Geopolymer hybrid fly ash concrete for construction and conservation in peat environment: A review

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Abstract. Fly ash is industrial residue from the coal combustion in electric and steam generating plants and recognized as an environmental pollutant. Fly ash contains a high concentration of silica and alumina and can be used as geopolymer concrete. Studies the use of fly ash as a geopolymer concrete mixture has been developing in recent decades. This review focuses on the characteristics of fly ash as hybrid geopolymer concrete, and its resistance is peat environment. The hybrid geopolymer is made by activating fly ash using an alkaline activator and Portland cement. The addition of fly ash geopolymer concrete with Portland cement forms N-A-S-H bond structure from fly ash, and C-S-H hydration bond from Portland cement forms C-A-S-H, which is more solid and stronger against aggressive environment such as peat. In addition, the geopolymer concrete is proven to be able to mobilize heavy metals in fly ash so the concrete has low leaching rate and not harmful to the peat ecosystem. This review proves that hybrid geopolymer concrete using fly ash is a potentially innovative and promising material in the future. The geopolymer hybrid not only has its resistance to peat and acts as conservative material in an environmentally friendly peat environment.

1. Introduction

Indonesia’s coal production is continuously increasing over time. In 2017, the realization of coal production reached 456 million tons and increased to 548 million tons in 2018; according to Dewi [1], fly ash waste resulting from coal combustion is classified as a toxic and hazardous substance to the environment and living creatures. Fly ash contains heavy metals such as Pb, Cu, Cd, Cr and Zn. These five elements are hazardous if dissolved in water and potential to disrupt the peat ecosystem. Therefore, fly ash waste needs to be transformed using stabilization and solidification methods such as geopolymer material. Geopolymer is an effective method to mobilize heavy metals in fly ash. The heavy metals in fly ash used in geopolymer concrete remain physically bonded solidly in concrete and will not cause long-term environmental pollution [2]. Therefore, geopolymer can be a construction material and can be conservative material that will minimize pollution potential from heavy metals in fly ash waste.

The peatland map compiled by BB Litbang SDLP [3] shows that the total area of peatland in three major islands is around 14.9 million ha. The details of the peatland area are in Sumatra 6.40 million ha, Kalimantan is 4.70 million ha and Papua 3.60 million ha. The largest peatland area in Sumatra is located in Riau Province, with an area of 3.861.401 ha or around 24% of the total peatland area in Indonesia [4]. The majority of construction in Riau Province is carried out on peatland, and around
57% of the total peatland area in Riau has been converted to infrastructure, agriculture, industry and even human settlement.

Peat environment generally has poor physical properties to concrete construction because it has high organic contents, high acidity (pH 3-5) and low bearing capacity [5]. Zivica & Bajza [6] explained that acid ions in peat would attack the cement paste bond in concrete and cause interference to the concrete bonding system. As a result, the concrete is easily porous, with reduced serviceability and decreased concrete performance. The study result [7] showed that OPC (Ordinary Portland Cement) experience a significant compressive strength decrease starting from 28 days to 150 days in peat water soaking.

Geopolymer is a polymerization material synthesized from silica and alumina, resistant to high temperatures [8]. The silica and alumina can be obtained from industrial residue such as fly ash. Geopolymer concrete is made from the aggregate mixture, water and binder material resulted from polymerization reaction between activator alkaline with silica and alumina in fly ash material [9]. Fly ash geopolymer almost has the same and even better physical and mechanical properties than OPC concrete, especially in an aggressive environment such as peat [10-13]. Bakharev [47] showed that fly ash geopolymer concrete compressive strength did not experience a significant decrease in the sulfuric acid environment.

The study by Mejia et al. [14], Suwan & Fan [15], Nath & Sarker [16] and Wijaya et al. [17] showed that the addition of OPC could increase setting time and increase the fly ash geopolymer strength without high temperature. Yanuari et al. [18] conducted a study on concrete geopolymer using palm ash, and it also showed the same trend. Therefore, the addition of PPC to geopolymer concrete can increase geopolymer strength without high temperature. Although the effect of PCC and OPC addition to hybrid geopolymer concrete has been studied, the relationship between the durability and the environmental performance of fly ash geopolymer concrete with Portland cement such as PCC and OPC has not been studied. Therefore, a literature review is conducted, which is purposed to discover the relationship between the durability and the environmental performance of hybrid geopolymer concrete in a peat environment

2. Methods
The study method used was a literature review using a tracing of secondary data, which is indirectly obtained from laboratory tests (primary data) or the primary study data. The flowchart of this review is presented in Figure 1.

The stages of data collection, data analysis and conclusion drawing are explained as follows:
1. A literature review is searching for information and data related and relevant to the keyword of fly ash, geopolymer concrete, hybrid, heavy metals and peat, through a searching database such as Google Scholar, ResearchGate and Scopus of 2010-2020. Two thousand articles related to the keywords were found, which will be selected and reviewed to be 50 full-text articles most relevant to the research topic and article review.
2. We are reducing and summarizing all research data obtained during data collection and focusing on the reviewed aspect. This study examines the strength performance (compressive strength and the change of compressive strength) and environmental performance (heavy metals leaching).
3. The data was analysed by tabulating, mapping the quantitative data, deriving them into other equations and comparing them to various comparable data and related regulations.
4. We present the analyzed data into narrative text, graphs, or tables for ease of understanding.
5. Conclusion drawing in the secondary data-based study is obtained from synthesizing preceding data, normalizing data, and making data from various sources as equal as possible to conclude the best recommendations.
3. Results and discussion

3.1. Result of Coal Fly Ash Chemical Composition Test
Fly ash is an industrial by-product of coal combustion. Coal combustion produces approximately 5% solid pollutants, 80-90% fly ash, and 10-20% is bottom ash. Fly ash is formed from inorganic mineral material and fine particles passing No. 200 sieves [19]. Fly ash is pozzolanic because it contains silica (Si) and alumina (Al) but little calcium (Ca). Fly ash handling is currently limited as an ameliorant material and mostly hoarded on empty spaces around steam power plants (Figure 2).

![Fly ash particles and Fly ash disposal](a) ![Fly ash disposal](b)

Figure 2. (a) Fly ash particles and (b) Fly ash disposal [19]

Fly ash can be used both as addition or partial replacement material of cement in concrete mixture. The reaction between fly ash and calcium will form adhesive properties similar to cement and has a better density compared to conventional concrete. Fly ash can be used as filler to reduce porosity in concrete thereby increasing the strength of the concrete. Based on the test result by Research and Development Center of Coal and Mineral Technology [20] it was found the heavy metal elements in fly ash as presented in Table 1. The heavy metal elements are not hazardous in open-air. However, they will be poisonous and deadly in water. Likewise in peat water, the presence of these elements indirectly causes living creatures around the peat water poisoned.
Table 1. Heavy metal content in coal fly ash [20]

| Type of Coal         | Heavy Metal Content (mg/L) |
|----------------------|----------------------------|
|                      | Cu | Pb | Zn | Cr | Cd |
| Asam-Asam fly ash    | 298| 19 | 391| 224| 11 |
| Ombilin fly ash      | 87 | 15 | 153| 120| tt |

ASTM C 618 [21] classifies fly ash into three classes: C, N and F. The C class has a minimum of 50% of SiO$_2$+ Al$_2$O$_3$+Fe$_2$O$_3$ and more than 10% CaO (low-calcium fly ash) content requirement. Meanwhile, the F class has a minimum of 70% of SiO$_2$+ Al$_2$O$_3$+Fe$_2$O$_3$ and a maximum 10% CaO (low-calcium fly ash) content requirement. Therefore, F class fly ash is more suitable for a concrete mixture in an acid environment such as peat water because it contains low calcium that is not easily dissolved by the peat water acidity.

Table 2. Chemical composition of fly ash in several steam power plants in Indonesia

| SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | K$_2$O | Na$_2$O | LOI | Origin                  | References |
|---------|-------------|-------------|------|-----|--------|---------|-----|------------------------|------------|
| 48.51   | 15.3        | 8.68        | 3.76 | 2.21| 1.71   | 1.05    | -   | Mpanau, Sulawesi        | [22]       |
| 52.2    | 38.6        | 2.90        | 0.70 | 0.50| 0.40   | 0.50    | 1.40| Paiton, East Java       | [23]       |
| 36.23   | 6.25        | 4.34        | 2.85 | 0.49| 0.14   | 0.93    | -   | Amurang, North Sulawesi | [9]        |
| 48.06   | 34.76       | 3.91        | 2.51 | 14.53| 28.56  | 0.75    | -   | North Sulawesi          | [24]       |
| 37.89   | 20.52       | 2.17        | 2.1  | 23.76| 0.58   | -       | -   | Pelalawan, Riau         | [25]       |
| 57.3    | 16.94       | 9.73        | 5.57 | 5.43| 0.79   | 0.73    | 0.96| Suralaya 2, Banten      | [26]       |
| 59.25   | 29.25       | 5.45        | 1.54 | 0.31| 2.23   | 0.68    | 18.98| Ombilin, West Sumatera  | [27]       |
| 61.63   | 17.71       | 9.30        | 4.24 | 1.98| 1.78   | 1.28    | 1.31| Sibolga                 | [28]       |
| 35.74   | 12.01       | 19.32       | 8.49 | 1.75| 0.69   | 0.25    | 0.68| Pangkal Pinang          | [28]       |
| 55.32   | 22.43       | 5.12        | 1.67 | 0.49| -      | -       | 12.96| Ombilin Unit 1          | [28]       |
| 50.29   | 24.66       | 6.41        | 0.78 | 0.78| -      | -       | 13.64| Ombilin Unit 2          | [28]       |

From Table 2, it can be seen the majority of fly ash from steam power plants in Indonesia contains approximately 70%-90% of SiO$_2$+ Al$_2$O$_3$+Fe$_2$O$_3$ and is included in the F class pozzolan has a low content of calcium. Therefore, according to Hardjito & Rangan [29], this fly ash is suitable for being applied as a geopolymer material because it has a high silica and alumina content and low calcium. Thereby, the geopolymer can react to alkaline to form a polymerization bond, having good performance and not quickly disintegrate in an acid environment.

3.2. Characteristics of Peat Water

Based on Wetland International calculation, the peatland area worldwide is 400 million m$^2$ where it covers approximately 2% of the whole land area on earth. Meanwhile, Indonesia is the world’s fourth-largest peatland area after Canada, Russia, and United States [30]. Indonesia is estimated to have 20.6 million hectares of peatland or 10.8% of the land area. Peat has a significant role in hydrology and the environment for the life of human beings and other living creatures. However, peat is a prone ecosystem to damage due to toxic substances. The damage occurring in peatland will result in disaster around the environment and disrupt biota living in it. Therefore, peatland must be protected and conserved.

Peat is formed from the accumulation of organic material from weathered plants decomposition found mostly in waterlogged conditions, swamps, and river basins [31]. Continuous stagnant water on the soil causes a change of water characteristics such as turbid, brownish red in colour, high content of mineral salt and low pH number between 3-5 resulting in acid peat water [32]. For example, peat
water in Riau Province is highly acid, pH 3-5, contains high organic substances and low hardness levels. Generally, the characteristics of peat water in several locations in Indonesia can be seen in Table 3.

| Table 3. Characteristics of peat water in several locations in Indonesia [32] |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Parameter                      | Unit            | South Kalimantan | West Kalimantan | South Sumatera |
| Color                          | PtCo            | 753             | 527             | 1315            | 1125            |
| Turbidity                      | mg/l SiO2       | 32              | 0               | 5               | 9               |
| DHL                            | µ mho/cm        | -               | 30              | 78              | 75              |
| pH                             | -               | 4.10            | 3.90            | 5               | 4               |
| Organic substances             | mg/l KMnO4      | 278             | 194             | 290             | 243             |
| Hardness                       | °D              | 2.05            | 0.48            | 5.50            | 1.40            |
| Calcium                        | mg/l            | -               | -               | 4.5             | -               |
| Magnesium                      | mg/l            | 8.83            | 2.10            | 20.90           | 6.20            |
| Iron                           | mg/l            | -               | -               | -               | -               |
| Manganese                      | mg/l            | -               | -               | -               | -               |
| Chloride                       | mg/l            | 11.11           | 5.48            | 162             | 18              |
| SO4                            | mg/l            | -               | -               | 11.20           | -               |
| HCO3                           | mg/l            | -               | -               | 51.40           | -               |

3.3. Performance of Conventional Concrete in Peat Water Acid Environment

Peat environment is acid that will impair the mechanism and performance of concrete. (Neville & Brooks [33] explained that Portland cement is not resistant to acidity. The acid ion in peat water will unravel calcium (Ca) in cement paste so that the concrete is easily porous. The higher the degree of acidity, the easier the concrete to suffer from structural damage and serviceability decrease and remain residual sediment in peat environment [6].

The compressive strength of concrete in peat water environments tends to decrease until the day of 180, by 40% [12]. This is because of the unwell cement hydration process and cement matrix decomposition with acid ion, thereby decreasing the density and compressive strength of the concrete. The formation of gypsum and ettringite in concrete reacting with acid will damage concrete durability. Excessive calcium in cement paste will unravel, resulting in the concrete experiencing cracks and pores, decreasing the compressive strength of the concrete. In addition, gypsum and ettringite are hazardous elements if released and decomposed in peat water. The acid endemic animals and even plants are no longer able to survive due to peat environment damage.

3.4. Fly Ash Geopolymer Concrete

Davidovits [8] first proposed the geopolymer in the 1990s. Initially, geopolymer was used as an anti-fire building material. The material then was developed as an alternative substitution of cement using the silica and alumina activator from industrial waste such as fly ash, palm oil fuel ash, and rice husk ash. The activation process of silica and alumina uses an activator solution of sodium hyroxide and sodium silicate [8].

Hybrid fly ash geopolymer concrete is the mixture of sand, gravel, water, and binder material from polymerization reaction between alkaline with silica and alumina from fly ash and Portland cement as a mixture. However, the pozzolanic reaction from fly ash reacts adequately slowly that the initial strength of fly ash geopolymer concrete is lower. Therefore, it is necessary to use the combination of PCC and alkaline activated fly ash geopolymer [34]. Figure 3 illustrates the composition of Portland cement and fly ash in hybrid geopolymer mortar.
Several geopolymer development studies with OPC addition can be seen in Table 4. Based on the study results, generally, Portland cement can function as an agent to accelerate the reaction, curing time, increase mechanical properties and reduce porosity due to the formation of a stronger hydration product than the pure geopolymer bond.

Table 4. Summary of hybrid geopolymer concrete studies

| References | Findings |
|------------|----------|
| [18]       | Replacement of PCC to POFA geopolymer mortar mixture increases compressive strength effectively under room temperature curing. Hybrid fly ash geopolymer mortar using OPC has higher compressive strength than PCC from the age of 7 to 28 days under room temperature curing. |
| [17]       | Replacement of fly ash with partial Portland cement can increase the compressive strength under room temperature curing. The addition of fly ash geopolymer concrete with OPC forms C-S-H hydration structure from OPC and N-A-S-H from fly ash resulting in stronger C-A-S-H. |
| [35]       | The addition of OPC or GBFS increases compressive strength (at 28 days of drying) up to 127% compared to fly ash-based geopolymer system. |
| [34]       | The addition of OPC helps heat process from fly ash geopolymer concrete; thereby, the concrete no longer requires high temperature (oven) curing but adequate room temperature. The replacement of fly ash with cement in geopolymer will decrease bonding time, porosity and increase compressive strength and modulus of elasticity. |

3.5. Resilience Performance of Hybrid Fly Ash Geopolymer Concrete in Peat Environment

Based on Table 5, several tests present the relationship between the type and composition of concrete with the compressive strength of concrete. The study result by [37,38] showed decreased compressive strength of OPC and PCC concrete with peat water immersion kept increasing along with the age of the concrete. The study by Olivia et al. [37], Nath et al. [39] showed a similar decrease trend with OPC concrete by pure fly ash addition. Meanwhile, the fly ash geopolymer concrete with the addition of OPC showed a different result. The compressive strength in peat water immersion increased along with the concrete age.
Table 5. Summary of earlier compressive strength studies in peat water immersion [38] [37] [39]

| Concrete Mixture (kg/m³) | Alkali Activator | Compressive Test (MPa) | Ref. |
|--------------------------|------------------|------------------------|------|
|                          | Water (kg)       | Coarse agg (kg)        |      |
|                          | Fly Ash          | Fine agg (kg)          |      |
|                          | NaOH             | Na₂SiO₃                |      |
|                          | 0 day            | 7 days                 | 28 days |
|                          |                  | 90 days                | 120 days |
| OPC                      | 507.89           | 987.4                  | 8     | -     | -     | -     | -     | -     | 35    | 34    | 30.85 | [38]  |
|                          | 5                 | 194.78                 | 25    | 684.13 | -     | -     | -     | -     | -     | 35.05 | 31.75 | 31.72 |
| PCC                      | 95               | 194.78                 | 25    | 684.13 | -     | -     | -     | -     | -     | 35.05 | 31.75 | 31.72 |
| Fly Ash                  | 224.01           | 930.8                  | 3     | 829.96 | -     | -     | 21.75 | 22.7  | 20.1  | -     | -     |
|                          | 512.2            | 120                    | 1014  | 546    | 109.27 | 218.54 | 15.59 | 16.7  | 6     | -     | -     |
|                          | 116.4            | 225.36                 | 932.7  | 814.81 | -     | -     | 11.16 | 12.9  | 14.6  | -     | -     |
| Fly Ash                  | 225.36           | 932.7                  | 3     | 814.81 | -     | -     | 19.64 | 21.1  | 21.3  | -     | -     |
| Fly Ash                  | 225.36           | 932.7                  | 814.81 | -     | -     | -     | -     | -     | -     | -     | -     | [37]  |
| Fly Ash                  | 1178             | 83.4                   | 208.60 | -     | 28     | 55     | 65     | -     |
| Fly Ash                  | 1178             | 83.4                   | 208.60 | -     | 31     | 56     | 50     | 62.50 | -     | [39]  |
| Fly Ash                  | 1178             | 83.4                   | 208.60 | -     | 26     | 58     | 71     | -     |

Furthermore, [40] conducted study on the change of compressive strength of hybrid geopolymer concrete in peat environment. The formula used to calculate the compressive strength change is based on ASTM C-267 [41].

\[
\text{Compressive Strength Change} = \frac{S_2 - S_1}{S_1} \times 100
\]  

Where S1 = the average compressive strength of concrete after 28 days curing (initial strength) period, S2 = the average compressive strength of concrete after a test period of peat water exposure.

A change of compressive force with a positive number shows that the strength (durability) increases after peat water exposure from its initial strength. Otherwise, the change of compressive strength with a negative number indicates that the strength decreases after peat water exposure.

Figure 4. The graph of compressive strength change of concrete in peat water immersion [40]

Figure 4 presents that the change of compressive strength of OPC concrete (control concrete) decreases until the age of 28 days in peat water immersion. This is because the OPC concrete contains high calcium, which is susceptible to the acid ion of peat water. Meanwhile, the change of compressive strength of GP OPC (Geopolymer with the addition of OPC cement) and GP PCC
Geopolymer with the addition of PCC cement) increases at the age of 14 days in peat water immersion. GP PCC has the most significant change of compressive strength compared to the other concretes because PCC contains high pozzolanic material and less Ca (calcium) than OPC. After 28 days of immersion, GP OPC and GP PCC concrete decrease slightly in strength.

3.6. Environmental Performance of Hybrid Fly Ash Geopolymer Concrete in Peat

In this study of environmental performance in peat environment, earlier research data of heavy metals leaching of fly ash hybrid geopolymer concrete in peat environment is conducted and compared to other concretes. Fly ash has leachate potential with a high concentration of heavy metals, resulting in terrible and severe environmental impacts. Heavy metals are metals having high toxicity if released into the environment. The toxic substances in heavy metals pollute soil, air and water but will also cause damage to human health through the food chain [42]. One of the tests to determine heavy metals leaching level is TCLP (Toxicity Characteristic Leaching Procedure) test. This test is used to identify the toxic concentration of waste.

Table 6 presents the leaching concentration of heavy metals in various types of concrete mixtures. Based on the study of [40], fly ash geopolymer concrete with the substitution of OPC 15% and PCC 15% by fly ash did not experience a significant change of heavy metals leaching after 28 days of immersion. However, if compared to the study of Prasanda et al. [43] and Aziz & Azhari [44], the concrete with the addition of fly ash has a higher leaching concentration.

| Concrete Mixtures (Immersion Water) | Immersion Time | Pb (mg/l) | Cd (mg/l) | Cu (mg/l) | Cr (mg/l) | Zn (mg/l) | References |
|-------------------------------------|----------------|-----------|-----------|-----------|-----------|-----------|------------|
| Fly Ash (Peat)                      | 0              | 0.396     | 0.114     | 0.29      | 0.397     | 0.582     | [40]       |
| Fly Ash (Water)                     | 28             | 0.472     | 0.185     | 0.382     | 0.432     | 0.687     |            |
| Geopolymer FA + OPC (Peat)          | 0              | 0.491     | 0.157     | 0.461     | 0.5       | 0.731     |            |
| Geopolymer FA + PPC (Peat)          | 28             | 0.717     | 0.19      | 0.553     | 0.69      | 0.836     |            |
| Fly Ash (Water)                     | 28             | -         | -         | -         | 0.23      | 0.29      |            |
| Bottom Ash (Water)                  | 28             | -         | -         | -         | 0.24      | 1.25      | [43]       |
| SCBA + 20% Steam (Water)            | 28             | -         | -         | -         | 0.36      | 1.27      |            |
| SCBA + 20% Non-Steam (Water)        | 28             | -         | -         | -         | 0.34      | 1.28      |            |
| Bauxite Residue Geopolymer (Water)  | 28             | -         | -         | -         | 0.021     | 0.0002    | 0.021 0.002 0.043 [46] |
| Fly Ash (Water)                     | -              | 8.9       | -         | 7.978     | 5.735     | -         |            |
| Fly Ash 25% Carbide Waste 2,5 % Cement 72,5% (Water) | - | 1.31 | - | 0.245 | 0.087 | - | [44] |
| Fly Ash 25% Carbide Waste 5 % Cement 70% (Water) | - | 1.232 | - | 0.245 | 0.055 | - | |
| Fly Ash 25% Carbide Waste 10 % Cement 65% (Water) | - | 0.969 | - | 0.261 | 0.043 | - | |
| U.S.EPA                             | -              | 5         | 0.5       | -         | 5         | 200       | [46]       |
| PP 101/2014                         | -              | 5         | 0.15      | 10        | 2.5       | 50        | [45]       |
The table above also describes the concentration limit of heavy metals, such as Cu (copper), Pb (lead), Cd (cadmium), Cr (chromium) and Zn (zinc) allowed by Government Regulation No. 101 [45] and the United States Environmental Protection Agency (USEPA) [46]. Based on Table 6, it can be concluded that the concentration of all heavy metals in hybrid geopolymer concrete is allowed according to [45] and [46]. In contrast to regular fly ash concrete without geopolymer, the heavy metals concentration in concrete using fly ash mixture exceeds the limit allowed by [45], except for Zn (zinc), which is still allowed. Furthermore, the concentration of heavy metals decreases significantly before and after the solidification of fly ash to be geopolymer concrete. This evidence shows that geopolymer concrete is effective to mobilize heavy metals in fly ash.

4. Conclusions
This study investigated the mechanical properties and shrinkage of FABA-GP (fly ash bottom ash) This literature study concludes that most fly ash in Indonesia has a high concentration of Silica and Alumina in chemical composition and have hazardous heavy metals content for peat environments such as Cu, Pb, Cd, Cr and Zn. The solidification technique of fly ash to be hybrid geopolymer material effectively increases concrete strength in an acid environment and mobilises heavy metals in fly ash. Thereby, it is suitable for conservative construction material to have superior resistance in a peat environment.

Acknowledgement
This research was funded through PKM-Research activities, Program Kreativitas Mahasiswa, Direktorat Pembelajaran dan Kemahasiswaan, Direktorat Jenderal Pendidikan Tinggi Kementerian Pendidikan dan Kebudayaan Republic Indonesia year 2020.

References
[1] Dewi N R, Dermawan D, and Ashari M L 2016 Studi Pemanfaatan Limbah B3 Karbit dan Fly Ash Sebagai Bahan Campuran Beton Siap Pakai (Bsp) (Studi Kasus : Pt. Varia Usaha Beton) Media Komunikasi Dan Pengembangan Teknik Lingkungan 13(1) 34-43
[2] Arioz E, Arioz O, and Kockar Ö M 2012 Leaching of F-type fly ash based geopolymers Procedia Engineering 42 1114–1120.
[3] Ritung S, Wahyunto N K, Sukarman H and Suparto TC 2011 Peta Lahan Gambut Indonesia Skala 1: 250.000 BB Litbang SDLP Bogor
[4] Agus F, Anda M and Jamil A 2016 Lahan gambut Indonesia: pembentukan, karakteristik, dan potensi mendukung ketahanan pangan I AARD Press
[5] Moayedi H, Kassim K A, Kazemian S, Raftari M, and Mokhberi M 2014 Improvement of Peat Using Portland Cement and Electrokinetic Injection Technique Arabian Journal for Science and Engineering 39(10) 6851–6862.
[6] Zivica V, and Bajza A 2001 Acidic attack of cement based materials - A review. Part 1. Principle of acidic attack Construction and Building Materials 15(8) 331–340.
[7] Olivia M 2015 Kuat Tekan Beton dengan Semen Campuran Limbah Agro-Industri di Lingkungan Asam. Andalas Civil Engineering National Conference 306–312.
[8] Davidovits J 1994 Properties of Geopolymer Cements First International Conference on Alkaline Cements and Concretes 131–149.
[9] Manuahe R, Sumajouw M DJ, and Windah R S 2014 Kuat Tekan Beton Geopolymer Berbahan Dasar Jurnal Sipil Statik 2(6) 277–282.
[10] Bakharev T 2005 b Resistance of geopolymer materials to acid attack. Cement and Concrete Research 35(4) 658–670
[11] Olivia M 2011 Durability Related Properties of Low Calcium Fly Ash Based Geopolymer Concrete Issue Doctoral dissertation, Curtin University
[12] Olivia M, Wulandari C, Sitompul I R, Darmayanti L, and Djauhari Z 2016 Study of fly ash (FA) and palm oil fuel ash (POFA) geopolymer mortar resistance in acidic peat environment Materials Science Forum 841 126–132.

[13] Part W K, Ramli M, and Cheah C B 2015 An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products Construction and Building Materials 77 370-395.

[14] Mejía J M, Rodríguez E, Mejía De Gutiérrez R, and Gallego N 2015 Preparation and characterization of a hybrid alkaline binder based on a fly ash with no commercial value. Journal of Cleaner Production 104 346–352.

[15] Suwan T, and Fan M 2014 Influence of OPC replacement and manufacturing procedures on the properties of self-cured geopolymer. Construction and Building Materials 73 551–561.

[16] Nath P, and Sarker P K 2015 Use of OPC to improve setting and early strength properties of low calcium fly ash fly ash geopolymer concrete cured at room temperature Cement and Concrete Composites 55 205–214.

[17] Wijaya M F, Olivia M, and Saputra E 2019 Kuat Teken Mortar Geopolimer Abu Terbang Hybrid menggunakan Semen Portland Jurnal Teknik 13(1) 60–68.

[18] Yanuar R, Ikrammulah M, Septa D, Wijaya M F, and Olivia M 2020 Studi parametrik mortar geopolimer hybrid abu sawit (Palm Oil Fuel Ash/POFA) Rekayasa Sipil 14 83-90.

[19] Munir M 2008 Pemanfaatan Abu Batubara (Fly Ash) untuk Hollow Block yang Bermutu dan Aman Bagi Lingkungan Doctoral dissertation, Program Pascasarjana Universitas Diponegoro.

[20] Damayanti R 2018 Abu batubara dan pemanfaatannya: Tinjauan teknis karakteristik secara kimia dan toksikologinya Jurnal Teknologi Mineral dan Batubara 14(3) 213-231.

[21] ASTM C 618 2014 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete ASTM International West Conshohocken PA.

[22] Suarnita I W 2011 Kuat tekan beton dengan aditif fly ash ex. PLTU Mpanau Tavaeli Jurnal Smartek 9(1) 1–10.

[23] Ekaputri J J, and Triwulan T 2013 Sodium sebagai Aktivator Fly Ash, Trass dan Lumpur Sidoarjo dalam Beton Geopolimer Jurnal Teoritis Dan Terapan Bidang Rekayasa Sipil 20(1) 1–10.

[24] Philip A, Marthin M, Sumajouw D J, and Windah RS 2015 Pengaruh Penambahan Abu Terbang (Fly Ash) Terhadap Kuat Tarik Belah Beton Jurnal Sipil Statik 3(11) 729–736.

[25] Islami A N, Saputra E, and Olivia M 2015 Kajian Parameter Mortar Geopolimer Menggunakan Campuran Abu Terbang (Fly Ash) dan Abu Sawit (Palm Oil Fuel Ash) Prosiding 2nd Andalas Civil Engineering National Conference 160–167.

[26] Utami R I A, Herbudiman B, and Irawan R R 2017 Efek Tipe Superplasticizer terhadap Sifat Beton Segar dan Beton Keras pada Beton Geopolimer Berbasis Fly Ash Reka Racana 3(1) 1–12.

[27] Olivia M, Wibisono G, and Saputra E 2019 Early strength of various fly ash based concrete in peat environment MATEC Web of Conferences 276 01022.

[28] Gunawan G, and Nono 2019 Potensi Pemanfaatan Bahan Limbah Fly Ash dan Bottom Ash untuk Lapisan Fondasi Jalan Semen (Potential for Utilization of Fly Ash and Bottom Ash Waste Materials for Cement Road Foundation) Jurnal Jalan-Jembatan 36.

[29] Hardjito D, and Rangan B V 2005 Development and properties of low-calcium fly ash-based geopolymer concrete Research Report GC 94.

[30] Tjahjono E 2006 Kajian Potensi Endapan Gambut Indonesia Berdasarkan Aspek Lingkungan Pusat Sumber Daya Geologi 1–8.

[31] Arioz E, Arioz O, and Kockar O M 2012 Leaching of F-type fly ash based geopolymers 42 1114–1120.

[32] Kusnaedi 2006 Mengolah Air Gambut Dan Air Kotor Untuk Air Minum. Penebar Swadaya Jakarta.
[33] Neville A M, and Brooks J J 1987 Concrete technology (2nd ed.) Longman Scientific & Technical.

[34] Garcia-Lodeiro I, Donatello S, Fernández-Jiménez A, and Palomo A 2016 Hydration of hybrid alkaline cement containing a very large proportion of fly ash: A descriptive model Materials 9(8)

[35] Assi L N, Eddie E, Elbatanouny MK, and Ziehl P 2016 Investigation of early compressive strength of fly ash-based geopolymer concrete. Construction & Building Materials 112 807–815

[36] Phoo-Ngernkham T, Chindaprasirt P, Sata V, and Sinsiri, T 2013 High calcium fly ash geopolymer containing diatomite as additive Indian Journal of Engineering and Materials Sciences 20(4) 310–318.

[37] Olivia M, Ismeddiyanto, Wibisono G, and Sitompul IR 2017 Early age compressive strength, porosity, and sorptivity of concrete using peat water to produce and cure concrete. AIP Conference Proceedings

[38] Olivia M, Pradana T, and Sitompul I R 2017 Properties of Plain and Blended Cement Concrete Immersed in Acidic Peat Water Canal Procedia Engineering 171 557–563

[39] Nath P, Sarker P K, and Rangan V B 2015 Early age properties of low-calcium fly ash geopolymer concrete suitable for ambient curing Procedia Engineering 125 601–607.

[40] Wijaya MF, Olivia M, Wibisono G, Saputra E, and Wang S 2019 Characteristics of geopolymer hybrid concrete in peat water. IOP Conference Series: Materials Science and Engineering 615(1)

[41] ASTM C-267 1998 Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic. ASTM International West Conshohocken PA

[42] Damayanti R 2018 Abu batubara dan pemanfaatannya: Tinjauan teknis karakteristik secara kimia dan toksikologinya Jurnal Teknologi Mineral Dan Batubara 14(3) 213–231.

[43] Prasanda A F E, Triwulan and Ekaputri JJ 2015 Paving Geopolimer Berbahan Dasar Bottom Ash dan Sugar Cane Bagasse Ash (SCBA) JURNAL TEKNIK ITS 4(2) D110-D115.

[44] Aziz M and Azhari 2014 Pembuatan Bahan Geopolimer Berbasis Residu Bauksit untuk Bahan Bangunan Jurnal Teknologi Mineral dan Batubara 10(1) 32–43.

[45] U.S Environmental Protection Agency 1993 Clean water act. Section 503 58 32.

[46] Peraturan Pemerintah No 101 2014 Pengelolaan Limbah Bahan Berbahaya dan Beracun, Republik Indonesia 7 219–232

[47] Bakharev, T 2005 a. Durability of geopolymer materials in sodium and magnesium sulfate solutions Cement and Concrete Research 35(6) 1233–1246.