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CHARACTERISTICS OF GEOPOLYMER MORTAR PRODUCED USING NICKEL SLAG

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ABSTRACT: Nickel slag is a non-metallic mineral waste primarily composed of olivine, generated from the nickel mining industry. Indonesia holds a large quantity of this waste, but its utilization remains limited. Proper processing of nickel slag has the potential to enhance industrial productivity, contribute to economic growth, and mitigate environmental impacts. In North Maluku, the rapid development of the nickel industry has increased slag production, which, if unmanaged, poses a threat to environmental balance. This research aims to utilize nickel slag as the base material for producing geopolymer bricks, using fly ash from the Rum Steam Power Plant as the binder and an alkaline activator mixture of NaOH and Na_2SiO_3. The mixture consisted of 50% nickel slag and 50% binder, with the binder composed of 55% fly ash and 45% activator. Two concentrations of NaOH solution—8 M and 10 M—were used, with a 1:1 ratio of NaOH to Na_2SiO_3. Compressive strength and water absorption tests were conducted on 5×5×5 cm^3 cube specimens. Results showed that compressive strength increased with curing temperature, from 40°C to 80°C. The highest compressive strength was recorded at 80°C: approximately 32 kg/cm^2 for the 8 M solution and 34 kg/cm^2 for the 10 M solution. Water absorption decreased with higher curing temperatures, with the lowest value of 23.88% at 80°C using the 10 M solution. According to SNI 03-2493 standards, the geopolymer mortar produced in this study is classified as quality grade IV.

Keywords: Nickel slag, Fly ash, Geopolymer, Mortar quality

1. INTRODUCTION

Law Number 32 of 2009 concerning Environmental Protection and Management, which is enforced through Government Regulation Number 22 of 2021, is the mandatory legal framework for waste management in Indonesia. The regulation ensures integrated environmental protection efforts through planning, utilization, control, maintenance, monitoring, and law enforcement. Moreover, individuals using or producing waste, especially B3, are required to be fully responsible for the environmental damage caused.

This legislation has contributed significantly to the improvement of waste management practices and innovation in the recycling field. Moreover, the advancement of material measurement technology is also considered significant to construction, especially in the application of waste or materials discarded from industrial processes.

The utilization of by-products or waste materials is basically driven by the need for resource efficiency. The concept requires replacing conventional products with industrial by-products or waste materials, thereby reducing the environmental burden associated with potential pollution. Therefore, the optimization of resource utilization needs to be prioritized by replacing conventional, easily accessible commodities with by-products or waste materials from industrial processes. The action is considered the most feasible short-term alternative to enhance recycling and produce secondary materials for sustainable construction.

The development of environmentally friendly and sustainable construction materials has received significant attention from relevant stakeholders in the industry. The most significant activities emphasized by engineers and scientists include the introduction of raw materials for binding in order to improve cement characteristics and concrete durability, towards supporting the concept of green concrete and construction [1-2]. The green concrete concept is based on three main objectives, and the first is to reduce greenhouse gas emissions, such as carbon dioxide, from the cement industry. This is necessary because 1 ton of cement manufacturing emits 1 ton of carbon dioxide. The second is to reduce the use of natural resources such as limestone, shale, clay, river sand, and rocks without replacement. The third is the utilization of waste materials in construction to reduce the large area of land often used for storage and the subsequent air, soil, and water pollution. This shows that the concept is focused on ensuring sustainable development without damaging natural resources [3].

One of the emerging innovations in construction materials is the use of geopolymers as an alternative to Portland cement. Geopolymers are aluminosilicate-based materials that are chemically activated using alkaline solutions, such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The aluminosilicate sources commonly originate from industrial waste, such as fly ash from coal combustion and blast furnace slag from the steel industry. Geopolymer technology not only utilizes abundant solid waste but also significantly reduces energy consumption and carbon emissions during production, making it a more environmentally friendly material solution [4-5].

Several industries in North Maluku currently have operations that produce unutilized waste. For example, a Steam Power Plant (PLTU) in Tidore Islands City uses coal as an energy source and produces 5% of the total solid waste in the form of 10-20% fly ash and 80-90% bottom ash. Physically, fly ash is a material containing fine-sized grains and is gray. It is a heterogeneous mixture of amorphous and crystalline phases and is generally considered a ferro-aluminosilicate [6].

The waste is placed in an open area without any specific management process. This shows the potential for environmental pollution and the need to determine an appropriate management system. A method is to use waste as an additional material in the field of civil engineering, such as in concrete mixtures, paving blocks, and road pavement [7-10]. Fly ash has been applied as a construction material to replace fine aggregates in previous research. It varied from 0% to 40% with an interval of 10%, and the proportion of both coarse and fine aggregate was 50%. The results showed that an increase in the fly ash content tended to improve the water absorption characteristics of the paving blocks significantly. The trend showed that the porosity of the paving blocks reduced as the quantity of the fly ash increased, leading to a lesser possibility of micro-crack formation [11]. Fly and bottom ash (FABA) were also used in manufacturing internal materials, as well as other external building materials, and this led to the reduction of non-B3 waste produced [12]. For example, the introduction of fly ash in geopolymer concrete (GPC) had some benefits, including the reduction of waste and CO_2 emissions, as well as cost savings in concrete production because the material was often cheaper than traditional cement materials. The process led to the determination of GPC as a more economical choice for construction projects [13]**.** Another research showed that the water absorption capacity of paving blocks containing fly ash as a geopolymer decreased significantly in line with the reduction in the $NaOH/Na_2SiO_3$ ratio [14].

The nickel ore processing mining industry on Obi Island, South Halmahera Regency, is another industry experiencing growth in Indonesia. Ferronickel is the main product produced from the ferronickel smelter unit activity. It was observed that the unit could produce 1 million tons of nickel slag per year. The efforts to reduce the continuous accumulation of nickel slag require the determination of its alternative usage.

The Ministry of Environment and Forestry (KLHK), through Government Regulation Number 22/2021, excludes 9 components considered waste from hazardous toxic materials (B3). These materials are stated in Attachment XIV to include iron and steel slag, nickel slag, mill scale, electric arc furnace (EAF) dust, fly and bottom ash (FABA) from an Electric steam power plant, spent bleaching earth (SBE), and foundry sand.

This study provides a practical solution for the construction industry by utilizing industrial by-products such as fly ash and nickel slag to produce geopolymer mortar. The developed material shows adequate mechanical properties and water resistance, meeting the SNI standards for non-structural applications like paving blocks. This supports sustainable construction practices by reducing reliance on Portland cement and promoting circular economy principles.

Traditional Portland cement production contributes approximately 0.8–0.9 tons of CO_2 per ton of cement produced [15]. In contrast, alkali-activated materials such as those used in this study, utilizing fly ash and nickel slag, have been reported to reduce CO_2 emissions by up to 80%. Based on the binder composition used in this research, the potential CO_2 savings can be estimated at approximately 0.6–0.7 tons per ton of binder, demonstrating a significant environmental benefit. By replacing OPC with industrial waste-based geopolymers, this study directly contributes to reducing the carbon footprint of the construction sector.

This study aims to utilize nickel slag as a basic material for making mortar with a binder made from a mixture of fly ash and activator. Compression tests and absorption tests are carried out to determine the class of brick produced. The aim of this research is to produce mortar products using nickel slag as the base material.

2. RESEARCH SIGNIFICANCE

The nickel processing industry is growing rapidly on Obi Island, in the process producing waste in the form of nickel slag. This waste has not been utilized optimally, so it can be used as a basic material for forming mortar. In this area, a coal-fired steam power plant operates. The results of burning coal produce fly ash waste. These two wastes are used as brick-forming materials, nickel slag as a substitute for sand, and fly ash mixed with an activator as a binder instead of cement. Utilizing both in producing bricks can reduce environmental pollution and develop alternative building materials.

3. MATERIALS AND METHODS

3.1 Nickel Slag

The nickel slag was collected from Kawasi Village, Obi District, South Halmahera Regency. Nickle slag was used as a substitute for fine aggregates and presented in Figure 1. Moreover, the results obtained from examining the characteristics of the nickel slag are presented in Table 1.

Fig. 1. Nickel slag

Table 1. Nickel slag characteristics

No	Testing	Result	Standard
1	Sludge content	0,0 %	0,2-5,0 %
2	Water content	1,2 %	3,0-5,0 %
3	Volume weight		
	Solid condition	1,85 kg/ltr	1,6-1,9 kg/ltr
	Loose condition	1,71 kg/ltr	1,6-1,9 kg/ltr
4	Specific gravity and absorption		
	Bulk SG	2,80	1,6-3,2
	SSD SG	2,83	1,6-3,2
	Apparent SG	2,87	1,6-3,2
	Absorption	0,8%	0,2-2,0%
5	Sieve analysis (SG)	3,72%	1,5-3,8%

An X-ray fluorescence (XRF) analysis was conducted to determine the number of elements and metal oxides contained in nickel slag specimens. The results obtained are presented in the following table 2. The main constituents identified were silicon (Si), iron (Fe), and magnesium (Mg). This showed that the material exhibited prominent pozzolanic characteristics, as evidenced by the large proportion of Si and Fe elements exceeding 60% [16].

The characterization of nickel slag reveals dominant contents of iron (Fe) at 35.84%, silica (Si) at 27.99%, and magnesium (Mg) at 24.49%, with other elements such as calcium, chromium, manganese, and titanium present in smaller quantities. The significant amount of transition metal oxides suggests the potential of nickel slag as a reactive pozzolanic precursor in geopolymer synthesis. As the slag originates from a controlled industrial nickel smelting process, its chemical composition is relatively consistent across batches, which is critical to ensuring the reactivity and mechanical performance of the resulting geopolymer mortar.

Table 2. Elements in nickel slag

No	Atomic Element	Concentration (%)
1	Si	27,992
2	Fe	35,840
3	Mg	24,490
4	Ca	3,840
5	Cr	3,130
6	Mn	3,510
7	Px	0,930
8	Ti	0,688
9	Ni	0,363
10	Zn	0,107
11	Nb	0,060
12	In	0,025
13	Sn	0,025

3.2 Fly Ash

The fly ash used was obtained from the Rum PLTU, Tidore Islands City. The XRF analysis was applied to the fly ash, with the results presented in Table 3. It was also observed that the fly ash was brownish, as shown in Figure 2.

Table 3. Characteristics of fly ash from Rum PLTU

No	Compound	Composition (%)
1	SiO_3	38,97
2	Fe_2O_3	19,93
3	CaO	15,05
4	Al_2O_3	13,84
5	SO_3	8,36
6	K_2O	2,15
7	Ti_2O_2	0,92
8	P_2O_5	0,37
9	SrO	0,166
10	BaO	0,098
11	ZrO_2	0,060
12	Nb_2O_5	0,0257
13	Rb_2O	0,0193
14	MoO_3	0,0185
15	SnO_2	0,0079

Chemical characterization was conducted to evaluate the consistency of the fly ash and nickel slag materials used in this study. The analysis results show that the fly ash primarily consists of silica (SiO_3) at 38.97%, iron oxide (Fe_2O_3) at 19.93%, calcium oxide

(CaO) at 15.05%, and alumina (Al_2O_3) at 13.84%. This composition indicates that the fly ash is classified as Class C, with the potential to form both C-A-S-H and N-A-S-H gel phases in the geopolymer system. Minor components such as K_2O, TiO_2, and P_2O_5 appear in low and stable concentrations, reflecting good batch-to-batch homogeneity, especially when sourced from the same combustion process.

Fig. 2. Fly ash from PLTU Rum

3.3 Alkali Activator

The activators used were sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Each of these activators is explained in the following subsections.

3.3.1 Sodium Hydroxide (NaOH)

The NaOH used was in the form of crystals or flakes with a purity of 98%, as shown in Figure 3. It was first dissolved in water to become a NaOH solution and the concentrations used were 8M and 10M.

Fig. 3. Sodium Hydroxide in Crystal Form

3.3.2 Sodium Silicate (Na_2SiO_3)

The Na_2SiO_3 used was a thick liquid purchased from a chemical supply store in a ready-to-use condition. The material is presented in the following Figure 4.

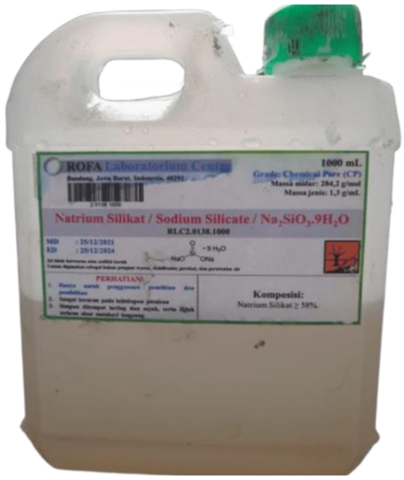

Fig. 4. Sodium Silicate in Gel Form

3.4 Research Design

The research was conducted in a structure and material laboratory. The nickel slag was used as a fine aggregate substitute while fly ash was the binder mixed with 8M and 10M of NaOH and Na_2SiO_3 activators. NaOH solutions with molarities of 8 M and 10 M were selected to evaluate the effect of alkali solution strength on the geopolymerization activation process. A concentration of 8 M represents a medium-strength alkali solution, while 10 M indicates a higher strength. This variation aims to determine the extent to which increasing the molarity of the alkali solution can influence the activation reaction, the formation of the geopolymer structure, as well as the mechanical properties and durability of the final product.

The composition of slag and binder each is 50% of the mixture volume. The binder composition consists of 55% fly ash and 45% activator with a ratio of NaOH and Na_2SiO_3, namely 1:1. Composition comparison is shown in Figure 5. Moreover, compressive strength and absorption capacity were determined using a cube measuring 5x5x5 cm as the test object with the detailed characteristics presented in Table 4.

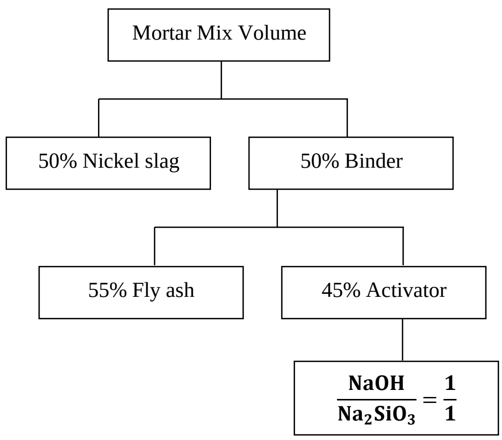

Fig 5. Geopolymer Mortar Mix Composition

In the geopolymerization process, temperature plays a crucial role in accelerating the chemical reactions between precursor materials, such as fly ash or slag, and the alkaline solution. In this study, the reaction temperature was varied from room temperature (as a control) up to 100°C, with an increment of 20°C. The temperature range used includes 25°C (room temperature), 40°C, 60°C, 80°C, and 100°C. In the geopolymerization process, temperatures ranging from 40°C to 100°C are selected because they have been proven to enhance the chemical reaction rate between precursor materials such as fly ash or slag and alkaline solutions, accelerating the dissolution of silica and alumina as well as the formation of geopolymer gels such as N-A-S-H or C-A-S-H. Heating within this temperature range promotes faster early strength development and results in a denser microstructure compared to curing at room temperature (without heating). Additionally, these temperatures are sufficient to reduce the amount of free water needed for gel condensation without causing excessive evaporation, thereby minimizing the risk of thermal shrinkage and cracking. Unlike the conventional production of Portland cement, which requires temperatures up to 1450°C, geopolymerization at these lower temperatures is significantly more energy-efficient and environmentally friendly, and can be implemented using simple heating methods in both laboratory and industrial settings.

Table 4. Details of the test object

Heating Temperature	8 Molar (piece)	10 Molar (piece)	Total Test Object (piece)
Room Temperature	20	20	40
40°C	20	20	40
60°C	20	20	40
80°C	20	20	40
100°C	20	20	40

This study investigated the effects of heating temperature on geopolymer mortar. The following mixing strategy was utilized in the research:

a) The materials were assembled according to the specifications.
b) Nickel slag and fly ash were combined in the mixing bowl.
c) A mixer at low speed was used to blend the nickel slag and fly ash for 1 min. Then, manual stirring was employed until the mixture was thoroughly combined.
d) The NaOH, previously dissolved in water, was added while mixing the nickel slag and fly ash. Mixing was conducted at a slow pace for 1 min.
e) The mixture was stirred manually to ensure even distribution.
f) Using a tamping rod, the resulting slurry was printed onto a mould in three layers.
g) The mixture was allowed to solidify in the mold for 8 h.
h) The test object is removed from the mold, and the curing process is carried out by heating at temperatures of 40, 60 and 100 degrees Celsius.
i) Finally, tests for compressive strength, porosity and chemical component composition (XRD and SEM) were conducted.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength of Mortar

The compressive strength of nickel slag-based geopolymer mortar was tested using 15 specimens for each heating temperature variation and NaOH solution molarity. The results are presented in the following Figure 6.

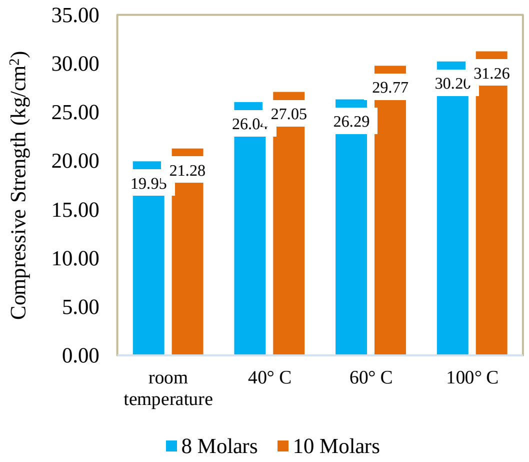

Fig. 6. Relationship between the Compressive Strength of Nickel Slag-Based Mortar and Heating Temperature.

The heating of the mortar using an oven for 8 hours showed that the compressive strength increased along with the heating temperature up to 80°C. At 100°C, the value was reduced but was still higher than that of the mortar without heating or at room temperature. This was in line with the results of previous research, which showed that the heating time on 8M and 10M mortars increased compressive strength [17-18]. Moreover, the introduction of fly ash as a binder led to an improvement in compressive strength at longer curing times. It was also reported that the optimum compressive strength was produced at a curing time of 8 hours [19].

The data and graphs used for comparison showed that geopolymer slag mortar with 8M NaOH solution produced lower compressive strength than 10M NaOH solution. This was in line with the usage of geopolymer mixtures in the form of fly ash and Porong mud as binders and concrete curing at room temperature [20-21]. Moreover, the geopolymer mortar was varied at 6M, 8M, and 10M. The results showed that the optimum compressive strength, 32.9 MPa, was found in a mixture containing a 10M molarity activator with room temperature curing at the age of 28 days [22]. It was concluded that temperature was important in increasing compressive strength[23-27].

The decrease in compressive strength at 100°C compared to 80°C can be explained by several mechanisms. At elevated temperatures, the evaporation rate of both free and bound water increases significantly, which can disrupt the development of the N-A-S-H (sodium aluminosilicate hydrate) or C-A-S-H (calcium aluminosilicate hydrate) gel structures, depending on the type of precursor used. Rapid moisture loss can lead to increased porosity and the formation of microcracks due to thermal stress [28]. Additionally, exposure to 100°C may trigger over-condensation—a reaction that proceeds too quickly and reduces the degree of polymerization and structural homogeneity of the geopolymer matrix [29].

A curing temperature of 80°C is often considered optimal for many geopolymer systems, as it is sufficient to accelerate dissolution and polycondensation reactions effectively without inducing significant microstructural damage [30-31], Heating to this level promotes the formation of a denser and more uniform geopolymer network, resulting in maximum compressive strength before microstructural degradation becomes prominent at higher temperatures.

Based on previous studies, the use of nickel slag as a fine aggregate in geopolymer mortar tends to result in lower compressive strength compared to mortar utilizing nickel slag with a Portland cement-based binder. This reduction may be attributed to several factors, including incomplete geopolymerization reactions, limited formation of optimal aluminosilicate gels, and potentially unstable interactions between nickel slag and alkaline activators. Additionally, the higher porosity and weaker interparticle bonding in the geopolymer system may contribute to the decreased mechanical performance when compared to cement-based systems, which are more established in terms of hydration and the formation of binding products such as calcium silicate hydrate (C-S-H) [32].

4.2 Mortar Absorption

The absorption capacity of the nickel slag-based geopolymer mortar was tested using 5 specimens for each variation of heating temperature. The results are presented in the following Figure 7.

The absorption capacity of the mortar was reduced as the temperature increased to 80°C. Meanwhile, at 100°C, the value increased but was still lower than the mortar that was not heated or placed at room temperature. The graphs showed that compressive strength and absorption capacity were inversely proportional. This supported previous research that water absorption capacity could affect the resistance of geopolymer mortar [33-34].

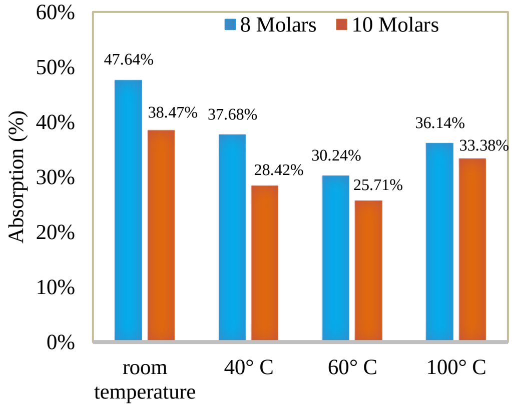

Fig. 7. Relationship between Mortar Absorption of Nickel Slag with Heating Temperature

Overall, nickel slag-based geopolymer mortar demonstrates superior durability performance compared to traditional cement mortar in several aspects, such as resistance to sulfate attack, acid exposure, and high temperatures. The aluminosilicate structure formed in geopolymers provides greater chemical and thermal stability, as well as potentially lower water absorption when the mix design is optimized. However, geopolymers tend to be slightly more susceptible to carbonation than cement-based mortars due to their lower system pH [35-36]. Therefore, nickel slag-based geopolymer mortar is a promising alternative for structural applications in aggressive environments, provided that formulation and curing processes are properly controlled [37-38].

4.3 X-Ray Diffraction (XRD)

As shown in Figure 8, the crystallinity index (Xc) has been shown by using Segal's methods [39]. The differences in crystallinity index (Xc) among the geopolymer mortars cured at various temperatures can be attributed to the influence of thermal energy on the geopolymerization process. At room temperature (RT), the process is slower, allowing the formation of more amorphous or partially crystalline phases, leading to a moderate Xc value (27.58%). When the temperature is raised to 60 °C, the geopolymerization reaction accelerates, enhancing the dissolution of aluminosilicate species and promoting a more homogeneous gel structure, but possibly with a more disordered atomic arrangement [40-41], thus lowering the Xc to 23.06%. At 100 °C, however, the high thermal energy provides enough activation for the formation of crystalline reaction products or recrystallization of unreacted phases, resulting in the highest Xc (31.81%).

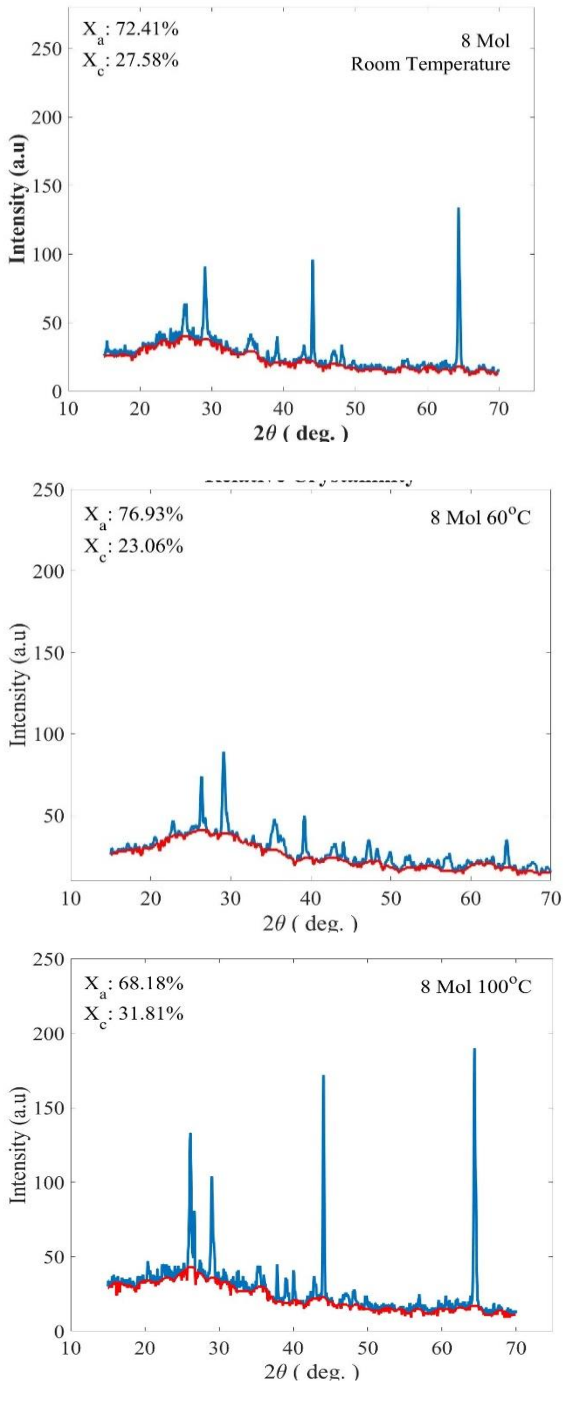

Fig. 8. Crystallinity Index and Its Change as a Function of Temperature.

These microstructural and phase differences significantly affect the characteristics of the geopolymer mortar. Mortars cured at higher temperatures, especially at 100 °C, are expected to exhibit superior mechanical strength, lower porosity, and enhanced durability due to their higher crystallinity and finer particle distribution. Conversely, the mortar cured at 60 °C, despite improved reaction kinetics compared to RT, may display slightly lower structural order (lower Xc) but still benefits from a denser structure compared to RT. Overall, the curing temperature plays a pivotal role in tailoring the microstructure and phase composition, which directly governs the performance characteristics of geopolymer mortars produced using nickel slag.

4.4 Scanning Electron Microscopy (SEM)

The SEM analysis reveals a clear trend in particle distribution with increasing curing temperature as shown in Figure 9. The particle size distribution becomes finer from RT (53.97 ± 0.17 μm) to 60 °C (41.95 ± 2.35 μm) and further to 100 °C (32.17 ± 0.94 μm). This reduction in particle size can be linked to improved dissolution of nickel slag and fly ash components at higher temperatures [42-43], which promotes a more thorough geopolymerization reaction and results in a denser and more refined microstructure. The finer microstructure at elevated temperatures indicates enhanced material consolidation and better reaction kinetics, leading to fewer voids and more compact gel networks in the matrix.

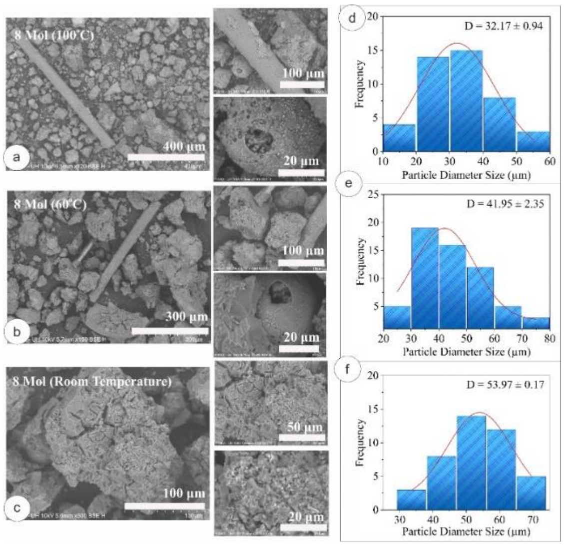

Fig. 9. (a) Morphology, and (b) diameter of particle distribution of each sample

4.5 Mortar Quality

The quality class of the mortar produced was determined based on compressive strength and absorption using the Indonesian National Standard on concrete bricks for wall masonry as the reference. The average compressive strength and absorption are presented in Tables 5 and 6. The brick produced had quality IV in all heating variations except when there was no heat or at room temperature. However, it was observed that the quality was not included in the specifications required by SNI 0349.

Table 5. The physical characteristics of 8M mortar

Heating Temperature	Compressive Strength (kg/cm^2)	Absorption (%)	Quality Class
Room temperature	19,50	47,64	-
40°C	26,04	37,68	IV
60°C	26,29	30,24	IV
80°C	32,57	27,34	IV
100°C	30,20	36,14	IV

Table 6. The physical characteristics of 10M mortar

Heating Temperature	Compressive Strength (kg/cm^2)	Absorption (%)	Quality Class
Room Temperature	21,28	38,47	-
40°C	27,05	28,42	IV
60°C	29,77	25,71	IV
80°C	33,70	23,88	IV
100°C	31,26	33,38	IV

5. CONCLUSION

This study demonstrates that nickel slag-based geopolymer mortar subjected to heat treatment up to 100°C achieved a maximum compressive strength of 32.57 kg/cm² at 80°C with a relatively low water absorption of 27.34% using an 8M alkaline solution. When using a 10M solution, the maximum compressive strength increased to 33.70 kg/cm² at 80°C, accompanied by an even lower water absorption rate of 23.88%. All temperature variations yielded Grade IV quality based on the SNI classification for paving blocks, indicating the material's suitability for non-structural applications such as pedestrian pathways, parks, and residential areas with light traffic. Although the compressive strength remains below structural-grade thresholds, the observed decrease in water absorption at the optimal curing temperature suggests a denser and more stable microstructure, supporting long-term resistance to weathering and moisture. These findings reinforce the potential of nickel slag-based geopolymer materials to partially replace cement-based products in light construction, aligning with efforts to reduce carbon emissions and promote sustainable utilization of industrial waste.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Qingren W., Qiongyu H., Hongguang L., and Yongjun Z., Research on Using Waste Sludge of Smelting Lead and Zinc to Sinter Cement Clinker, in International Workshop on Sustainable Development and Concrete Technology, 2004, pp. 171–191.

[2] Li Z., Ding Z., and Zhang Y., Development of Sustainable Cementitious Materials, in International Workshop on Sustainable Development and Concrete Technology, 2004, pp. 55–76.

[3] Suhendro B., Toward Green Concrete for Better Sustainable Environment, in Procedia Engineering, Elsevier Ltd, 2014, pp. 305–320. doi: 10.1016/j.proeng.2014.12.190.

[4] Okoye F. N., Geopolymer Binder: A Veritable Alternative to Portland Cement, in Materials Today: Proceedings, Elsevier Ltd, 2017, pp. 5599–5604. doi: 10.1016/j.matpr.2017.06.017.

[5] Singh N. B., and Middendorf B., Geopolymers as an Alternative to Portland Cement: An Overview, Constr Build Mater, vol. 237, 2020, pp. 1–15, doi: 10.1016/j.conbuildmat.2019.117455.

[6] Agusta H., Nisya F. N., Iman R. N., and Bilad D. B. C., Granulation of Coal Fly Ash by Using Different Types of Granule Agents, in IOP Conference Series: Earth and Environmental Science, Institute of Physics Publishing, Jun. 2017. doi: 10.1088/1755-1315/65/1/012023.

[7] Arshad M. T., Ahmad S., Khitab A., and Hanif A., Synergistic Use of Fly Ash and Silica Fume to Produce High-Strength Self-Compacting Cementitious Composites, Crystals (Basel), vol. 11, no. 915, 2021, pp. 2–14, doi: 10.3390/cryst11080915.

[8] Gopalakrishnan R., Strength and Durability of High Volume Fly Ash Concrete in Severe Environment, International Journal of Civil Engineering and Technology (IJCIET), vol. 9, no. 11, 2018, pp. 718–727.

[9] Pangestuti E. K., Julianto E.N., Hapsari R. N. A., Sholahudin F., Aida N., Ardiasnyah D., Bagaskara P., and Heriyanto F. R., Utilization of Fly Ash and Bottom Ash as a Mixture for Making Paving Blocks, in IOP Conference Series: Earth and Environmental Science, Institute of Physics, 2024. doi: 10.1088/1755-1315/1381/1/012015.

[10] Sha A., Liu Z., Jiang W., Qi L., Hu L., Jiao W., and Barbieri D. M., Advances and

Development Trends in Eco-Friendly Pavements, Journal of Road Engineering, vol. 1, 2021, pp. 1–42, doi: 10.1016/j.jreng.2021.12.002.

[11] Sahu S. K., Kamalakkannan S., and Pati P. K., Fly Ash Utilization in Concrete Tiles and Paver Blocks, in New Materials in Civil Engineering, Elsevier, 2020, pp. 897–917. doi: 10.1016/B978-0-12-818961-0.00030-2.

[12] Ami, R. A. and Sriwahyuni S., Processing of Fly Ash and Bottom Ash in the Manufacturing of Paving Blocks to Reduce the Total Pollution of Non-B3 Waste at PLTU Nagan Raya, ORFAI Journal, vol. 2, no. 2, 2022, pp. 315–320.

[13] Amran M., Debbarma S., and Ozbakkaloglu T., Fly Ash-Based Eco-Friendly Geopolymer Concrete: A Critical Review of the Long-Term Durability Properties, Constr Build Mater, vol. 270, 2021, pp. 1–23, doi: 10.1016/j.conbuildmat.2020.121857.

[14] Jonbi J., and Fulazzaky M. A., Modeling the Water Absorption and Compressive Strength of Geopolymer Paving Block: An Empirical Approach, Measurement, vol. 158, 2020, pp. 1–7, doi: 10.1016/j.measurement.2020. 107695.

[15] Provis J. L., Alkali-Activated Materials, Cem Concr Res, vol. 114, 2018, pp. 40–48, doi: 10.1016/j.cemconres.2017.02.009.

[16] Rahman M. A., Sarker P. K., Shaikh F. U. A., and Saha A. K., Soundness and Compressive Strength of Portland Cement Blended with Ground Granulated Ferronickel Slag, Constr Build Mater, vol. 140, 2017, pp. 194–202, doi: 10.1016/j.conbuildmat.2017.02.023.

[17] Hardjito D., Wallah S. E., Sumajouw D. M. J., and Rangan B. V., Factors Influencing the Compressive Strength of Fly Ash-Based Geopolymer Concrete, Civil Engineering Dimension, vol. 6, no. 2, 2004, pp. 88–93.

[18] Adam A. A., and Horianto H., The Effect of Temperature and Duration of Curing on The Strength of Fly Ash Based Geopolymer Mortar, Procedia Eng, vol. 95, 2014, pp. 410–414, doi: 10.1016/j.proeng.2014.12.199.

[19] Sultan M. A., Kusnadi K, and Adingku J., Determination of Geopolymer Mortar Characterization Using Fly Ash and Pumice Sand, International Journal of GEOMATE, vol. 23, no. 100, 2022, pp. 86–94, doi: 10.21660/2022.100.3630.

[20] Karolina R., Tarigan J., Hardjasaputra H., and Hermanto K.., Study on Compressive Strength of Geopolymer Mortar Based on Fly Ash and GGBFS with Various Molar Variations, in Proceedings of the International Conference on Emerging Smart Cities, 2022, pp. 13–28. doi: 10.1007/978-981-99-1111-0_2.

[21] Pathirana C., and Dissanayake D. M. H., Effect of Curing Temperature on the Mechanical Behaviour of Geopolymer Concrete Prepared Using Locally Available Fly Ash, in 6 th International Symposioum on Advances in Civil Engineering Practices for Sustainable Development (ACEPS-2018), 2018, pp. 278–285. [Online]. Available: https://www.researchgate.net/publication/336717108

[22] Dewi E. S., Darayani D. H., and Iskandar O., Utilization of Fly Ash and Bottom Ash Waste of PLTU Jeranjang on Geopolymer Paving, in IOP Conference Series: Earth and Environmental Science, Institute of Physics, 2024. doi: 10.1088/1755-1315/1321/1/012042.

[23] Muhammad N., Baharom S., Ghazali N. A. M, and Alias N. A., Effect of Heat Curing Temperatures on Fly Ash-Based Geopolymer Concrete, International Journal of Engineering & Technology, vol. 8, no. 1, 2019, pp. 15–19, doi: 10.14419/ijet.v8i1.2.24866.

[24] Mohamed R., Razak R. A., Abdullah M. M. A. B., Shuib R. K., and Subaer S., Effect of Heat Evolved During Geopolymerization to the Compressive Strength of Class C Fly Ash Based Geopolymers, in AIP Conference Proceedings, American Institute of Physics Inc., Jul. 2019, pp. 1–9. doi: 10.1063/ 1.5118069.

[25] Bachtiar E., Marzuki I., Erdawaty E., Junaedy M. F., Ramadhan F., Setiawan A. M., Rachim F., The Relationship of Temperature and Compressive Strength on Geopolymer Mortar using Fly Ash-Based, in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Aug. 2020, pp. 1–9. doi: 10.1088/ 1757-899X/885/1/012019.

[26] Hager I., Sitarz M., and Mróz K., Fly-Ash Based Geopolymer Mortar for High-Temperature Application – Effect of Slag Addition, J Clean Prod, vol. 316, 2021, pp. 1–10, doi: 10.1016/j.jclepro.2021.128168.

[27] Sitarz M., Hager I., and Kochanek J., Effect of High Temperature on Mechanical Properties of Geopolymer Mortar, in MATEC Web of Conferences, EDP Sciences, Jun. 2018, pp. 1–6. doi: 10.1051/matecconf /201816306004.

[28] Temuujin J., Riessen A. V., and Williams R., Influence of Calcium Compounds on the Mechanical Properties of Fly Ash Geopolymer Pastes, J Hazard Mater, vol. 167,

2009, pp. 82–88, doi: 10.1016/ j.jhazmat.2008.12.121.
[29] Zawrah M. F., Gado R. A., Feltin N., Ducourtieux S., and Devoille L., Recycling and Utilization Assessment of Waste Fired Clay Bricks (Grog) with Granulated Blast-Furnace Slag for Geopolymer Production, Process Safety and Environmental Protection, vol. 103, 2016, pp. 237–251, doi: 10.1016/ j.psep.2016.08.001.
[30] Hardjito D., Cheak C. C., and Ing C. H. L., Strength and Setting Times of Low Calcium Fly Ash-based Geopolymer Mortar, Mod Appl Sci, vol. 2, no. 4, 2008, pp. 3–11, doi: 10.5539/mas.v2n4p3.
[31] Zhang Z., Wang H., Provis J. L., Bullen F., Reid A., and Zhu Y., Quantitative kinetic and structural Analysis of Geopolymers. Part 1. The Activation of Metakaolin with Sodium Hydroxide," Thermochim Acta, vol. 539, 2012, pp. 23–33, doi: 10.1016/ j.tca.2012.03.021.
[32] Ahmad S. B., and Asik J., Compressive Strength of Fly Ash-Slag Based Geopolymer Mortar, in Prosiding Seminar Nasional Penelitian & Pengabdian Kepada Masyarakat 2019, 2019, pp. 6–10.
[33] Adam A. A., Deviana L., Siregar A. P. N., and Mustofa M., Water Absorption of Ambient-Cured Geopolymer Concrete, in IOP Conference Series: Earth and Environmental Science, Institute of Physics, 2023, pp. 1–10. doi: 10.1088/1755-1315/1157/1/012025.
[34] Thokchom S., Ghosh P., and Ghosh S., Effect of Water Absorption, Porosity and Sorptivity on Durability of Geopolymer Mortars, ARPN Journal of Engineering and Applied Sciences, vol. 4, no. 7, 2009, pp. 28–32, [Online]. Available: https://www.researchgate.net/publication/237215851
[35] Zhang Z., Provis J. L., Reid A., and Wang H., Fly Ash-Based Geopolymers: The Relationship Between Composition, Pore Structure and Efflorescence, Cem Concr Res, vol. 64, 2014, pp. 30–41, doi: 10.1016/j.cemconres.2014.06.004.
[36] Bernal S. A., Gutierrez R. M. D., Provis J. L., and Rose V., Effect of Silicate Modulus and Metakaolin Incorporation on the Carbonation of Alkali Silicate-Activated Slags, Cem Concr Res, vol. 40, no. 6, 2010, pp. 898–907, doi: 10.1016/j.cemconres.2010.02.003.
[37] Hardjito D., and Rangan B. V., Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete, Pert, Australia, 2005.
[38] Provis J. L., and Deventer J. S. J., Alkali-Activated Materials State-of-the-Art Report, RILEM TC 224-AAM, 2014.
[39] Nam S., French A. D., Condon B. D., and Concha M., Segal Crystallinity Index Revisited by the Simulation of X-ray Diffraction Patterns of Cotton Cellulose Iβ and Cellulose II, Carbohydr Polym, vol. 135, 2016, pp. 1–9, doi: 10.1016/j.carbpol.2015.08.035.
[40] Heryanto H., Mutmainna I., Rahmi M. H., Ola A. T. T., Tang M. F.R., Mohamed M. A., and Tahir D., Favourable Peak Diffraction Shift moments as a Function of Mg Doping on ZnO Matrix as a Promising Catalyst for Methylene Blue Waste, Mater Chem Phys, vol. 313, 2024.
[41] Abdullah B., Tahir D., Heryanto H., Tang N. F. R., and Rahmat R., Highly Ordered Structure and Susceptibility to Light Absorption of ZnO/Calcium Phosphate (5%) to Enhance the Stability of Charge Diffusion as a Methylene Blue Bond Breaker, Phys Scr, vol. 99, no. 2, 2024.
[42] Rauf I., Saputra M. T. Y., Heryanto H., and Marsaoly M. F., Laboratory investigation of the influence of aluminum hydroxide on the compressive strength of nickel slag-stabilized soft soils, AIMS Mater Sci, vol. 11, no. 6, 2024, pp. 1220–1231, doi: 10.3934/MATERSCI.2024060.
[43] Gaus A., Rauf I., Siregar F., and Heryanto H., Proximity Porosity and Crystallinity Analysis as Clay/Nickel Slag Characteristics for Material Stabilization Application, Trends in Sciences, vol. 21, no. 8, Aug. 2024, doi: 10.48048/tis.2024.7970.