studi Parametrik Kuat Tekan Mortar Geopolimer Abu Terbang Parametric Study of Compressive Strength Fly Ash Geopololymer Mortar 18(2) 113–121
[8] Olivia M, Teknik F, Riau U, Struktur L, Teknik F and Riau U 2015 Geopolimer sebagai Material Infrastruktur Berkelanjutan di Lingkungan Gambut 978–979
[9] Oyebisi S, Ede A, Olutoge F and Oluwafemi T I J 2019 Effects of rest period on the strength performance of geopolymer concrete IOP Conf. Ser. Mater. Sci. Eng. Pap
[10] Lakhsassi M Z, Alehyn S, El Alouani M and Taibi M 2019 The effect of aggressive environments on the properties of a low calcium fly ash based geopolymer and the ordinary Portland cement pastes Mater. Today Proc 13 1169–1177
[11] Nath P and Sarker P K 2014 Use of OPC to improve setting and early strength properties of low calcium fly ash geopolymer concrete cured at room temperature Cem. Concr. Compos
[12] Olivia M and Nikraz H 2013 Properties of fly ash geopolymer concrete in seawater environment Proc. 13th East Asia-Pacific Conf. Struct. Eng. Constr. EASEC 2013
[13] Pasupathy K, Berndt M, Sanjayan J, Rajeev P and Cheema D S 2017 Durability of low–calcium fly ash based geopolymer concrete culvert in a saline environment Cem. Concr. Res 100 297–310
[14] Jun Y, Yoon S and Oh J E 2017 A comparison study for chloride-binding capacity between alkali-activated fly ash and slag in the use of seawater Appl. Sci 7(10)
[15] Ge X, Duran L, Tao M, DeGroot D J, Li E and Zhang G 2020 Characteristics of underwater cast and cured geopolymers Cem. Concr. Compos 114 103783
[16] Sata V, Sathonsawaphak A and Chindrapasirt P 2012 Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack Cem. Concr. Compos 34(5) 700–708
[17] Ariffin M A M, Blutta M A R, Hussin M W, Tahir M M and Aziah N 2013 Sulfuric acid resistance of blended ash geopolymer concrete Constr. Build. Mater 43 80–86
[18] Mehta A and Siddique R 2017 Sulfuric acid resistance of fly ash based geopolymer concrete,” Constr. Build. Mater 146 136–143

[19] Valencia-Saavedra W G, Mejia de Gutiérrez R and Puertas F 2020 Performance of FA-based geopolymer concretes exposed to acetic and sulfuric acids Constr. Build. Mater 257 119503

[20] Abdulkareem O A, Al Bakri A M M, Kamarudin H and Nizar I K 2014 Fire resistance evaluation of lightweight geopolymer concrete system exposed to elevated temperatures of 100–800 °C 595 427–432

[21] Hussin M W, Bhutta M A R, Azreen M, Ramadhansyah P J and Mirza J 2015 Performance of blended ash geopolymer concrete at elevated temperatures 709–720

[22] Zhang H Y, Kodur V, Wu B, Yan J and Yuan Z S 2018 Effect of temperature on bond characteristics of geopolymer concrete Constr. Build. Mater 163 277–285

[23] Hassan A, Arif M and Shariq M 2019 Use of geopolymer concrete for a cleaner and sustainable environment – A review of mechanical properties and microstructure J. Clean. Prod 223 704–728

[24] Olivia M 2011 School of Civil and Mechanical Engineering Department of Civil Engineering Durability Related Properties of Low Calcium Fly Ash Based Geopolymer Concrete

[25] Wattanachai P and Suwan T 2017 Strength of Geopolymer Cement Curing at Ambient Temperature by Non-Oven Curing Approaches: An Overview IOP Conf. Ser. Mater. Sci. Eng

[26] ASTM C 39/C 39M 2012 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens 1 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens 1

[27] Yang S, Zhang X, Yu M and Yao J 2019 An analytical approach to predict fracture parameters of coral aggregate concrete immersed in seawater Ocean Eng 191 106508

[28] Aguirre-Guerrero A M, Robayo-Salazar R A and de Gutiérrez R M 2017 A novel geopolymer application: Coatings to protect reinforced concrete against corrosion Appl. Clay Sci 135 437–446

[29] Reddy D V, Edouard J B and Sobhan K 2013 Durability of Fly Ash–Based Geopolymer Structural Concrete in the Marine Environment J. Mater. Civ. Eng 25(6) 781–787

[30] Megahed S Y, Elthakeb A M, Mohamed W A, Nooman M T and Soufy W H 2019 The Impact of Marine Water on Different Types of Coarse Aggregate of Geopolymer Concrete J. Miner. Mater. Charact. Eng 7(5) 330–353

[31] Li M C X, Wu F R and Hu S S 2020 Synthesis and anticorrosion characterization of marine geopolymer concrete,“ Universidad Michoacana De San Nicolas De Hidalgo Instituto

[32] Elyamany H E, Abd Elmoaty A E M and Elshabouy A M 2018 Magnesium sulfate resistance of geopolymer mortar Constr. Build. Mater 184 111–127

[33] Palankar N, Shankar A U R and Mithun B M 2016 Durability studies on eco-friendly concrete mixes incorporating steel slag as coarse aggregates J. Clean. Prod 129 437–448

[34] Karthik A, Sudalaimani K and Vijayakumar C T 2017 Durability study on coal fly ash-blast furnace slag geopolymer concretes with bio-additives Ceram. Int 43(15) 11935–11943

[35] Okoye F N, Prakash S and Singh N B 2017 Durability of fly ash based geopolymer concrete in the presence of silica fume J. Clean. Prod 149 1062–1067

[36] Albitar M, Ali M S M, Visintin P and Drechsler M 2017 Durability evaluation of geopolymer and conventional concretes Constr. Build. Mater 136 374–385

[37] Hassan A, Arif M and Shariq M 2020 A review of properties and behaviour of reinforced geopolymer concrete structural elements- A clean technology option for sustainable development J. Clean. Prod 245 118762

[38] Singh B, Ishwarya G, Gupta M and Bhattacharyya S K 2015 Geopolymer concrete: A review of some recent developments Constr. Build. Mater 85 78–90

[39] Rashad A M and Zeedan S R 2011 The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load Constr. Build. Mater 25(7) 3098–
3107

[40] Zhang H, Li L, Yuan C, Wang Q and Kumar P 2020 Deterioration of ambient-cured and heat-cured fly ash geopolymer concrete by elevated temperature exposure and prediction of its residual compressive strength Constr. Build. Mater 262 120924

[41] Zhang H Y, Kodur V, Qi S L, Cao L and Wu B 2014 Development of metakaolin-fly ash based geopolymers for fire resistance applications Constr. Build. Mater 55 38–45

[42] Zhang H Y, Qiu G H, Kodur V and Yuan Z S 2019 Spalling behavior of metakaolin-fly ash based geopolymer concrete under elevated temperature exposure Cem. Concr. Compos 106 103483

[43] Pasupathy K, Sanjayan J, Rajeev P and Law D W 2021 The effect of chloride ingress in reinforced geopolymer concrete exposed in the marine environment J. Build. Eng 39 102281

[44] Lee W H, Wang J H, Ding Y C and Cheng T W 2019 A study on the characteristics and microstructures of GGBS/FA based geopolymer paste and concrete Constr. Build. Mater 211 807–813

[45] Noushini A and Castel A 2018 Performance-based criteria to assess the suitability of geopolymer concrete in marine environments using modified ASTM C1202 and ASTM C1556 methods Mater. Struct. Constr 51(6) 1–16

[46] Olivia M and Nikraz H 2012 Properties of fly ash geopolymer concrete designed by Taguchi method Mater. Des 36 191–198

[47] Zhang W, Yao X, Yang T and Zhang Z 2018 The degradation mechanisms of alkali-activated fly ash/slag blend cements exposed to sulfuric acid Constr. Build. Mater 186 1177–1187

[48] Duan P, Yan C, Zhou W, Luo W and Shen C 2015 An investigation of the microstructure and durability of a fluidized bed fly ash-metakaolin geopolymer after heat and acid exposure Mater 74 125–137

[49] Khan H A, Castel A and Khan M S H 2020 Corrosion investigation of fly ash based geopolymer mortar in natural sewer environment and sulfuric acid solution Corros. Sci 168 108586

[50] Çevik A, Alzeebaree R, Humur G, Niş A and Gülşan M E 2018 Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete Ceram. Int 44(11) 12253–12264

[51] Negahban E, Bagheri A and Sanjayan J 2021 Pore gradation effect on Portland cement and geopolymer concretes Cem. Concr. Compos 122 104141

[52] John S K, Nadir Y and Girija K 2021 Effect of source materials, additives on the mechanical properties and durability of fly ash and fly ash-slag geopolymer mortar: A review Constr. Build. Mater 280 122443

[53] Sarazin J, Davy C A, Bourbigot S and Lambertin D 2021 Flame resistance of geopolymer foam coatings for the fire protection of steel 222

[54] Cong S, Sun C and Etxeberria M 2014 Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures Cem. Concr. Compos 53 73–82

[55] Yu X, Chen L, Komarneni S and Hui C 2016 Fly ash-based geopolymer: clean production, properties and applications J. Clean. Prod 125 253–267