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Performance of fly ash-ferronickel slag-based geopolymer mortar under heat curing

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ABSTRACT

This paper aimed to examine the engineering and environmental properties of C-type fly ash (FA-C)-ferronickel slag 4 (FNS 4)-based geopolymer mortar under heat curing. The series of C-type fly ash-based geopolymer mortar was generated with 0%, 10% and 20% ferronickel slag 4. The heat curing was applied at a temperature of 60 ± 5 °C for 6 hours. Fresh geopolymer mortar developed greater workability with the addition of FNS 4. The porosity of geopolymer mortar was determined by immersing the sample and vacuuming it at a pressure of 0.5 bar for 24 hours. To study the formation of calcium-aluminate-silicate-hydrate (CASH) gel of RPC, the scanning electron microscope-energy dispersive X-ray spectroscopy (SEM-EDX) mapping was carried out. The life cycle assessment was used for measuring the environmental impact of FNS 4 in FA-C-based geopolymer mortar. The results obtained showed that the addition of FNS 4 increased the workability of geopolymer mortar. FNS 4 has a higher effect on the development of compressive strength in geopolymer mortar under normal curing. Under heat and normal curing, the bending strength of geopolymer mortar raises for all curing ages. The porosity of the geopolymer mortar containing FNS 4 decreased. The formation of CASH gel in geopolymer was formed in large quantities as the Ca and Si were detected in higher amounts. The use of ferronickel slag 4 has the potential to decrease ozone depletion, fossil fuel depletion, and global warming impact.

Keywords: geopolymer mortar, ferronickel slag 4, heat curing, compressive strength, porosity.

INTRODUCTION

Global demand for natural resources is projected to double by 2050 (Belaïd, 2022). The fossil fuel supplies are predicted to deplete within a century. Both biodiversity and carbon footprints will be threatened. This situation necessitates a more sustainable and logical use of resources.

Nickel is a crucial industrial metal that is utilized extensively in steel and alloys production (Zhang et al., 2025). Even now, nickel is widely used for electric car batteries, which is increasing the industrial demand for nickel. The solid slag created by smelting nickel-iron alloy is known as ferronickel slag (FNS). The particles are typically spherical and range in size from 0 to 5 mm (Chen et al., 2023). Presently, FNS is used for cement and aggregate replacement in mortar and concrete production (Edwin, et al., 2022; Kimsan et al., 2021), and it is still rarely used in the production of geopolymer materials (Edwin et al., 2025). FNS production from each smelter continues to increase. The annual production of FNS in Indonesia exceeds 4 million tons. FNS remains underutilized in construction, requiring extensive storage space. In the meantime, fly ash, a by-product of burning coal in power plants, continues to grow in quantity. Around 800 million metric tons of fly ash are generated worldwide each year (Bae et al., 2014). This figure suggests that the fly ash storage availability will become an issue in the future due to the hazards of heavy metals. This necessitates finding a way to stop environmental harm.

In the cement sector, the need for this material increases every year for infrastructure development. Cement clinker presents a special problem because the chemistry of the process and the fossil fuels needed to produce it both contribute to CO_2 emissions (Pisciotta et al., 2023). To lessen the negative environmental and energy-related effects of cement manufacture in the near future, an alternative approach that can be used is to apply waste materials in the concrete industry. However, the use of industrial waste such as fly ash, slag, etc., as a substitute for cement and aggregates still does not solve environmental and energy problems because its utilization is still limited while waste production continues to increase. Therefore, geopolymer materials can be proposed as a comprehensive solution to environmental and energy problems, because geopolymer materials do not require cement, so industrials waste can be fully utilized.

Geopolymer is more cost-effective than cement, because it uses fewer natural resources, produces less pollution in the environment, and has better durability. Because they both contain significant percentages of amorphous silica and alumina, slag and fly ash are great sources of suitable material to use in the production of alkali-activated mortars or concrete (Sathonsaowaphak et al., 2009). The use of nano-bauxite has the potential to improve the mechanical performance and durability of geopolymer concrete (Salman et al., 2023). Calcium-alumina-silicate hydrates (CASH), which have a quicker setting time and a higher early strength than fly ash with a lower calcium content, can be formed by the direct interaction of Class C fly ash (FA-C) with high or moderate calcium content, silicate, and alumina (Edwin et al., 2025; Mohamed et al., 2021).

In the context of curing technology applied to the geopolymer, most researchers studied the effect of heat curing for geopolymer concrete using fly ash type F. The temperature range at which geopolymer concrete hardens is between 60 °C and 90 °C. Nevertheless, the compressive strength was negatively impacted by curing at 80 °C (Shoaei et al., 2024). Curing at higher temperatures will lower the quality of the reaction products due to rapid production, which impacts the strength and structure of the mix (Rovnaník, 2010). Therefore, the combination of FA-C-FNS 4 and heat curing at the right temperature to investigate the engineering properties and environmental impact of geopolymer mortar was the aim of this current research.

MATERIAL AND METHOD

Materials

FNS 4 is a by-product of the nickel smelting process in which ferronickel is the main product. FNS 4 is produced from a preheating process using furnace 4, which uses a more efficient and better copper cooler cooling system and a slag granulation system using a safer bucket elevator. The extraction process of nickel ore produces various forms of nickel slag. The FNS utilized in this investigation was produced by one of Indonesia's nickel companies, which applies a pyrometallurgical process in its production. This process results in denser FNS with smaller particle sizes. After the procedure is finished, ferronickel will undergo additional processing, and the slag from the smelting will be extracted out and fast cooled with water (Edwin et al., 2022). FNS 4 is mainly composed of SiO_2, Fe_2O_3, and MgO as tabulated in Table 1.

In this study, the initial form of FNS 4 before being ground is rough, irregular and sharp with a particle size of 0–10 mm. To obtain an optimum reactivity between FNS 4 and FA-C, FNS 4 was ground intensively using a planetary ball mill. The wet method was applied to reduce the size of FNS 4 to obtain a higher fineness. As FNS 4 has a similar toughness to copper slag (Mohs hardness scale of 6-7), a higher energy in the grinding process was applied. The speed of the planetary ball mill was set at 400 rpm. A long duration milling (3 times for 15 minutes) and 7 balls charged were chosen to obtain one level of fineness. This duration is 5 minutes longer than the grinding duration on FNS 3 (ferronickel slag from FeNi plant 3) in the previous study (Edwin et al., 2024). To avoid re-compaction of powder particles of FNS 4 due to high temperature during the milling process, a superplasticizer (Glenium Sky 8851) in an amount of about 0.2–0.3 ml was inserted into 120 g of FNS 4 in a grinding jar. This method was also performed by (Edwin et al., 2017) to prevent the re-compaction of secondary copper slag during the milling process. To assess the particle size distribution of FNS 4, the laser diffraction method was applied. Regarding the fly ash, NII Tanasa Company, a coal-fired plant located in Konawe, Indonesia, generates FA-C as a by-product. FA-C was then sieved using no.100 mesh size. The chemical composition of FA-C is seen in Table 1, and the grain size distribution of FA-C and

FNS 4 is shown in Figure 2. The sand used in this study was obtained from Pohara, Indonesia. The specific gravity and water absorption of sand are 2.58 g/cm^3 and 1.43%, respectively. Figure 1 presents the FA-C, FNS 4, and sand used in this study. It is seen that FNS 4 is finer than FA-C, as the grain size of FNS 4 varies from 0.8 μm to 100 μm, meanwhile the grain size of FA-C ranges from 3 μm to 300 μm, as it is seen in Figure 2.

Method

Alkaline activator and mix proportion

In this study, the first step was to prepare NaOH 14M by mixing NaOH (flakes) with water. This preparation is carried out 24 hours before mixing for the cooling process. After that, Na_2SiO_3 was combined with NaOH solutions in a 2:1 ratio for two hours before being combined with dry materials. This ratio is also similar to previous finding (Edwin et al., 2024).

Three mixes of geopolymer mortar were designed in this research. The reference mixture was a geopolymer mortar using 100% FA-C, fine aggregate, and alkaline activator. FNS 4 was used to replace FA-C with the proportions of 10% and 20% FNS 4 combined with fine aggregate and alkaline activator. The proportions of FNS 4 as FA-C replacement used in this research are also studied by (Edwin et al., 2025) in geopolymer paste. The alkaline liquid-to-binder ratio is 1.33, which corresponds to previous study (Edwin et al., 2025) and the binder-to-sand ratio is 2.86. The mix composition in this research is displayed in Table 2.

Table 1. Chemical compound of FNS 4 and FA-C (wt%)

Constituent	FNS 4	FA-C
SiO_2	53.6	19.9
CaO	5.2	24.0
Al_2O_3	5.6	12.0
Fe_2O_3	12.7	12.6
MgO	20.9	8.7
TiO_2	-	0.6
MnO_2	0.5	0.2
Na_2O	-	7.5
K_2O	0.1	2.2
P_2O_5	-	0.2
SO_3	0.2	10.3

Heat curing and normal curing

In this investigation, after the normal curing phase at room temperature was achieved for 24 hours, the samples were demolded and placed in the isolated container to start the heat curing phase for 24 hours. The sample was placed on the steel grid about two centimeters above the water bath. The temperature was set at slow speed to reach the maximum temperature at 60 ± 5 °C for 6 hours. This method was selected to circumvent the negative consequences of heat curing, which results in obtaining larger capillary pores when the temperature is raised quickly. In addition, the higher temperature (> 80 °C) used for heat curing might affect the early release of water, which leads to the polymerization process taking place without water, developing in the formation of numerous pores (Rabie et al., 2022).

In the case of normal curing, the samples were demolded after 24 hours, sealed with plastic, and cured at room temperature until the time of testing.

Workability

According to EN 1015-3:1999/A2:2006 (EN-1015-3, 2006), the specimens were tested for their workability using a mini slump flow test and a flow table test in a room at a relative humidity of 65±5% and a temperature of 28 °C.

Mechanical test

The tests for compressive and flexural strength were performed at 7 days and 28 days based on (EN-196-1, 2007). Each measurement was based on the average of three specimens.

Porosity

The purpose of porosity testing is to determine the percentage of pores in mortar geopolymer relative to the volume of solid mortar geopolymer. Testing and calculating porosity values are carried out by immersing the test specimen and vacuuming it at a pressure of 0.5 bar for 24 hours (ASTM 642-13, 2013).

Life cycle assessment and inventory analysis

Geopolymer mortar compositions including fly ash and FNS 4 were evaluated for environmental sustainability using life cycle assessment (LCA), a methodical and quantitative approach. LCA is a four-phase process that includes (1) aim

Figure 1. FA-C (left), FNS 4 (middle) and sand (right)

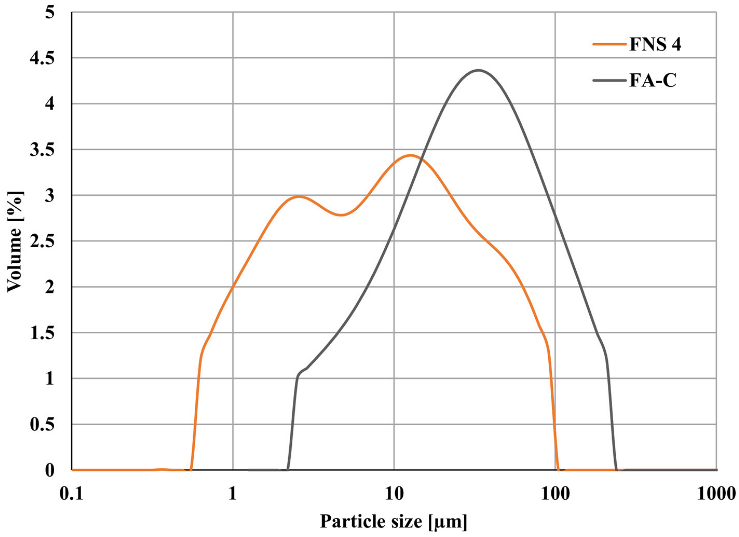


Figure 2. Grain size distribution of FNS 4 and FA-C

Table 2. Mix composition of geopolymer mortar

Constituents	0%	10%	20%
Fly ash	1103.29	992.96	882.631
FNS 4	0.	110.33	220.66
Sand	386.15	386.15	386.15
NaOH 14 M	275.82	275.82	275.82
Na_2SiO_3	551.64	551.64	551.64

and scope definition, (2) inventory collection and analysis, (3) life cycle impact assessment of the product, as well as (4) analysis, interpretation, and discussion (Ren et al., 2017; Zhou et al., 2024). For LCA analysis in this work, OpenLCA, an open-source software tool, was used because of its transparency (codes are available for verification) and appropriateness for validation and benchmarking. In this study, a gate-to-gate variant was chosen. The analysis included resource extraction, production of raw materials, and concrete production (lab scale). Characteristic factors are used to determine the contribution of each material to each impact category indication in the system under analysis.

RESULT AND DISCUSSION

Workability

The workability of fresh geopolymer mortar containing FA-C and FNS 4 is shown in Figure 3. It is evident that when the amounts of FNS 4 in the geopolymer mixture increased, the workability rose. In comparison to the workability of mixture 0%, the addition of 10% FNS 4 to the geopolymer mixture increased the flowability by almost 21%. In the meantime, the workability was increased by about 60% when 20% FNS 4 was added to the mixture. The increase in workability of the geopolymer mixture with FNS 4 might be caused by the physical properties of FNS 4, which is less absorbent of water. This phenomenon is also mentioned by Edwin et al. (Edwin et al., 2025). In addition to the less absorbing water of FNS 4, FA-C contains about 24% of CaO and 12% of Al_2O_3. These two elements are in charge of the reaction rate following their mixing with an alkaline solution. The flowability loss will occur automatically as the mixture becomes viscous due to its rapid hardening. Since the FNS 4 contains less CaO and

Al_2O_3, as seen in Table 1, the substitution of FA-C with FNS 4 will also reduce the CaO and Al_2O_3 content, resulting in an increase the flowability, as shown in Figure 3. Other publications explained the similar impact of CaO content on the workability of geopolymer paste (Zhang et al., 2023). The substitution of ferronickel slag (FNS=1.19 of CaO) with slag (SL= 38.74 of CaO) decreased the workability of geopolymer paste (Zhang et al., 2023). The gel formed more quickly as the CaO content increased because of the strong electrostatic attraction and charge neutralization of calcium ion (Ze-sheng, 2009).

Compressive strength

Figure 4 summarizes the development of compressive strength of FA-C-FNS 4-based geopolymer mortar under normal and heat curing. Incorporating FNS 4 leads to a slight increase in compressive strength of geopolymer mortar at 7 days under normal and heat curing compared to the plain mixture. The compressive strength of 10% FNS 4 and 20% FNS 4 of geopolymer mortar under normal curing increased by about 10% and 8%, respectively, compared to the reference mixture. A similar trend also occurred for the evolution of compressive strength of geopolymer mortar with 10% and 20% FNS 4 under heat curing, which increased about 4% and 5% compared to the reference mixture. It can be seen that the effect of FNS 4 under normal curing in strength development is higher compared to heat curing.

The compressive strength at 28 days of geopolymer mortar made with FA-C-FNS 4 under normal and heat curing is summarized in Figure 4. It is noticed that the strength development of 10% FNS 4 and 20% FNS 4 to the reference mixture increased about 21% and 11%, respectively, as seen in Figure 4. When compared to the plain mixture, the compressive strength of geopolymer mortar with 10% and 20% FNS 4 under heat curing rose by approximately 3% and 1%, respectively.

It is valuable to notice that the Calcium-Aluminate-Silicate-Hydrate gel (CASH gel) is the key to the higher strength development of geopolymer. From Table 1, it can be observed that FNS 4 has higher SiO_2 and lower CaO. These two components are responsible for the formation of CASH gel. The addition of FNS 4 will increase the amount of silica ions and decrease the amount of CaO ions. The replacement of FA-C with FNS 4 up to 20% still contributed to the sufficient amount of CaO ion and SiO_2 ion to react with alkaline solution to generate CASH gel. Therefore, the compressive strength is still higher at the replacement level of 20% FNS 4. This indicates an increase in porosity improvement and increased CASH gel formation. This outcome is consistent with previous research (Bhatt et al., 2019; Edwin et al., 2025; Hui-teng et al., 2021), which found that geopolymer mortar and paste significantly improved the compressive strength after mixing the Si-rich binders (silica fume, GBFS, and FNS 4). The CASH hydration products are created when the aluminosilicate oxides from FNS 4 react with the Ca^{2+} in FA-C and dissolve as Al $(OH)^{4-}$ and $SiO_2(OH)_2^{2-}$ or SiO $(OH)^{3-}$.

The effect of heat curing on the development of compressive strength of mortar seems higher than normal curing at 7 days, as seen in Figure 4. The average improvement of compressive strength after applying heat curing achieved about 17% at early days of curing (7 days), as observed in Figure 4. Meanwhile, the development of the compressive strength of geopolymer mortar showed a similar trend after applying heat curing, which increased

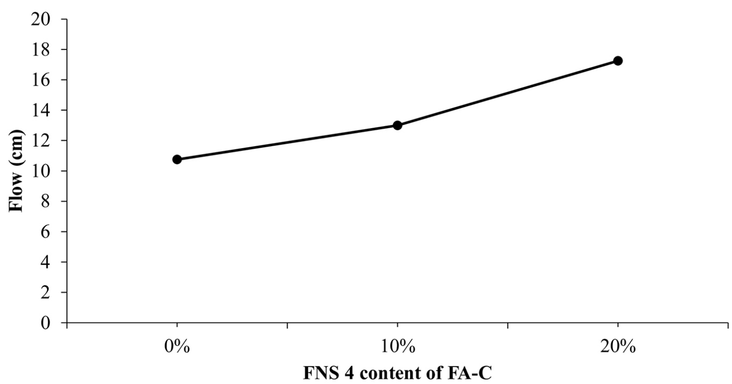


Figure 3. The workability performance of a fresh geopolymer mortar

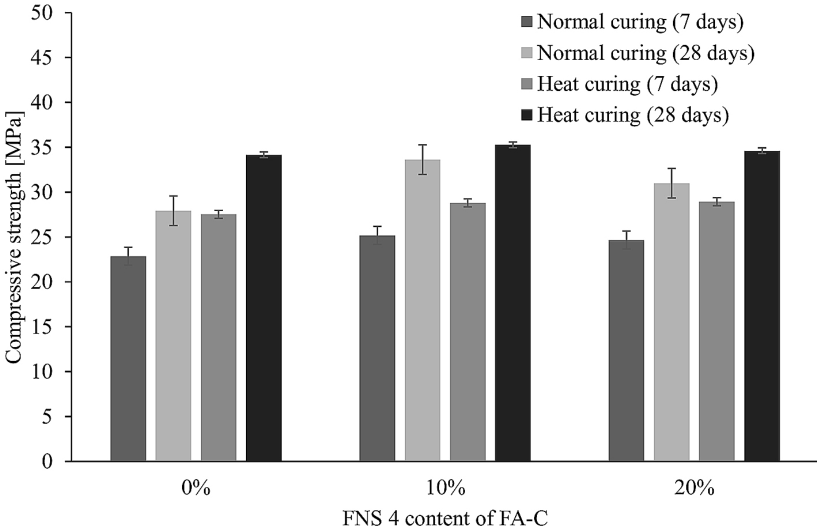


Figure 4. The compressive strength result geopolymer mortar

an average of about 16% in comparison to normal curing, as shown in Figure 4. In addition, there is no adverse effect on the later age strength, which is caused by the relaxation phenomenon due to the heat curing, as mentioned by (Edwin et al., 2017) in their research on reactive powder concrete.

Flexural strength

The flexural strength evolution of geopolymer mortar containing FA-C substituted by FNS 4 is shown in Figure 5. The positive effect is noticed on the flexural strength after FNS 4 substitution for all curing ages under normal and heat curing. Comparing 10% and 20% FNS 4 geopolymer mortar under normal curing conditions at 7 days to the reference mixture, the compressive strengths rose by roughly 21% and 30%, respectively, as seen in Figure 5. The evolution of flexural strength of geopolymer mortar with 10% and 20% FNS 4 under heat curing also showed a similar trend at early curing times (7 days), increasing by about 7% and 21% in comparison to the reference mixture.

Figure 5 summarizes the flexural strength at 28 days of geopolymer mortar prepared with FA-C-FNS 4 under both normal and heat curing conditions. The flexural strength development of 10% and 20% FNS 4 to reference mixtures rose by almost 16% and 23%, respectively. The flexural strength of the geopolymer mortar with 10% and 20% FNS 4 after applying heat curing increased by roughly 18% and 31%, respectively, in comparison to the reference mixture, as seen in Figure 5.

The inclusion of FNS 4 has a beneficial effect on the flexural strength development of FA-C-based geopolymer mortar. FNS 4 supplied SiO_2 to generate CASH gel after reacting with CaO + alkaline solution during the geopolymerization process. One of the weaknesses of FA-C is the higher amount of CaO, which accelerates the hardening of geopolymer material before pouring into the mold due to the large amount of heat release. Indeed, the CaO is still needed in the geopolymerization process in a moderate amount. However, the higher amount of CaO will also create cracks and decrease the flexural strength. The substitution of FNS 4 will solve the problem related to the high heat hydration, numerous cracks, and increased the flexural strength of geopolymer mortar, as mentioned in Figure 5. This conclusion aligns with the findings of (Edwin et al., 2025; Yong-Sing et al., 2021), who discovered that increasing the ratio of ladle furnace slag (Yong-Sing et al., 2021) and FNS 4 (Edwin et al., 2025) to F-type fly ash increased the flexural strength of geopolymer.

In general, applying heat curing at 60 °C for 6 hours gives a positive impact on the development of flexural strength at young ages (7 days) as shown in Figure 5. The average increase in flexural strength following the application of heat curing was approximately 3% at 7 days. However, the negative effect occurred on the flexural strength at longer curing times after applying heat curing due to the material relaxation phenomenon, as observed in Figure 5. Normally, this phenomenon is only temporary, because the strength gain will be obtained at longer curing periods (Al Noman et al.,

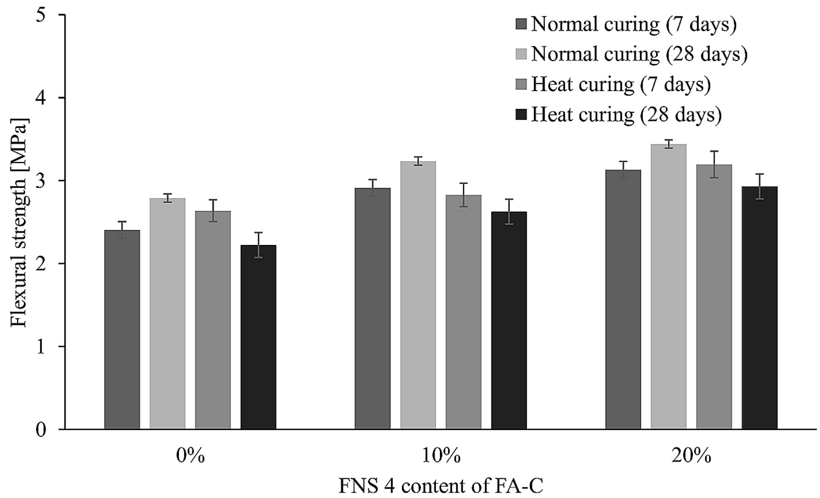


Figure 5. The flexural strength result geopolymer mortar

2025; Nurruddin, 2018; Rabie et al., 2022; Shoaei et al., 2024) and after the end of the relaxation phenomenon, as mentioned by (Edwin et al., 2017).

Microstructure development

The result of the porosity of FA-C-FNS 4-based geopolymer mortar under normal and heat curing is illustrated in Figure 6. It can be observed that the porosity of geopolymer mortar decreased with the increasing proportion of FNS 4. The decrease in porosity is due to the development of microstructure. This is caused by the continued geopolymerization process to generate CASH gel when normal and heat curing. The porosities consisted of macropores, entrained air voids, and capillary pores, as mentioned by (Edwin et al., 2017) in reactive powder concrete. Macropores and air voids have a pore size distribution from 0.50–200 μm, while the pore size distribution of capillary pores is <0.0045 μm. In deep analysis, the CASH gel only filled macropores and air voids in a limited amount during the geopolymerization process. This is the reason for the lowest porosity, only about 26.5% achieved by 20% FNS 4 after heat curing. This result is acceptable for the geopolymer mortar with the compressive strength of nearly 35 MPa, as seen in Figure 6, which was also achieved by Lv et al. (Lv et al., 2024) with the porosity of about 19% using the volumetric method for the compressive strength about 28 MPa.

As it was mentioned above, the formation of CASH gel filled the porosities in the mortar geopolymer matrix. To study this phenomenon, SEM EDX mapping was performed to verify the formation of CASH gel. The image studied was a geopolymer paste containing 10% FNS 4, as seen in

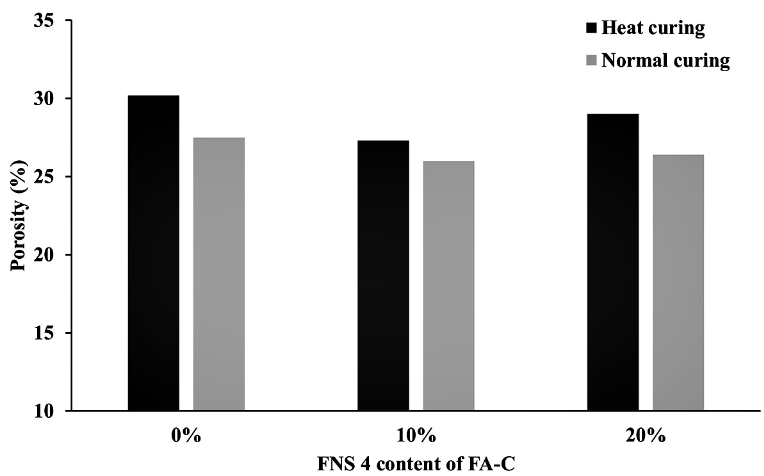


Figure 6. The porosity result geopolymer mortar at 28 days

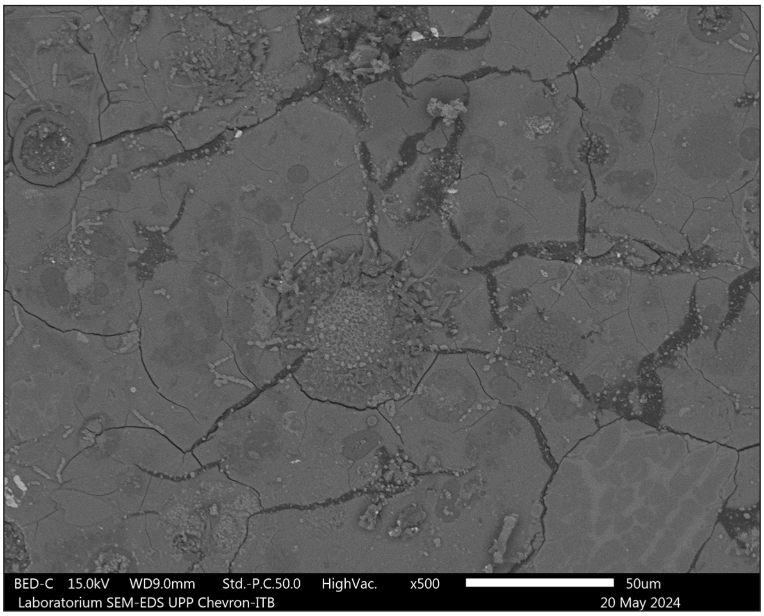
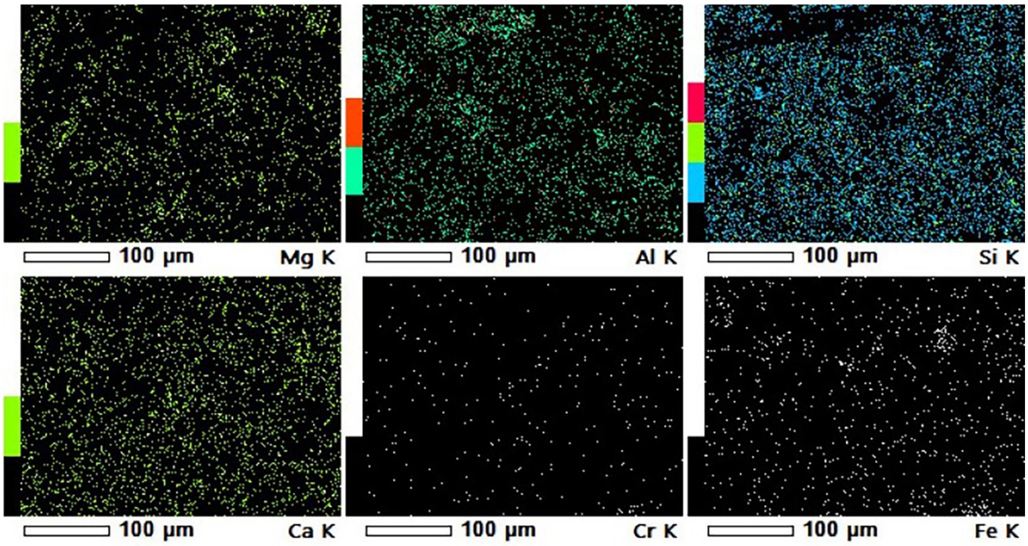


Figure 7. SEM-BSE image of geopolymer paste with 10% FNS 4 at magnification of 500 x

Figure 7. The fine aggregate was excluded to avoid the ITZ region for more accurate results. It can be detected that Si and Ca were in higher amounts, which indicated that the CASH gel is formed in large quantities, as seen in Figure 8. The Si/Al ratio was 1.739 and 1.486, respectively. Previous research indicated that when the Si/Al ratio is greater than 1 and less than 4, high mechanical strength is obtained (Chub-uppakarn et al., 2023). In deep analysis, it can be predicted that the Si/Al ratio will increase in the case of heat curing. Also, the mass of Si and Ca will increase to generate CASH gel as well as fill the macropores and air voids.

Life cycle assessment impact analysis

Table 3 depicts the results of the environmental impact assessment of the FA-C-FNS 4-based geopolymer mortar, showing considerable differences in indicator values between several categories. All the impact categories show that the increase of FNS 4 decreased the environmental impacts, except for ecotoxicity and eutrophication, as shown in Table 3. The highest reduction of environmental impacts is achieved by ozone depletion, which decreased by about 96% for the mixtures with 10% and 20% FNS 4. Another key idea utilized in LCA to assess the environmental impact of building materials is global warming and fossil fuel depletion. In this research, the result of fossil fuel depletion of geopolymer mortar with 10% FNS 4 and 20% FNS 4 were about 1,065.473 and 1,074.306 MJ surplus, which decreased about 16% and 15%, respectively, compared to the geopolymer mortar with 100% FA-C. In the context of global warming, a similar trend is also achieved by the geopolymer mortar with 10% FNS 4 and 20% FNS 4 (568.105 and 572.946 kg CO_2-Eq, respectively), which reduced approximately 21% and 20%, respectively. In this study, the LCA result of conventional cement mortar based on the mix design is also studied and compared with FA-C-FNS 4-based geopolymer mortar. The impact of fossil fuel depletion on conventional cement mortar is lower than that of geopolymer mortar. It seems that the use of portland cement in construction materials still provides a high contribution, especially to acidification, global warming, and smog. In addition, the use of 10% and 20% FNS 4 in geopolymer mortar reduced the acidification, global warming, and smog in comparison to that of conventional cement mortar. The application of geopolymer technology in the building sector signifies a major advancement in ecologically conscious and sustainable methods (Amari et al., 2024). Due to its capacity to integrate by-products, such as FA-C and FNS 4, geopolymers present a strong substitute for traditional portland cement. In addition, the utilization of industrial waste in geopolymers has effectively mitigated environmental degradations evaluated by the LCA method and has emerged as a key objective in waste management to promote sustainability in the construction industry, as also studied by (Dina et al., 2020).



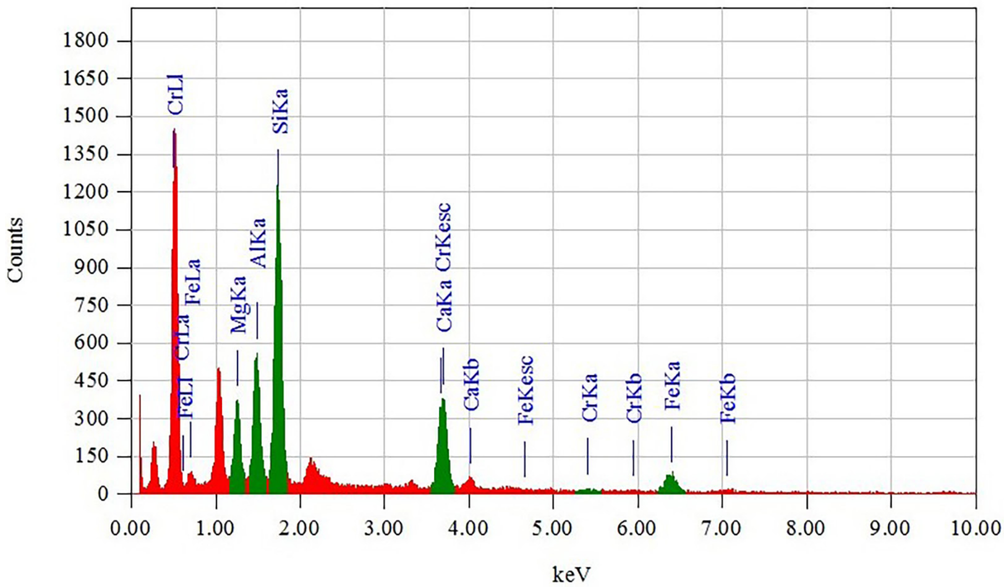


Figure 8. EDS analysis of geopolymer paste containing 10% FNS 4

Table 3. Environmental impacts of geopolymer mortar and conventional cement mortar

Impact category	Unit	Scenarios			
		0% FNS 4	10% FNS 4	20% FNS 4	Mortar
Acidification	kg SO_2-Eq	0.785	0.529	0.543	2.088
Carcinogenics	CTUh	1.170E-06	9.160E-07	9.185E-07	3.660E-07
Ecotoxicity	CTUe	13.941	24.821	37.682	14.558
Eutrophication	Kg N-Eq	0.031	0.053	0.084	0.079
Fossil fuel depletion	MJ surplus	1,265.656	1,065.473	1,074.306	254.399
Global warming	kg CO_2-Eq	716.046	568.105	572.946	788.948
Non carcinogenics	CTUh	1.593E-05	1.442E-06	1.699E-06	2.267E-05
Ozone depletion	kg CFC-11-Eq	3.162E-05	1.026E-06	1.026E-06	4.827E-05
Respiratory effects	kg PM2.5-Eq	0.043	0.028	0.029	0.115
Smog	kg CO_3-Eq	10.370	7.555	7.557	26.224

CONCLUSIONS

This study examined the fresh and mechanical properties of the FA-C-FNS 4-based geopolymer mortar under normal and heat curing. The microstructure evolution and life cycle assessment of geopolymer mortar are also investigated. On the basis of the outcomes of the investigation, the presence of FNS 4 enhanced the workability of fresh geopolymer mortar. FNS 4 has a greater impact on strength development under normal curing than under heat curing of geopolymer mortar. The impact of heat curing on the development of compressive strength of the mortar appears to be greater than that of normal curing at 7 days. Following FNS 4 substitution, the flexural strength of geopolymer mortar improves for all curing ages under heat and normal curing. Applying heat curing causes a negative effect on the flexural strength at 28 days of curing due to the material relaxation phenomenon, even though this phenomenon is only temporary. As the amount of FNS 4 increased, the porosity of the geopolymer mortar decreased. The substitution of FNS 4 for FA-C increased the Si/Al ratio, generating the CASH gel and filling the macropores and air voids of geopolymer mortar. Ozone depletion, which dropped by almost 96% for combinations containing 10% and 20% FNS 4 of geopolymer mortar, had the greatest reduction of environmental effects. Also, the use of FNS 4 in FA-C-based geopolymer mortar decreased fossil fuel depletion and global warming.

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