Tersedia online di: http://ejournal.undip.ac.id/index.php/teknik

TEKNIK, 44 (1), 2023, 39-45

Mechanical Performance Analysis of Geopolymer Concrete using Fly Ash Tanjung Jati B for Sustainable Construction Materials

Bobby Rio Indriyantho*, Purwanto, Rydell Riko

Departement of Civil Engineering, Faculty of Engineering, Universitas Diponegoro, Jl. Prof. Soedarto, SH, Kampus UNDIP Tembalang, Semarang, Indonesia 50275

Abstract

Concrete use as primary building construction material caused serious problems in the construction industry. Concrete is not regarded as an environmentally friendly material since the use of cement results in high carbon emissions during the manufacturing process. One effort to replace cement without reducing concrete strength is to use fly ash as a concrete ingredient known as geopolymer concrete. This research aimed to determine the basic mechanical properties of geopolymer concrete and compare it to conventional concrete with the same material proportions. The mix design of the three different proportions with the ratio of aggregates to the binder as 70%: 30%, 60%: 40%, and 50%: 50% was maintained such that the concrete mix has good workability. As a result, the so-called workable fly ash-based geopolymer concrete has higher compressive strength, splitting tensile strength, and modulus of elasticity compared to conventional concrete. At the same time, Poisson's ratio is slightly lower.

Keywords: *concrete; geopolymer; fly ash; workability; compressive strength*

1. Introduction

As a country ages, it undergoes various developments, including technological advancements, which lead to progress in various fields, such as infrastructure. Infrastructure development is now the primary focus of governments in developing countries, such as roads and various buildings that support the economy and government. According to Global Cement and Concrete Association, this increases the demand for concrete production up to approximately 14 billion m^3 globally only in 2020, where housing sectors contribute 40% of the total concrete production. With the increased use of concrete as the primary building material, several issues arise, such as the use of excessive cement. Based on data reported by (Ritchie et al., 2020), written in Our World in Data, concrete production was followed by cement manufacture at 4.2 billion tons.

In recent decades, massive cement production, especially in construction sectors, has become a major issue related to sustainability, as stated in the Sustainable Development Goals (SDGs), particularly number 9 regarding industry, innovation, and infrastructure. Meanwhile, the cement manufacturing process is one of the main contributors to carbon emissions which cause greenhouse gases since as much as 6-8% of the emissions is originated from Ordinary Portland Cement (OPC) production using energy consumption as 12-15% of the total industrial energy (Ali et al., 2011; Andrew, 2019) which occurs during the massive heating of limestone to produce clinker (Suhendro, 2014).

According to (Mehta, 2001), the need for concrete is directly proportional to the need for cement; the greater the need for concrete, the greater the need for cement. The use of cement, on the other hand, harms the environment. Among them are the massive amounts of natural resources used and carbon dioxide gas emissions produced during the cement manufacturing process. As a result, it is necessary to consider the use of concrete constituent materials manufactured with an environmentally friendly concept in which the manufacturing process tries to produce as few CO_2 emissions as possible, low energy consumption, and minimal use of natural materials. Alternatively, other materials with similar characteristics, performance, and strength to the concrete constituent materials but must be environmentally friendly can be sought.

A more natural and environmentally friendly cement replacement material is required in order to reduce the negative impact on the environment. One of the renowned materials technologies that can be used is geopolymer, introduced by (Davidovits, 1985). The so-called geopolymer is the synthesis of natural organic materials through a polymerization process using

*) Corresponding author
E-mail: bobbyrio@live.undip.ac.id

doi: 10.14710/teknik.v44i1.52958

Table 1. Chemical compositions of fly ash obtained by the XRF analysis

Compounds	Percentage (%)
Al_2O_3	16.17%
SiO_2	41.04%
Fe_2O_3	26.39%
CaO	8.16%
Others	8.24%

materials containing silicate and aluminum elements, such as iron blast furnace slag, bottom ash, or fly ash, as industrial waste materials. A geopolymer paste is created by chemically reacting silicate and alumina with an alkaline solution. Geopolymer paste is combined with aggregate results in geopolymer concrete that does not require Portland cement completely (Alwash et al., 2022; Davidovits, 1994, 1999, 2002; Dawood & Mohammed, 2021; Mangi et al., 2020; Palomo et al., 1999; Salih & Ahmed, 2020).

At present, there have been several studies related to cement substitute pozzolanic materials. Fly ash is a byproduct of coal-fired power plants that is round-shaped and has a diameter of 1-150 microns (Siddique, 2004). The increase of fly ash waste from 1.66 million tons in 2000 to two million tons in 2006 is thought to have coincided with the increased construction of coal-fired power plants in Indonesia. This unused ash waste will become an environmental pollution problem, with the impact of pollution caused by fly ash being extremely hazardous to both the environment and human health.

Many studies have been conducted to date in order to optimize geopolymer concrete as a solution to reduce existing environmental impacts (Formisano et al., 2018; Gunasekara et al., 2019; Hardjito et al., 2004a, 2004b; Hardjito & Rangan, 2005; Kustirini et al., 2022; Luukkonen et al., 2018; Muslikh et al., 2018; Noushini et al., 2020; Purwanto et al., 2021, 2022a, 2022b; Purwanto & Indarto, 2019; Romadhon et al., 2022; Siddique, 2004). However, no specific standard code exists for designing a geopolymer concrete mix. As a result, this study used several variations in mix design proportions to obtain good fly ash-based geopolymer concrete (FAGC) performance.

Based on this background, the purpose of this study is to compare the compressive strength of geopolymer concrete and conventional concrete (CC) with weight ratios of aggregate and binder of 70%: 30%, 60%: 40%, and 50%: 50% at 14 days, 28 days, and 56 days, as well as the increase in compressive strength of geopolymer concrete against conventional concrete maintaining good workability. Furthermore, the splitting tensile strength of concrete, the stress-strain relationship between geopolymer concrete and conventional concrete, and the modulus of elasticity and Poisson's ratio of geopolymer concrete and conventional concrete at 56 days are all investigated in this study.

2. Materials and Methods

2.1. Materials

The materials used in this study include fly ash class F originating from PLTU Tanjung Jati B in Jepara, Indonesia, fine aggregate, coarse aggregate with a maximum size of 10 mm, alkaline activator solution, which is a mixture of sodium hydroxide (NaOH) with a molarity of 12 mol (Kustirini et al., 2022) and sodium silicate (Na_2SiO_3) type Be52 for the FAGC as well as Ordinary Portland Cement (OPC) for the CC.

In order to achieve a high strength of the FAGC, fly ash class F should be utilized. According to ASTM C618–19, fly ash could be categorized as class F if the three chemical compounds, i.e., silicon dioxide or silica (SiO_2), aluminum oxide (Al_2O_3), and iron(III) oxide or ferric oxide (Fe_2O_3), are greater than 70% in total. Additionally, calcium oxide (CaO) composition should be less than 10%. The X-Ray Fluorescence (XRF) analysis was performed in this study to obtain the chemical composition of fly ash. Table 1 shows the chemical composition of fly ash obtained by the XRF required for determining class F.

According to the table, fly ash contains 41.04% of SiO_2, 16.17% of Al_2O_3, 26.39% of Fe_2O_3, and 8.16% of CaO. Based on the XRF test results, it is possible to conclude that this fly ash is categorized as fly ash class F since the total compounds of SiO_2, Al_2O_3, and Fe_2O_3 are greater than 70%, while CaO is less than 10%.

In order to obtain good workability with maintaining the concrete compressive strength, no additive such as superplasticizers was added to the concrete mix, so the activator Na_2SiO_3 type Be52 was utilized and played a role in obtaining a more dilute mixture. Hence, the FAGC was expected to be the fly ash-based workable geopolymer concrete (FAWGC), as investigated by (Purwanto et al., 2022b).

Cylindrical tested specimens of the FAWGC were denoted as BG-1, BG-2, and BG-3 with the ratios of aggregate and binder of 70%: 30%, 60%: 40%, and 50%: 50%, respectively, while the CC was denoted as BK-1, BK-2, and BK-3 with the similar ratios of aggregate and binder. The identical fixed proportions used for BG and BK were coarse aggregate: a fine aggregate of 60%: 40% and binder: activator of 65: 35%. The proportions used for BG and BK were based on previous research (Purwanto et al., 2021, 2022a, 2022b; Purwanto & Indarto, 2019). Both concrete types were manufactured using a predetermined mix design. Tables 2 and 3 show the identical material proportions in the concrete mix with the binder (fly ash and the alkaline activator) substituting the OPC and water.

doi: 10.14710/teknik.v44i1.52958

Table 2. Material proportions of the FAWGC

Materials	BG-1	BG-2	BG-3
Coarse aggregate	42%	36%	30%
Fine aggregate	28%	24%	20%
Fly ash	20%	26%	33%
NaOH of 12 mol	3%	4%	5%
Na_2SiO_3 type Be52	8%	10%	13%

Table 3. Material proportions of the CC

Materials	BK-1	BK-2	BK-3
Coarse aggregate	42%	36%	30%
Fine aggregate	28%	24%	20%
OPC	20%	26%	33%
Water	11%	14%	18%

Meanwhile, the other materials used as constituents of geopolymer concrete must meet the requirements of applicable standard codes. Material properties were performed to determine and identify the characteristics of the material. Sieve analysis, silt content, water content, specific gravity, and bulk density were all performed on fine and coarse aggregates.

2.2. Methods

The experimental research method was used in this study carried out at the Material and Construction Laboratory, Department of Civil Engineering, Universitas Diponegoro. The ratio of aggregate to geopolymer concrete binder of 70%: 30%, 60%: 40%, and 50%: 50% was chosen and used as an independent variable to determine the effect on compressive strength, splitting tensile strength, modulus of elasticity, and Poisson's ratio of geopolymer concrete.

A compression test was performed using a Computer-Controlled Servo Hydraulic Concrete Compression Testing Machine to determine the value of compressive strength, modulus of elasticity, and Poisson's ratio in both geopolymer concrete and conventional concrete until the specimen reached ultimate strength. The test yields load (P), displacement (Δ), and strain in both the transversal (ε_t) and longitudinal (ε_l) axes. The compressive strength (f_c') will be converted from the P value. Furthermore, P and Δ will be transformed to stress and strain values before calculating the modulus of elasticity (E). Meanwhile, ε_t and ε_l were used to compute the Poisson's ratio (υ).

Tensile testing, often known as the Brazilian splitting tensile test, calculates the splitting tensile strength. In this test, specimens in the shape of cylinders with a diameter of 15 cm and a height of 30 cm in both geopolymer concrete and conventional concrete are subjected to a compressive force in the lateral direction from the specimen's diameter to attain the ultimate strength. The test yields P, which is then converted to a splitting tensile strength (f_{sp}). The ultimate conditions for compressive strength, splitting tensile strength, and modulus of elasticity are the best from the experiments. The ultimate condition is a parameter that determines the material's ability to withstand compressive and tensile loads.

Geopolymer concrete was tested at three different ages of 14 days, 28 days, and 56 days with the general curing method using wet gunny bags. Geopolymer concrete must first be covered with plastic to prevent it from directly contacting water. Wet gunny sacks serve to keep the geopolymer concrete cool and moist. This method was chosen to be used as a reference for the ease of application of geopolymer concrete in the field. This method of curing concrete is also applied to conventional concrete.

Subsequently, to obtain the aforementioned mechanical properties and analyze their performance, the slump test, the compressive test, the Brazilian splitting test, the modulus of elasticity, and the Poisson's ratio test were carried out at the determined age. The experimental results of the FAWGC were eventually compared to the results of the CC to find out how good the performance of the FAWGC.

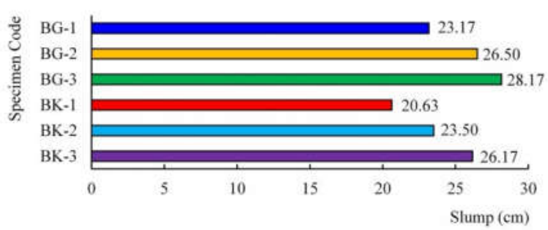

Figure 1. Slump test results of both FAWGC and CC

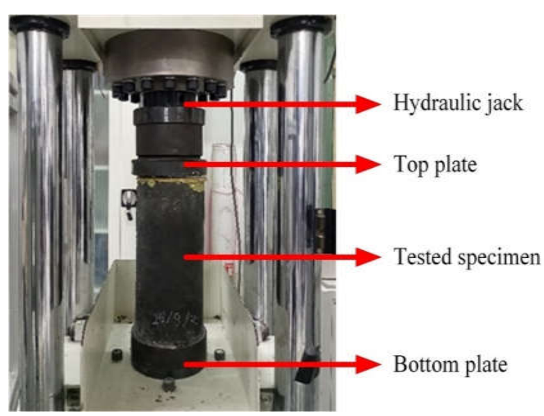

Figure 2. Compression test

doi: 10.14710/teknik.v44i1.52958

Table 4. Compressive strength results of the FAWGC and the CC

Specimen Code	Compressive Strength (MPa)		
	14 days	28 days	56 days
BG-1	30.84	40.93	43.61
BG-2	26.77	36.40	37.85
BG-3	22.39	29.24	33.35
BK-1	20.54	25.84	26.09
BK-2	17.39	22.45	23.39
BK-3	14.76	19.38	20.58

3. Results and Discussions

3.1. Slump

The slump test is used to assess the workability of a concrete mix. The slump test employs an Abrams cone to measure vertical slump. Due to the different influences of the solution used, the difference in slump value between the FAWGC and the CC was quite significant. For the FAWGC, alkaline activators such as NaOH and Na_2SiO_3 type Be52 type were utilized to replace the water used for the CC. Figure 1 shows the slump test results.

Based on the concrete slump test results, the FAWGC has higher workability than the CC. However, even though the slump value of the FAWGC was higher, its concrete mix had a viscous and sticky nature due to the alkaline activator used. The geopolymer concrete mixture will be thicker and stickier if the less alkaline activator is utilized.

3.2. Compressive Strength (f_c')

The compressive test can be seen in Figure 2, at the ages of 14, 28, and 56 days by comparing three types of mix designs. Table 4 and Figure 3 show the comparison results of the compressive strength test for both the FAWGC and the CC. Overall, according to the experimental results, geopolymer concrete has a higher compressive strength than conventional concrete using similar proportions of mix design (Muslikh et al., 2018; Purwanto et al., 2022a). The highest increase in compressive strength at 28 days to 56 days for geopolymer concrete in this investigation is up to 14,08%, while it is only 6% for conventional concrete (see Figure 4).

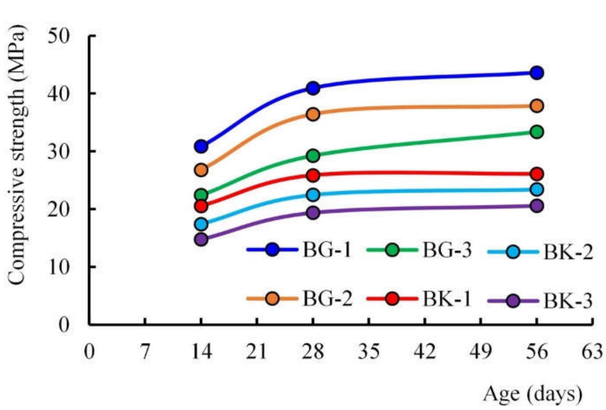

Figure 3. Comparison of compressive strength at the ages of 14, 28, and 56 days for both FAWGC and CC

Table 5. Compressive strength ratios of the FAWGC to the CC

Compressive strength ratios	Concrete age		
	14 days	28 days	56 days
BG-1/BK-1	1.50	1.58	1.67
BG-2/BK-2	1.54	1.62	1.62
BG-3/BK-3	1.52	1.51	1.62

As can be seen in Figure 4, the compressive strength of BG-1 at the age of 14 days is 50% greater than BK-1 (BG-1/BK-1). Likewise, at 28 days, it was 58% larger, and at 56 days, it was 67% larger. Analogously, it also applies to BG-2/BK-2 and BG-3/BK-3. Table 5 provides the compressive strength ratios for all tested specimens at the corresponding concrete ages.

3.3. Splitting Tensile Strength (f_{sp})

In addition to compression tests, the cylindrical specimens were tested only at the concrete age of 56 days to obtain the splitting tensile strength, as can be seen in Figure 5. The splitting tensile strength f_{sp} of geopolymer concrete is proportional to the compressive strength f_c', where the higher the concrete strength, the greater the tensile strength (Purwanto et al., 2021). The specimen BG-1 has the highest splitting tensile strength of 4.24 MPa followed by BG-2 with f_{sp} of 3.39 MPa and BG-3 with f_{sp} of 2.55 MPa. Since the compressive strength was obtained previously, then the tensile strength was also recorded by this test, and the relationship between those

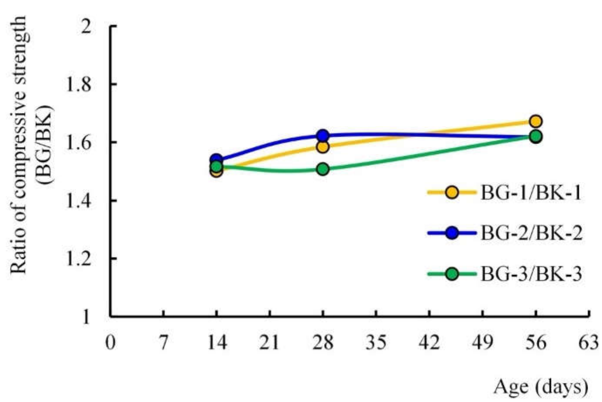

Figure 4. Compressive strength ratios of the FAWGC to the CC at the ages of 14, 28, and 56 days

doi: 10.14710/teknik.v44i1.52958

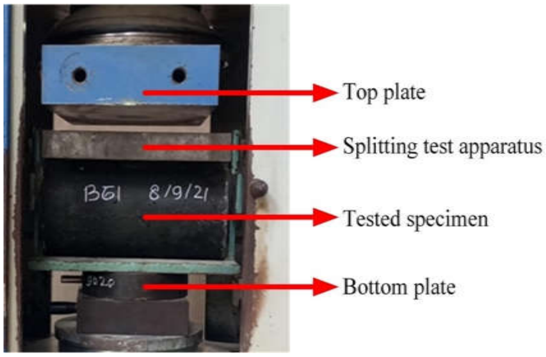

Figure 5. Splitting tensile test

two strengths could be considered (Table 6). The proposed formula is then compared to the existing standard codes for conventional concrete, such as ACI 318 or SNI 03-2847:2019, in terms of the splitting tensile strength.

Table 6 shows that BG-1 has the highest splitting tensile strength f_{sp} at 4.24 MPa or $0.64\sqrt{f_c'}$. When compared to the tensile strength of conventional concrete in general, which is around $0.56\sqrt{f_c'}$ (ACI 318 and SNI 03-2847:2019), it can be concluded that geopolymer concrete with a mix proportion of 70%: 30% has 14% higher splitting tensile strength.

3.4. Modulus of Elasticity and Poisson's Ratio

At the concrete age of 56 days, the modulus of elasticity of the FAWGC and the CC was tested. The elastic modulus applies between 0% and 40% of the maximum concrete stress that can occur. The modulus of elasticity E is the ratio of applied pressure to change in shape per unit length due to applied pressure, or the ratio of stress σ to strain ε. Figure 6 depicts the set-up of the modulus of elasticity and Poisson's ratio tests.

When a concrete cylinder is compressed, the cylinder's length changes in both the lateral and longitudinal directions. The longitudinal strain is the strain whose direction is parallel to the force's motion, whereas the transversal strain is the strain whose direction is perpendicular to the force's motion. The ratio of strain in the transversal direction ε_x to strain in the longitudinal direction ε_y is called Poisson's ratio υ. Lateral strain readings utilized LVDT and strain gauges mounted laterally, while longitudinal strain readings used strain gauges mounted longitudinally. Similar to the previous procedure, the relationship between the calculated modulus of elasticity and the compressive strength obtained by this test was compared to the existing formula in ACI 318 or SNI 03-2847:2019 (see Table 7). Furthermore, Figure 7 depicts a graph of the stress-strain relationship between the FAWGC and the CC.

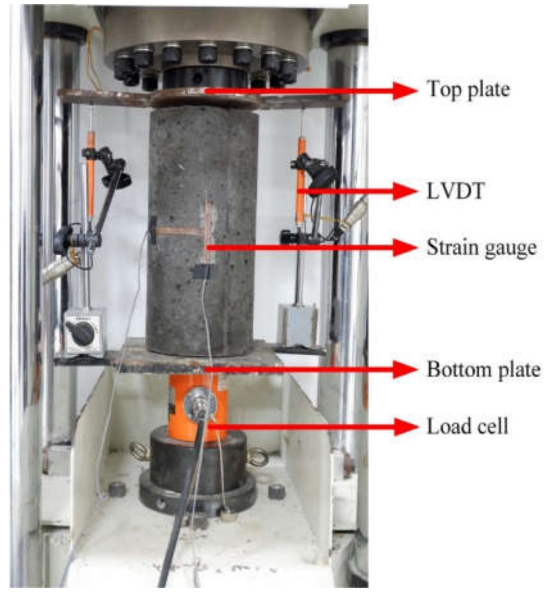

Figure 6. Modulus of elasticity and Poisson's ratio tests

Based on the calculation, the modulus of elasticity for BG-1 is 31,910.01 MPa or $4832\sqrt{f_c'}$. The modulus of elasticity for BG-2 and BG-3 is shown in Table 7. If the value of E is compared to $4700\sqrt{f_c'}$ as stated in ACI 318 and SNI 03-2847:2019, the modulus of elasticity of geopolymer concrete is greater than that of conventional concrete (Purwanto et al., 2022a). In addition, with a greater modulus of elasticity, geopolymer concrete is slightly stiffer than conventional concrete. This statement is confirmed by the results of Poisson's ratio in these experimental investigations (see Table 8). Based on these findings, geopolymer concrete has a slightly lower

Table 6. Compressive and tensile splitting strength relationship

Specimen Code	f_c' (MPa)	f_{sp} (MPa)	Ratio f_{sp}/f_c'	$x = f_{sp}/\sqrt{f_c'}$
BG-1	43.61	4.24	0.097	0.64
BG-2	37.85	3.39	0.090	0.55
BG-3	33.35	2.55	0.076	0.44

Table 7. Compressive strength and modulus of elasticity relationship

Specimen Code	f_c' (MPa)	$E = \sigma/\varepsilon$ (MPa)	$x = E/\sqrt{f_c'}$
BG-1	43.61	31,910.01	4832
BG-2	37.85	29,071.30	4725
BG-3	33.35	27,173.71	4705

doi: 10.14710/teknik.v44i1.52958

Table 8. Poisson's ratio of the FAWGC and the CC

Specimen Code	Poisson's ratio
BG-1	0.211
BG-2	0.218
BG-3	0.221
BK-1	0.229
BK-2	0.235
BK-3	0.237

Poisson's ratio than conventional concrete in the order $\upsilon_{BG-1} < \upsilon_{BG-2} < \upsilon_{BG-3} < \upsilon_{BK-1} < \upsilon_{BK-2} < \upsilon_{BK-3}$. This demonstrates that the value of Poisson's ratio is closely related to the compressive strength of the resulting concrete. The lower the Poisson's ratio, the higher the concrete compressive strength.

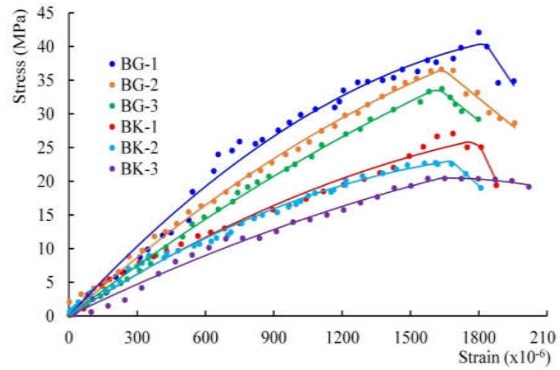

Figure 7. Stress-strain relationship of both FAWGC and CC

4. Conclusions

The present study investigated the fly ash-based geopolymer concrete's mechanical performance considering good workability. The ratio of aggregates to binder of 70:30 for geopolymer concrete mix produced the highest compressive strength. Geopolymer concrete had a compressive strength of 50%-67% higher than conventional concrete and tent to increase at each test age. Regarding splitting tensile strength, geopolymer concrete had 14% higher tensile strength than conventional concrete. According to this study, geopolymer concrete is slightly stiffer since its modulus of elasticity is greater than that of conventional concrete. For all mixture proportions, geopolymer concrete has better compressive strength, splitting tensile strength, and modulus of elasticity than conventional concrete. Moreover, compared to conventional concrete, geopolymer concrete has a lower Poisson ratio. The higher the compressive strength of the concrete produced, the smaller the Poisson's ratio.

Acknowledgment

The authors gratefully acknowledge the financial support of the World Class Research funding by Universitas Diponegoro through the decreed number 118-20/UN7.6.1/PP/2021.

References

Ali, M. B., Saidur, R., & Hossain, M. S. (2011). A review on emission analysis in cement industries. *Renewable and Sustainable Energy Reviews*, *15*, 2252–2261.

Alwash, M., Alwash, J. J. H., & Jassim, H. S. H. (2022). Impact of Different Curing Techniques on Some Mechanical Properties of Self-Compacting Concrete Containing Silica Fume. *International Review of Civil Engineering*, *13*(3), 208–215.

Andrew, R. M. (2019). Global CO_2 emissions from cement production, 1928–2018. *Earth System Science Data*, *11*, 1675–1710.

Davidovits, J. (1985). *Early high-strength mineral polymer* (US Patent No. 4,509,985).

Davidovits, J. (1994). Properties of geopolymer cements. *First International Conference on Alkaline Cements and Concretes*, 131–149.

Davidovits, J. (1999). Chemistry of geopolymeric systems terminology. *International Conference on Geopolymers*, 9–40.

Davidovits, J. (2002). 30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs. *Geopolymer 2002 Conference*, *October*, 1–16.

Dawood, E. T., & Mohammed, W. T. (2021). Characteristics of green mortar containing fly ash with the addition of different plasticizers. *International Review of Civil Engineering*, *12*(3), 167–175.

Formisano, A., Galzerano, B., Durante, M., Marino, O., & Liguori, B. (2018). Mechanical Response of Short Fiber Reinforced Fly Ash Based Geopolymer Composites. *International Review of Mechanical Engineering*, *12*(6), 485–491.

Gunasekara, C., Law, D., Bhuiyan, S., Setunge, S., & Ward, L. (2019). Chloride induced corrosion in different fly ash based geopolymer concretes. *Construction and Building Materials*, *200*, 502–513.

Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., & Rangan, B. V. (2004a). Factors influencing the compressive strength of fly ash-based geopolymer concrete. *Civil Engineering*, *6*(2), 88–93.

Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., & Rangan, B. V. (2004b). On the development of fly ash-based geopolymer concrete. *ACI Materials Journal*, *101*, 467–472.

Hardjito, D., & Rangan, B. V. (2005). Development and properties of low-calcium fly ash-based geopolymer concrete. In *Research Report GC1, Curtin University of Tecnology, Perth, Australia*.

Kustirini, A., Antonius, & Setiyawan, P. (2022). Effect of sodium hydroxide concentration on the compressive strength of geopolymer mortar using fly ash PLTU Tanjungjati B Jepara. *IOP Conference Series: Earth and Environmental Science*, *955*, 1–8.

Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., Kinnunen, P., & Illikainen, M. (2018). One-part alkali-activated materials: A review. *Cement and Concrete Research*, *103*, 21–34.

Mangi, S. A., Memon, Z. A., Khahro, S. H., Memon, R. A., & Memon, A. H. (2020). Potentiality of Industrial Waste as Supplementary Cementitious Material in Concrete Production. *International Review of Civil Engineering*, *11*(5), 214–221.

Mehta, K. (2001). Reducing the Environmental Impact of Concrete. *Concrete International*, 61–66.

Muslikh, Anggraini, N. K., Hardjito, D., & Antonius. (2018). Behavior of Geopolymer Concrete Confined by Circular Hoops. *MATEC Web of Conferences*, *159*, 1–7.

Noushini, A., Castel, A., Aldred, J., & Rawal, A. (2020). Chloride diffusion resistance and chloride binding capacity of fly ash-based geopolymer concrete. *Cement and Concrete Composites*, *105*.

Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research*, *29*, 1323–1329.

Purwanto, Ekaputri, J. J., Nuroji, Indriyantho, B. R., Han, A. L., & Gan, B. S. (2022a). Shear-bond behavior of self-compacting geopolymer concrete to conventional concrete. *Construction and Building Materials*, *321*.

Purwanto, Han, A., Ekaputri, J. J., Nuroji, & Prasetya, B. H. (2021). Self-Compacting-Geopolymer-Concrete (SCGC) Retrofitted Haunch. *International Journal on Engineering Applications*, *9*(4), 180–189.

Purwanto, Indriyantho, B. R., Nuroji, Ekaputri, J. J., Riko, R., Gan, B. S., & Lie, H. A. (2022b). Mix design formulation and stress-strain relationship of fly ash-based workable geopolymer concrete: an experimental study. *International Review of Civil Engineering (IRECE)*, *13*(4), 234–245.

Purwanto, & Indarto, H. (2019). Study of Proportional Variation of Geopolymer Concrete which Self Compacting Concrete. *Journal of Advanced Civil and Environmental Engineering*, *2*(2), 65–75.

Ritchie, H., Roser, M., & Rosado, P. (2020). CO_2 and Greenhouse Gas Emissions. *Our World in Data*.

Romadhon, E. S., Antonius, A., & Sumirin, S. (2022). Design of Low Alkali activator Geopolymer Concrete Mixtures. *Astonjadro*, *11*(3), 627–638.

Salih, M. A., & Ahmed, S. K. (2020). Mix Design for Sustainable High Strength Concrete by Using GGBS and Micro Silica as Supplementary Cementitious Materials. *International Review of Civil Engineering*, *11*(1), 45–51.

Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research*, *34*(3), 487–493.

Suhendro, B. (2014). Toward green concrete for better sustainable environment. *Procedia Engineering*, *95*, 305–320.

doi: 10.14710/teknik.v44i1.52958