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Research Article

Heat and fire resistance of geopolymer concrete

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Abstract

Geopolymer concrete, made from aluminosilicate materials like fly ash and an alkaline solution, is an eco-friendlier alternative to Portland cement. While its use is growing, more research is needed to explore its commercial applications, particularly for high-temperature resistance. The effects of high-temperature exposure on geopolymer concrete were evaluated and compared with those of normal concrete. Geopolymer concrete specimens were heat cured at 115°C for 24 hours, followed by storage at room temperature until 28 days of age. In contrast, normal concrete specimens were cured in water at room temperature. Both concrete types were then heated in an iron furnace at 400°C-800°C for 2 hours, after which they were cooled and tested. A visual inspection assessed the concrete for spalling, cracking, and discoloration, while tests measured mass loss and residual compressive strength. Results indicated that both geopolymer and traditional concrete lost compressive strength after burning; however, at 800°C, geopolymer concrete maintained a 10.09% higher residual strength. Geopolymer concrete also showed less weight loss due to lower water content and exhibited no spalling. In summary, geopolymer concrete resists high temperatures better than normal concrete.

1. Introduction

Concrete is the most applied construction material globally because of its favorable mechanical properties, which support the development of rigid, reliable, and durable infrastructure. In 2025, global concrete production reached 4.15 billion tons, and with a constant need to develop infrastructure to serve a growing population, it is projected to grow at around 4% annually [1].

The large-scale production and consumption of concrete pose another significant environmental issue, with concrete production accounting for 5–8% of global emissions [2-3]. Considering this, innovation in more environmentally friendly concrete varieties, such as geopolymer concrete, is very much needed [4]. This analysis aims to evaluate the heat resistance of geopolymer concrete and determine how it could be implemented across various types of infrastructure.

The term "geopolymer material" is no longer uncommon in scholars' research topics and experiments. Geopolymer concrete has been gaining a lot of attention in recent years due to its unique properties, beneficial aspects, and its ability to address emissions in the construction industry. Research also indicates that an FA or fly-ash-based geopolymer concrete beam has similar properties to a regular reinforced concrete beam used in construction [5]. This concrete has been a hot topic since 2016, even though it hasn't been internationally recognized for its cost-effectiveness and production efficiency [2].

Geopolymer concrete is a concrete mixture composed of aluminosilicate materials such as fly ash (FA), metakaolin (MK), slag (SG), rice husk ash (RHA), etc. Geopolymer concrete works by

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polymerizing the aluminosilicate materials with an alkaline base solution that reacts quickly with each other to promote the reaction between silica (Si) and alumina (Al) under alkaline conditions [2]. This reaction forms strong, three-dimensional polymeric chains (Si-O-Al-O) that result from the polycondensation of silica, alumina, and high alkali content [2]. This polycondensation will then contribute to the concrete's compressive strength. Materials categorized as geopolymers are usually amorphous rather than crystalline, making them easier to polymerize than other zeolitic materials [6].

Depending on the types of aluminosilicate materials used, the concrete's result and strength can vary. While MK-based geopolymer boasts the most persistent properties, it requires a lot of water, leading to flow issues. Fly ash-based geopolymer offers superior durability, and slag-based geopolymer shines with its rapid initial strength and strong acid resistance [7]. In addition to the materials used, the activator ratio also affects the concrete. For example, an activator such as Na_2SiO_3/NaOH at a 3:1 ratio can significantly improve the compressive strength of fly ash-based geopolymer concrete [8].

Since its initial discovery decades ago, numerous studies and advancements have been conducted to enhance the mechanical, physical, and chemical properties of geopolymer concrete. Laboratory findings suggest that geopolymer concrete samples can match or even surpass the properties of ordinary Portland cement concrete (OPC) [9-10].

Geopolymer concrete also offers sustainability advantages, with a significant portion of the admixture materials listed above, often being waste products used as partial replacements for cement in the mix design [10]. Hence, geopolymer concrete leads to lower CO_2 emissions than ordinary concrete, with OPC production contributing 9% more emissions. [11]. The superior sustainability of geopolymer concrete is well-suited to the concept of green buildings and to the principles of environmental responsibility and resource efficiency [12].

Fires are frequent disasters. The Director General of Regional Administration at the Ministry of Home Affairs revealed that there were 17,768 fire cases in Indonesia. The most common cause is a short circuit in the electrical system. Based on the ISO 834 curve in EN 1991-1.2, the temperature can reach 600°C during the first 5 minutes of fire. Therefore, structural materials with high-temperature resistance are important [13].

The inorganic structure of geopolymer concrete offers advantages such as non-toxicity, chemical resistance, and, notably, fire resistance [14]. Geopolymer concrete has been shown to withstand loading even after 2 hours of hydrocarbon fire exposure and to exhibit better shrinkage and spalling performance than Portland cement concrete [15-17]. This suggests that geopolymer concrete has strong potential as a high-temperature-resistant construction material.

A study investigated the heat resistance of geopolymer concrete exposed to a hydrocarbon fire for 120 minutes, in accordance with Australian standards [15]. The geopolymer concrete binder consisted of Gladstone fly ash activated with an alkaline solution of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The activator-to-fly ash ratio was 0.4, and the alkaline solution had a sodium silicate-to-sodium hydroxide ratio of 2.5. Two-cylinder sizes (150 mm and 100 mm diameter, 300 mm and 200 mm height) and panels (1075 mm x 1075 mm x 200 mm) were tested. The cylinder specimens were exposed to the fire on all sides, while the panels were exposed on one side. The geopolymer panels exhibited lower thermal diffusivity compared to ordinary Portland cement (OPC) concrete with a maximum aggregate diameter of 14 mm. Due to this lower diffusivity, geopolymer concrete panels offer superior heat resistance. The reduced ability for heat to permeate the material translates to a higher heat storage capacity, making geopolymer concrete less prone to spalling during hydrocarbon fires.

Due to the abovementioned properties of geopolymer concrete, it has many potential applications across various infrastructure sectors. Firstly, geopolymer concrete has been used in the construction of multiple-story buildings, with the first fully geopolymer concrete-based residential building being built in 1989 in Russia [10]. Geopolymer concrete is also advantageous for the production of precast concrete elements due to the controlled conditions required during the manufacturing process [10].

Table 1. Previous studies have examined how geopolymer concrete performs when exposed to high temperatures

References	Temperature	Note
Heikal et al. [18]	Room temperature, 200, 400, 600, 800°C	• The specimens are composed of normal concrete with fly ash as incorporated as a partial substitution. • The specimens were cured by water immersion and subsequently by oven drying at 105°C for 24 hours before the thermal treatment. • The heating rate was 3°C/min. At the target temperature, specimens were held for 3 hours. • At 400°C, the compressive strength increased by approximately 33%, whereas at 600–800°C, it decreased by approximately 9% (residual strength of about 91%).
Park et al. [19]	20, 200, 400, 600, 800°C	• The specimens were cured at room temperature for 28 days. • The heating rate was 10°C/min, and after reaching the target temperature, the specimens were maintained at that temperature for 2 hours. • When heated, the compressive strength increased and only began to decrease at 800°C.
Luhar et al. [20]	Room temperature, 200, 400, 600, 800°C	• The specimens were cured in an oven at 90°C for 48 hours. • The heating rate was 4.4°C/min, and after reaching the target temperature, the specimens were maintained at that temperature for 2 hours. • A decrease in compressive strength was observed from the initial temperature.
Tayeh et al. [21]	Room temperature, 100, 200, 300, 400, 500, 600, 700, 800°C	• The specimens were cured in an oven at 80°C for 24 hours. • The specimens were maintained at the target temperature for 2 hours. • When heated, the compressive strength increased at 100°C and decreased at 200-800°C.
Razak et al. [22]	25, 500, and 1200°C.	• The Ordinary Portland Cement specimens were cured at room temperature for 28 days. • The geopolymer concrete specimens were heated in an oven at 60°C for 24 hours. • The specimens were maintained at the target temperature for 2 hours. • The compressive strength of OPC specimens is decreased when heated. • When heated, the compressive strength of geopolymer concrete specimens is increased at 500°C and decreased at 1200°C.

An overview of studies and analyses on the heat resistance of geopolymer concrete concluded that overall performance at high temperatures is quite favorable compared to OPC, hence the plentiful

prospects of this type of concrete [9]. However, upon closer examination, studies on this topic exhibit considerable diversity in the variables considered, with significant variance in admixture components across studies. Previous studies on the performance of geopolymer concrete at elevated temperature is shown in Table 1 and will be compared with the result of this study. This variance has a substantial impact on heat resistance, as previously discussed. This presents a challenge when comparing results across different studies, which is why more studies and analyses are needed on this topic, particularly those that build on previous findings.

Previous research has found that geopolymer concrete is a suitable material for use as a structural component in infrastructure. One experimental study looked at the mechanical properties of low-aluminum, iron-rich, calcium fly ash-based geopolymer concrete and evaluated its compressive strength and moment capacity, comparing these results to those of OPC concrete. The study found that geopolymer concrete can match or even outperform regular Portland cement-based concrete in some areas, such as ultimate moment capacity [23].

Therefore, this study aims to examine the behavior of geopolymer concrete behaves when exposed to high temperatures and to compare its performance with normal concrete. The research specifically evaluates visual deterioration, mass loss, and residual compressive strength after exposure to temperatures ranging from 400°C to 800°C. Through this investigation, the study seeks to provide further insight into the potential application of geopolymer concrete in structures subjected to high-temperature conditions such as fire.

2. Research Significance

This analysis aims to investigate the effects of high temperature and fire exposure on the compressive strength of fly ash-based geopolymer concrete and Portland cement-based concrete (normal concrete). This analysis differs from previous analyses by Park et al. [19] and Razak et al. [22]. The curing method is conducted at elevated temperatures rather than the more common approach of curing at room temperature, as used for geopolymer concrete. Hence, the findings of this study will provide further insight and knowledge within this field of research, aiding future studies and the real-world application of geopolymer concrete.

3. Methodology

3.1. Limitations of the Study

This study has several limitations that should be considered when interpreting the results. The geopolymer concrete was produced using Class F fly ash obtained from a specific coal-fired power plant in Malang; therefore, the findings may not be directly generalizable to geopolymer systems with different source materials or chemical compositions. In addition, the specimens used in this study were limited to cylindrical samples with a diameter of 10 cm and a height of 20 cm, which may not fully represent the behavior of larger structural elements under fire exposure.

The curing method applied in this study also represents a specific condition, as geopolymer concrete specimens were heat-cured at 115°C to achieve higher compressive strength, whereas other studies commonly adopt ambient curing. This difference in curing regime may influence the material's microstructure and thermal response. Furthermore, the burning process was conducted through direct flame exposure rather than standard furnace heating curves, which may differ from real fire scenarios or standardized fire testing conditions.

The heating protocol was limited to temperatures ranging from 400°C to 800°C in 100°C increments, with a constant heating rate of 15°C/min and a fixed exposure duration of 2 hours. While this approach allows for controlled comparison, it does not fully capture the variability of actual fire events. Finally, the evaluation of material performance was limited to compressive strength, mass loss, and microstructural observation using scanning electron microscopy (SEM), without considering other mechanical or durability properties. Therefore, further studies are recommended to explore different material sources, curing conditions, fire exposure scenarios, and additional performance parameters.

3.2. Procedure

The analysis methodology can be broken down into five stages.

- Stage 1 involves preparation of materials and equipment, ensuring everything necessary for the research is readily available.
- Stage 2, material suitability is assessed through tests like determining the specific gravity of aggregates with ASTM C 127 [24].
- Stage 3 focuses on specimen casting. Here, 45 normal concrete and 45 geopolymer concrete specimens are cast in Ø100 mm × 200 mm cylindrical molds. The planned strength for normal concrete is 30 MPa, while the geopolymer concrete utilizes a 12 M NaOH alkaline solution. Curing then followed, with geopolymer concrete cured in an oven at 115°C for 24 hours and normal concrete cured by immersion for 7 days.
- Stage 4 deals with specimen testing. This includes a compressive strength test on day 7, followed by another on day 28 (without burning the sample). A burning test is then performed on a separate sample on day 28, and finally, a Scanning Electron Microscope (SEM) test is conducted.
- Stage 5 is dedicated to analyzing, discussing, and drawing conclusions from the gathered test results. This final stage ties together all the research findings.

3.3. Materials

The geopolymer concrete mix design comprises coarse aggregate, fine aggregate, water, and Portland Composite Cement (PCC), in accordance with the provisions of SNI 7657:2012. Here, the geopolymer concrete mix design uses coarse aggregate, fine aggregate, fly ash, and alkaline solution. The aggregates used in both varieties are the same to ensure a consistent and accurate comparative analysis. The maximum sizes for coarse and fine aggregates were 25 mm and 0.6 mm, respectively, and both were used under Saturated Surface Dry (SSD) conditions. Semen Tiga Roda was used as the PCC cement in accordance with SNI 7064:2012. The fly ash was sourced from Malang and classified as F per ASTM C 618 [25].

The alkaline solution used is composed of NaOH and Na_2SiO_3 (water glass) mixed in a 1:3 ratio. The NaOH solution used has a molarity of 12 M, in line with the calculations done within Perry's Handbook for Chemical Engineers, 8th Edition. The water glass solution was obtained from PT. Ajidharmamas Tritunggal Sakti. All materials in the mix design underwent preliminary testing, as highlighted in the steps of stage 2 of the diagram above.

(a) (b)

Fig. 1. Alkaline solution consisting of (a) NaOH crystals and (b) NaOH solution

3.4. Equipment

The testing process involved various pieces of equipment at each stage. For material testing (Stage 2), scales, a 500mL measuring cup, and sieves (with a sieving machine) were used. Stage 3 involved formwork (or cylinder molds), oil for releasing the molds, a concrete mixer for large batches, and Abram's cone to test the aggregate. An oven was used for curing geopolymer specimens. Stage 4

relied on a concrete compression tester to measure strength and a shake table for additional testing. Specialized equipment used for the burning test includes an iron furnace with a thermocouple for temperature control.

3.5. Concrete Specimens

This study analyses both normal and geopolymer concrete specimens to serve as a basis for comparison and to provide a control for evaluating the behavior of the geopolymer variety. The mix design of the normal concrete samples is highlighted in the table below with a target compressive strength of 30 MPa and a slump of 75-100 mm. The mix design for the geopolymer concrete specimens is highlighted in the table below and was calculated following the findings of an analysis by Prinya Chindaprasirt et al. [26].

Table 2. Mix design for normal concrete

Material	Percentage by Weight (%)
Coarse Aggregate	44.80
Fine Aggregate	23.68
Cement	23.32
Water	8.20

Table 3. Mix design for geopolymer concrete

Material	Percentage by Weight (%)
Coarse Aggregate	35
Fine Aggregate	30
Fly ash	23
Na_2SiO_3 (Water glass)	9

The steps of creation for both sets of concrete specimens include material and equipment preparation, mixing the admixture components of the mix design in a concrete mixer, casting specimens, removing specimens from cylinder moulds, and finally, the specimens are left to cure before the main testing stage. The curing conditions for each concrete specimen type differed. Normal concrete samples were cured by immersion in water at room temperature for 7 days, whereas geopolymer concrete samples were cured in an oven at 115°C for 24 hours. After the initial curing stage, all specimens were stored at room temperature until 28 days, then subjected to the burning test.

(a) (b)

Fig. 2. Casting of (a) normal concrete and (b) geopolymer concrete specimens

(a) (b)

Fig. 3. Unmolded (a) normal concrete and (b) geopolymer concrete specimens

A curing temperature of 115°C was used to ensure sufficient geopolymerization of the fly ash-based binder prior to high-temperature exposure. Elevated heat curing is commonly used in geopolymer concrete to accelerate the dissolution of aluminosilicate materials and promote the formation of a dense geopolymer matrix [27]. Previous studies have shown that curing temperatures above 90°C can further enhance the reaction rate and strength development of fly ash-based geopolymers [28-29]. Therefore, a curing temperature of 115°C was applied in this study to ensure that the geopolymer matrix was fully developed before the fire exposure tests.

Fig. 4. Curing process of specimens: (a) Submerged curing for normal concrete and (b) heated curing for geopolymer concrete specimens

3.6. Testing of Specimen

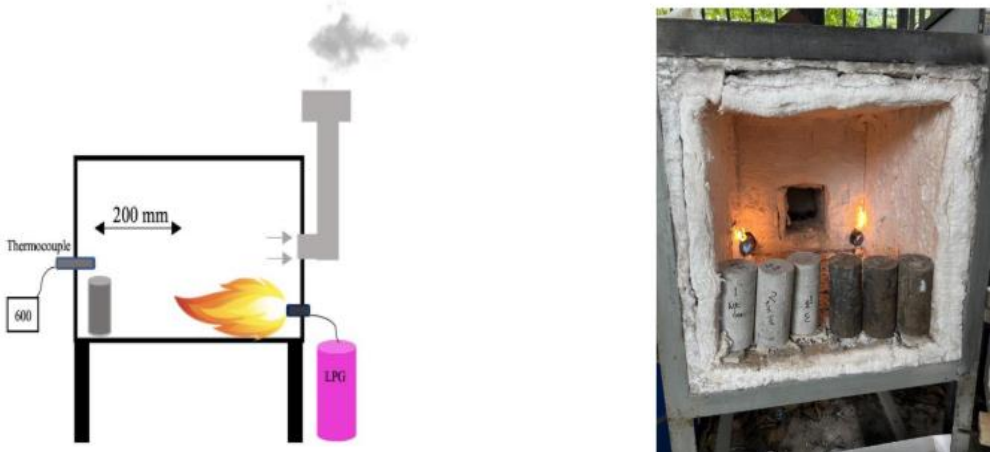
The burning test involves placing the concrete specimens in an iron furnace. The temperature inside the furnace will rise at a controlled rate of 15°C per minute. The heating rate was controlled at 15°C per min to ensure a gradual temperature increase and to avoid thermal shock in the concrete specimens. A controlled heating rate helps reduce excessive thermal gradients between the specimen's surface and core, which may otherwise induce internal stresses and premature cracking. In addition, maintaining a constant heating rate ensures that all specimens experience the same thermal history, allowing the effect of the target temperature to be evaluated consistently.

The specimens were placed at the center of the closed furnace chamber to ensure uniform heat exposure. Adequate spacing was maintained between specimens to allow uniform heat circulation. The specimens remained stationary during the heating process and were not rotated or repositioned during exposure.

Once the target temperatures of 400, 500, 600, 700, and 800°C are reached, the specimens will be held at each temperature for approximately 2 hours. After the heating period, the specimens were allowed to cool naturally in the furnace until room temperature was reached, after which further

testing was performed. The distance between the specimen and the heat source was maintained at approximately 20 cm, following the experimental setup used by Razak et al. [22].

Temperature levels of 400°C to 800°C, in 100°C increments, were selected to evaluate the progressive degradation of concrete under elevated temperatures. Previous studies on conventional concrete commonly used similar temperature ranges, allowing comparison between geopolymer concrete and ordinary Portland cement concrete under high-temperature exposure [30]. The selected temperature range also represents critical stages of thermal damage in concrete, including dehydration of hydration products (100-300°C), development of microcracking (400-600°C), and significant deterioration of the internal matrix (600-800°C) [27-28]. The 100°C increment provides sufficient resolution to observe the degradation trend and identify potential critical temperatures where significant reductions in mechanical properties occur.



(a) (b)

Fig. 5. Burning test: (a) experimental setup of the furnace used for high-temperature exposure of concrete specimens and (b) the burning test of the specimens

(a) (b)

Fig. 6. Compressive strength test: (a) cured and heated concrete prior to testing and (b) specimens testing using a universal compression testing machine

The heating protocol used in this study differs from standard fire testing methods such as ISO 834 or ASTM E119, which follow predefined temperature–time curves. In this study, a constant heating rate with direct flame exposure was adopted, following approaches reported in previous experimental studies. This method was selected to simulate more severe and localized heating conditions, representing a conservative scenario for evaluating the high-temperature performance of concrete. Heat and fire resistance are evaluated based on compressive strength, with specimens that have undergone heating and firing under controlled conditions tested in accordance with the standards highlighted in SNI 1974:2011. Specimens are first weighed and then heated. Molten

sulfur is used to create a smooth surface on the specimen, ensuring accurate results. The specimens are then placed into a Concrete Compression Tester to obtain results on the concrete's compressive strength. To analyze the effects of burning at a microscopic level, each specimen will be subjected to Scanning Electron Microscopy (SEM). This technique provides high-resolution images of the concrete's microstructure by scanning the surface with focused electron beams [33], revealing how the burning process has altered it. This information is crucial for understanding the concrete's behavior under heat application, improving the accuracy of the overall results and analysis, and as a means of investigating the mineral composition of the concrete.

4. Results and Discussion

The concrete and geopolymer concrete are subjected to each test, with three specimens of each type of concrete used in each test. The tests include a preliminary test (an early test to determine specimen suitability), a burning test, a compressive strength test, and an SEM test. The results of the various tests conducted on the specimens are presented in the following paragraphs.

4.1. Preliminary Test Results

The results of preliminary testing of the base materials of coarse aggregate, fine aggregate, and fly ash are shown in the following sections.

4.1.1. Specific Gravity and Absorption of Aggregate

Specific Gravity testing was done on both coarse (based on ASTM C 127) and fine aggregates (based on ASTM C 128) to calculate the mix design for the concrete samples. The specific gravity in these tests was measured at the Saturated Surface Dry (SSD) condition; hence, absorption tests were also conducted to determine the amount of water to be added to the respective aggregate materials to reach that condition. Below are the results of the specific gravity and absorption tests on both coarse and fine aggregates.

The test results show that the coarse aggregate used has a bulk specific gravity of 2320 kg/m^3, a bulk specific gravity in SSD condition of 2390 kg/m^3 and a percentage absorption of 3.07% of the aggregate weight. The test results show that the fine aggregate used has a bulk specific gravity of 2,230 kg/m^3, a bulk specific gravity in SSD condition of 2,320 kg/m^3, and a percentage absorption of 3.84% by weight.

Table 4. Specific gravity and absorption test results for coarse aggregate

No	Parameter	Test				Unit
		I	II	III		
1	Container Weight	164.2	134.5	198.2	-	gr
2	Container + Dry Aggregate Weight	2173.5	2163.2	2208.3	-	gr
3	Dry Aggregate Weight	2009.3	2028.7	2010.1	-	gr
4	Container + (SSD) Aggregate Weight	2244.9	2217.6	2268.4	--	gr
5	(SSD) Aggregate Weight	2080.7	2083.1	2070.2	-	gr
6	(Submerged Aggregate Weight	1208.3	1208.3	1208.2	-	gr
					Avg	-
7	Bulk Specific Gravity	2.30	2.32	2.33	2.32	gr/ cm^3
8	Bulk Specific Gravity (SSD)	2.39	2.38	2.40	2.39	gr/ cm^3
9	Apparent Specific Gravity	2.51	2.47	2.51	2.50	gr/ cm^3
10	Absorption	3.55	2.68	2.99	3.07	%

Table 5. Specific gravity and absorption test results for fine aggregate

No	Parameter	Test				Unit
		I	II	III		
1	Container Weight	82.8	72.3	97.4	-	gr
2	Container + Dry Aggregate Weight	564	555.8	577.3	-	gr
3	Dry Aggregate Weight	481.2	483.5	479.9	-	gr
4	(SSD) Aggregate Weight	500	500	500	--	gr
5	Measuring Cylinder Weight	905.8	894.2	903.5	-	gr
6	Measuring Cylinder + Aggregate + Water	1185.6	1182.3	1187.5	-	gr
					Avg	-
7	Bulk Specific Gravity	2.19	2.28	2.22	2.23	gr/ cm^3
8	Bulk Specific Gravity (SSD)	2.27	2.36	2.31	2.32	gr/ cm^3
9	Apparent Specific Gravity	2.39	2.47	2.45	2.44	gr/ cm^3
10	Absorption	3.91	3.41	4.19	3.84	%

4.1.2. Sieve Analysis for Coarse and Fine Aggregates

Sieve analyses were performed on both coarse and fine aggregates (based on ASTM C 136) to assess the gradation of particle sizes relative to the respective base materials. The tables below show the results for the sieve analyses.

Table 6. Sieve analysis results for coarse aggregate

Sieve No.	Sieve Size (mm)	Average Weight Captured from 3 Repetitions (gr)	% Captured	% Cumulative	
				Captured	Passed
1 1/2"	37.5	0.000	0	0	100
1"	25	4.100	0.4	0.4	99.6
3/4"	19	549.933	54.29	54.7	45.30
1/2"	12.5	419.000	41.37	96.07	3.93
3/8"	9.5	39.300	3.88	99.95	0.05
4	4.75	0.000	0	99.95	0.05
8	2.36	0.000	0	99.95	0.05
Pan	-	0.533	0.05	100.0	0
Total		1012.9	100		

Table 7. Sieve analysis results for fine aggregate

Sieve No.	Sieve Size (mm)	Average Weight Captured from 3 Repetitions (gr)	% Captured	% Cumulative	
				Captured	Passed
3/8"	9.5	1.433	0.14	0.14	99.86
4	4.75	2.833	0.28	0.42	99.58
8	2.36	38.333	3.81	4.23	95.77
16	1.18	99.700	9.90	14.13	85.87
30	0.5	313.700	31.16	45.29	54.71
50	0.3	311.600	30.95	76.25	23.75
200	0.15	237.100	23.55	99.80	0.20
Pan	-	2.033	0.20	100.0	0
Total		1006.7	100		

4.1.3. Water Content Analysis for Fine Aggregate

The water content of the fine aggregate was evaluated to determine the additional water required to achieve the SSD condition. The measured water content 0.143%.

Table 8. Water content analysis results for fine aggregate

No	Parameter	Test			Avg.	Unit
		I	II	III		
1	Container Weight	67.5	72.0	59.4	-	gr
2	Container + Aggregate Weight	588.9	581.1	570.4	-	gr
3	Weight of Aggregate before oven drying	521.4	509.1	511.0	-	gr
4	Container + Dry Aggregate Weight	588.2	580.2	569.8	--	gr
5	Dry Aggregate Weight	520.7	508.2	510.4	-	gr
6	Water Content	0.134	0.177	0.117	0,143	%

4.1.4. Sludge Content Analysis for Fine Aggregate

The sludge content in this analysis is evaluated using volume and weight methods, ensuring it does not exceed 5%. The sludge content was found to be 1.985% by volume and 1.330% by weight.

Table 9. Sludge content analysis results (volume method)

No	Parameter	Test			Avg.	Unit
		I	II	III		
1	Aggregate + Sludge Volume	256	255	245	-	gr
2	Aggregate Volume	251	250	240	-	gr
3	Sludge Content	1.953	1.961	2.041	1.985	%

Table 10. Sludge Content Analysis Results (Weight Method)

No	Parameter	Test			Avg.	Unit
		I	II	III		
1	Container Weight	67.5	72	59.4	-	gr
2	Container + Aggregate + Sludge Weight	588.2	580.2	569.8	-	gr
3	Aggregate + Sludge Weight	520.7	508.2	510.4	-	gr
4	Container + Dry Aggregate Weight	579.9	575.1	562.7	--	gr
5	Dry Aggregate Weight	512.4	503.1	503.3	-	gr
6	Sludge Content	1.594	1.004	1.391	1.330	%

4.1.5. X-Ray Fluorescence Analysis of Fly Ash

X-Ray Fluorescence (XRF) analysis was conducted on the fly ash incorporated in the geopolymer mix design, resulting in the chemical composition breakdown shown in the table below. The above results show that fly ash can be classified as C by ASTM.

Table 11. Chemical composition in percentage of fly ash

No	Compound	Percentage (%)
i.	SiO_2	49.48
ii.	Al_2SiO_3	16.46
iii.	CaO	13.13
iv.	Fe_2O_3	9.22
v.	MgO	5.52
vi.	Na_2O	4.54
vii.	K_2O	1.71
viii.	TiO_2	0.80
ix.	P_2O_5	0.42

4.2 Burning Test Result

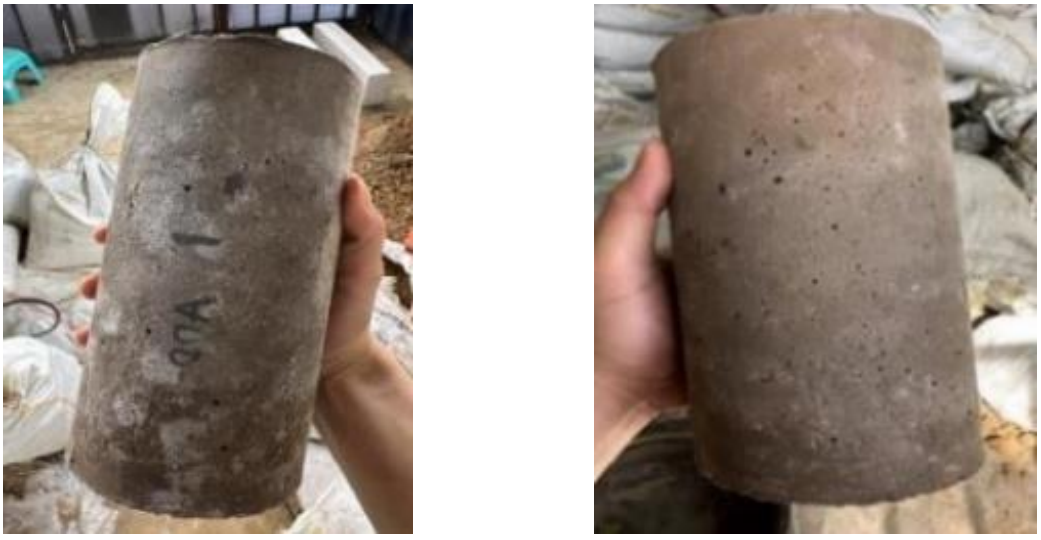
The burning test results are divided into two groups, each yielding a different type of data. Those two test results are the physical properties of the concrete, such as colour and physical differences of the specimens. The second test result will be the different in weight of the concrete before and after burning.

4.2.1. Color and Physical Differences in Samples

The results in this section will be analyzed based on the physical differences between normal and geopolymer concrete before and after the burning process. The analysis data is based on scientific observations of the physical properties of each concrete after burning at 400, 500, 600, 700, and 800°C. Below are figures of the resulting specimen before and after burning.

(a) (b)

Fig. 7. Physical condition of normal concrete specimens before and after exposure to 400°C: (a) before burning, bright gray in color; (b) after burning, showing no significant color change and fine surface cracks



(a) (b)

Fig. 8. Physical condition of geopolymer concrete specimens before and after exposure to 400°C: (a) before burning, dark gray in color; (b) after burning, showing no significant color change and fewer visible cracks

(a) (b)

Fig. 9. Physical condition of normal concrete specimens before and after exposure to 500°C: (a) before burning, bright gray in color; (b) after burning, showing no significant color change, with localized yellowish spots, fine cracking, and spalling

(a) (b)

Fig. 10. The figures show the physical condition of geopolymer concrete specimens prior to and after exposure to 500°C: (a) before burning, dark gray in color; (b) after burning, showing a slight orange hue, fine cracking, and no evidence of spalling

At 400°C, both normal concrete (Fig. 7) and geopolymer concrete (Fig. 8) exhibited no significant color change after burning. Fine surface cracking was observed in both materials; however, the geopolymer concrete exhibited less extensive cracking than normal concrete, indicating greater resistance to thermal exposure.

At 500°C, yellow spots were observed on some parts of the surface of the normal concrete (Fig. 9), while the geopolymer concrete (Fig. 10) changed colour to orange and grey. Both normal and geopolymer concrete developed fine cracks, but the geopolymer concrete had fewer cracks than the normal concrete. Only the normal concrete showed spalling.

At 600°C, some parts of the surface of normal concrete (Fig. 11) exhibited yellow-grey spots, whereas geopolymer concrete (Fig. 12) exhibited a colour change to orange, grey with additional red accents in some areas. Geopolymer concrete exhibited greater cracking with larger fibre sizes than normal concrete. Another phenomenon observed only in geopolymer concrete was expansion. However, geopolymer concrete did not undergo spalling as normal concrete did.

At 700°C, the color changes in both normal (Fig. 13) and geopolymer concrete (Fig. 14) were similar to those observed at 600°C. Normal concrete exhibited cracking and spalling at a higher fiber density than at 600°C. Geopolymer concrete also exhibited cracking of a similar size to that at 600°C, but with a higher fiber concentration. Additionally, geopolymer concrete experienced more severe cracking and exhibited swelling, while no spalling was observed.

(a) (b)

Fig. 11. Physical condition of normal concrete specimens before and after exposure to 600°C: (a) before burning, bright gray in color; (b) after burning, showing no significant color change, with increased localized yellowish spots, longer cracks, and spalling

(a) (b)

Fig. 12. The figures show the physical condition of geopolymer concrete specimens prior to and after exposure to 600°C: (a) before burning, dark gray in color; (b) after burning, showing a gray-orange color with reddish accents in some areas, more extensive cracking, no evidence of spalling, and noticeable expansion

(a) (b)

Fig. 13. Physical condition of normal concrete specimens before and after exposure to 700°C: (a) before burning, bright gray in color; (b) after burning, showing no significant color change, with increased localized yellowish spots, longer cracks, and spalling

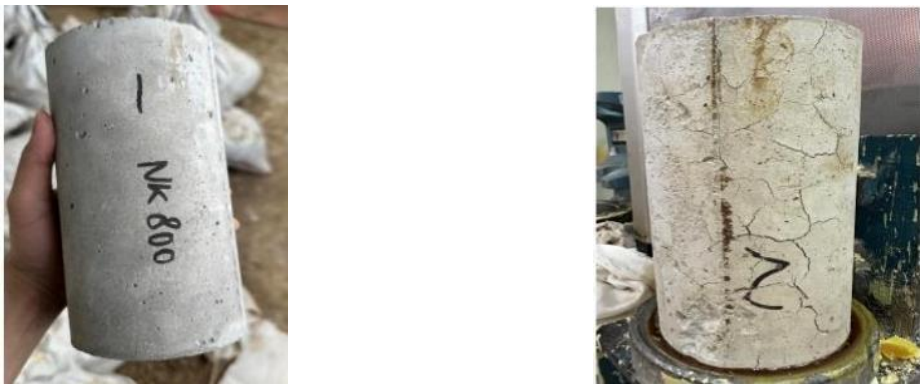
The result shows that normal concrete (Fig. 15) changed color to yellowish-white, while geopolymer concrete (Fig. 16) turned brownish at 800°C. Normal concrete experienced more cracking and spalling than at 700°C. In geopolymer concrete, numerous cracking fibers were observed, and the concrete swelled, but no spalling was observed.

The results indicated that normal concrete exhibited no significant color change at any tested temperature, with only isolated yellow spots observed on certain areas of the surface. Meanwhile, geopolymer concrete displayed a brown coloration. Normal concrete experienced cracking, with crack width increasing with temperature; however, the cracks in geopolymer concrete appeared

wider and more numerous. Geopolymer concrete experienced severe cracking, the severity of which increased with increasing burning temperature.

(a) (b)

Fig. 14. Physical condition of geopolymer concrete specimens before and after exposure to 700°C: (a) before burning, dark gray in color; (b) after burning, showing a brownish-gray color with reddish accents in some areas, more extensive cracking, no evidence of spalling, and noticeable expansion



(a) (b)

Fig. 15. Physical condition of normal concrete specimens before and after exposure to 800°C: (a) before burning, bright gray in color; (b) after burning, showing a yellowish-gray color, longer cracks, and increased spalling

(a) (b)

Fig. 16. Physical condition of geopolymer concrete specimens before and after exposure to 800°C: (a) before burning, dark gray in color; (b) after burning, showing a brownish-red color, more extensive cracking, no evidence of spalling, and noticeable expansion

It was observed that spalling was found in normal concrete starting at 500°C and increased with increasing burning temperature. In contrast, no spalling was found in geopolymer concrete up to 800°C. However, geopolymer concrete experienced both lateral and longitudinal deformation, or swelling.

Spalling in normal concrete occurs because steam trapped within its pores builds up pressure. Conversely, geopolymer concrete has a more complex pore structure, including nanopores, which reduce internal pore pressure and prevent spalling—cracking in concrete—resulting from the differing thermal expansion coefficients of the aggregate and the binder, which weaken the bond and lead to deformation. The color change in geopolymer concrete is caused by oxidation of the fly ash component [34].

4.2.2. Weight Comparisons Before and After Burning

The result of this test will be a comparison of the weight of the concrete specimen before and after burning. The tables below will show the results.

Table 12. Comparison of specimen weight before and after high-temperature exposure for normal concrete at temperatures ranging from 400°C to 800°C

Normal concrete weight comparison			
Temperature	Average Weight (kg)		Reduction (%)
	Before	After	
400	3.4	3.01	11.66
500	3.44	3.02	12.22
600	3.46	3.04	12.13
700	3.66	3.21	12.39
800	3.64	3.16	13.28
Average Reduction			12.33

Table 13. Comparison of specimen weight before and after high-temperature exposure for geopolymer concrete at temperatures ranging from 400°C to 800°C

Geopolymer concrete weight comparison			
Temperature	Average Weight (kg)		Reduction (%)
	Before	After	
400	3.61	3.42	5.26
500	3.54	3.36	5.18
600	3.43	3.24	5.54
700	3.58	3.36	6.05
800	3.61	3.35	7.20
Average Reduction			5.85

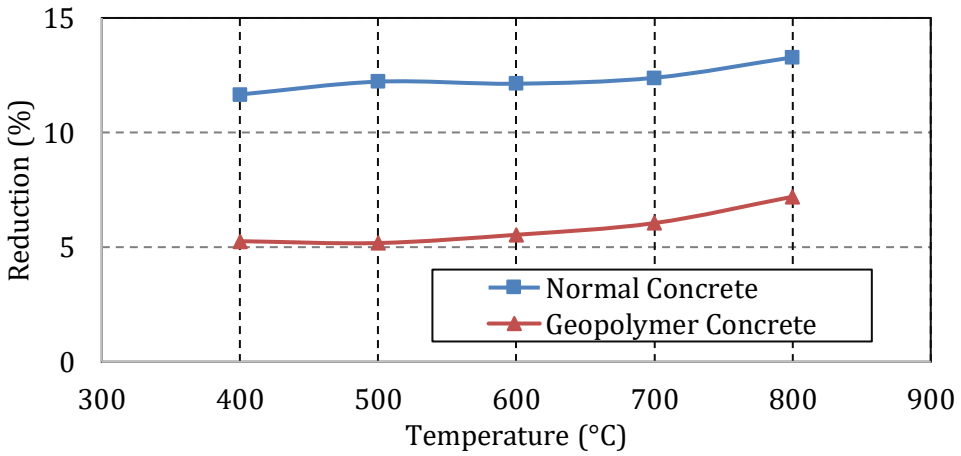


Fig. 17. Comparison of weight reduction between normal and geopolymer concrete specimens after exposure to temperatures ranging from 400°C to 800°C

From the results above, we can conclude that after both concrete specimens are burned, normal concrete experiences significantly greater weight shrinkage than geopolymer concrete. Normal

concrete experiences an average weight shrinkage of 12.33%, while geopolymer concrete experiences an average weight shrinkage of 5.85%. The increase in burning temperature does not significantly affect the weight shrinkage of concrete per unit increase in temperature. As can be seen in Figure 17, the percentage decrease is not very substantial.

4.3. Compressive Strength Test Results

The figure below shows the compressive strength of normal and geopolymer concrete before and after the burning test. Error bars representing the standard deviation are included in the figures to indicate the variability of the test results. The variability is evaluated using the coefficient of variation (COV), which ranges from 4% to 19% in this study.

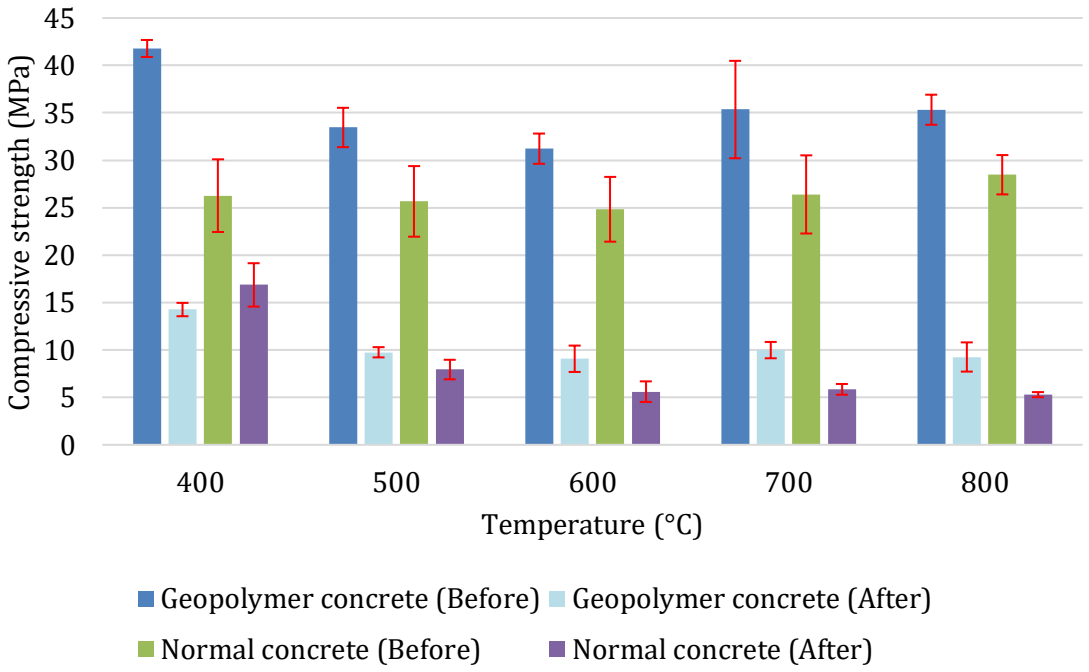


Fig. 18. Compressive strength of normal concrete and geopolymer concrete before and after exposure to elevated temperatures from 400°C to 800°C.

The tables below show the compressive strength test results for both normal and geopolymer concrete samples before and after varying degrees of fire and high heat exposure. The data above shows that geopolymer concrete exhibited a greater reduction in compressive strength at 400°C than normal concrete. However, at higher temperatures ranging from 500°C to 800°C, the reduction in compressive strength of geopolymer concrete was lower than that of normal concrete. The residual strength of normal concrete is 64.18%, 28.78%, 22.58%, 21.87%, and 18.58%, respectively. A similar trend was reported by Tayeh et al. [21] and Razak et al. [22], who observed residual strength values of 63.28%, 50.22%, 38.16%, 27.11%, and 18.08% at comparable temperatures [21, 22].

Heikal et al. [18] reported different results. Fig. 17 shows the compressive strength of normal concrete incorporating fly ash in their study. The results indicate that the compressive strength increased when heated up to 400°C, but decreased at higher temperatures. This behavior differs from the findings of the present study, where normal concrete did not exhibit strength gain at 400°C, suggesting that the effect of fly ash on thermal resistance may depend on its proportion and material composition [18].

The residual strength of geopolymer concrete is 34.13%, 29.16%, 29.06%, 28.25%, and 28.67%, respectively. However, Park et al. [19] and Razak et al. [22] reported a different trend: geopolymer concrete exhibited an increase in compressive strength after exposure to elevated temperatures [19, 22]. In the study by Park et al. [19], the compressive strength increased by 61%, 85%, and 45% at 200°C, 400°C, and 600°C, respectively, before decreasing at 800°C, with a residual strength of

76%. This result contrasts with the present study, where no strength gain was observed at comparable temperatures. This phenomenon is commonly attributed to continued geopolymerization and densification of the geopolymer matrix at moderate temperatures. In that study, the geopolymer specimens were cured at room temperature for 28 days. In contrast, the geopolymer specimens in the present study were cured at a higher temperature (115°C), which likely resulted in a more complete geopolymerization process prior to heating. Consequently, further strength gain during heating was limited, and the specimens mainly experienced thermal degradation.

Table 14. Compressive strength of geopolymer concrete specimens before and after exposure to elevated temperatures (400°C–800°C)

Temp. (°C)	Average Compressive Strength for 3 Samples (Before)		Average Compressive Strength for 3 Samples (After)		Residual%	Reduction%
	MPa	kN	MPa	kN		
400	41.79	328.01	14.26	111.94	34.13	65.87
500	33.46	262.63	9.76	76.59	29.16	70.84
600	31.22	245.10	9.07	71.23	29.06	70.94
700	35.35	277.50	9.99	78.40	28.25	71.75
800	35.33	277.34	10.13	79.52	28.67	71.33

Table 15. Compressive strength of normal concrete specimens before and after exposure to elevated temperatures (400°C–800°C)

Temp. (°C)	Average Compressive Strength for 3 Samples (Before)		Average Compressive Strength for 3 Samples (After)		Residual%	Reduction%
	MPa	kN	MPa	kN		
400	26.27	206.22	16.86	132.35	64.18	35.82
500	25.66	201.46	7.39	57.97	28.78	71.22
600	24.83	194.94	5.61	44.01	22.58	77.42
700	26.76	210.03	5.85	45.92	21.87	78.13
800	28.48	223.53	5.29	41.53	18.58	81.42

Similar trends were observed in studies where geopolymer specimens were cured at elevated temperatures. For example, in the study by Luhar et al. [9], where specimens were cured at 90°C, and Tayeh et al. [21], where curing was conducted at 80°C, the compressive strength decreased when exposed to high temperatures. In the study by Luhar et al. [9], the residual compressive strengths were 72.62%, 62.96%, 50.87%, and 54.78% at 200°C, 400°C, 600°C, and 800°C, respectively [20]. In another study by Tayeh et al. [21], Fig. 16(a) shows that the compressive strength of geopolymer concrete increased at 100°C and decreased at temperatures ranging from 200°C to 800°C [21]. This trend is consistent with the findings of the present study, where geopolymer concrete exhibited a continuous reduction in strength after exposure to elevated temperatures.

Overall, these results indicate that geopolymer concrete performs better at higher temperatures than normal Portland cement concrete. This behavior is generally attributed to the thermal stability of the aluminosilicate geopolymer binder, which undergoes less decomposition at elevated temperatures than the calcium-based hydration products in Portland cement concrete.

The curing conditions may also influence this difference in behavior. Comparing different curing methods for geopolymer concrete reveals that elevated-temperature curing (high-strength geopolymer) results in greater susceptibility to weight loss, volume instability, dehydration, and cracking upon fire exposure, primarily due to its compact internal structure [35]. In contrast, room-temperature curing (low-strength geopolymer) is more effective in mitigating these effects, mainly because the specimens undergo further polymerization and sintering when exposed to high

temperatures. Figure 19 illustrates the difference in internal structure between geopolymer concrete cured at elevated temperature and that cured at room temperature.

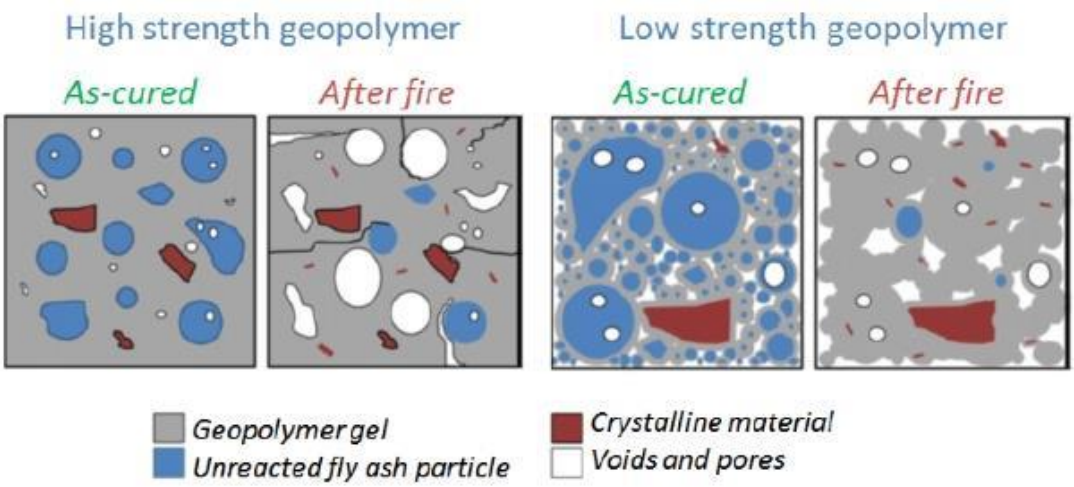


Fig. 19. Comparison of the internal structure of Geopolymer concrete with different curing methods

Due to the results of this study [21], further analysis was conducted to verify the theory of the effect of curing on the reduction in compressive strength after firing. The results of this analysis showed a 34.27% discrepancy between the decrease in oven-cured/elevated high-temperature curing and room-temperature curing. Hence, it is concluded that elevated-temperature curing may increase the susceptibility of geopolymer concrete to strength degradation after fire exposure.

4.4. Scanning Electron Microscope (SEM) Test Results

The results of this scan are used to compare the geopolymer concrete before and after burning at a structural level. Four geopolymer concrete samples are included in this test, each cured using a different method. The first sample will be cured at room temperature. The second sample will be cured using an elevated temperature of 115°C. The third and fourth samples will also be cured at elevated temperatures of 115°C, but will then be burned at 600°C and 800°C, respectively.

The SEM image of geopolymer concrete with room-temperature curing shows spherical particles, which represent either fly ash that has not yet fully reacted or fly ash that has not reacted at all. As explained in the theoretical basis, heat is crucial for activating fly ash and continuing the polymerization reaction [27]. The cracks in the geopolymer concrete are caused by stress during the compressive strength test.

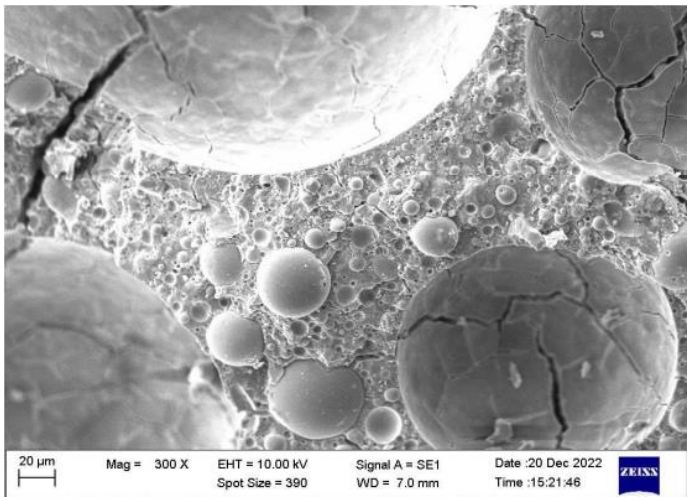


Fig. 20. SEM result of geopolymer concrete at room temperature curing

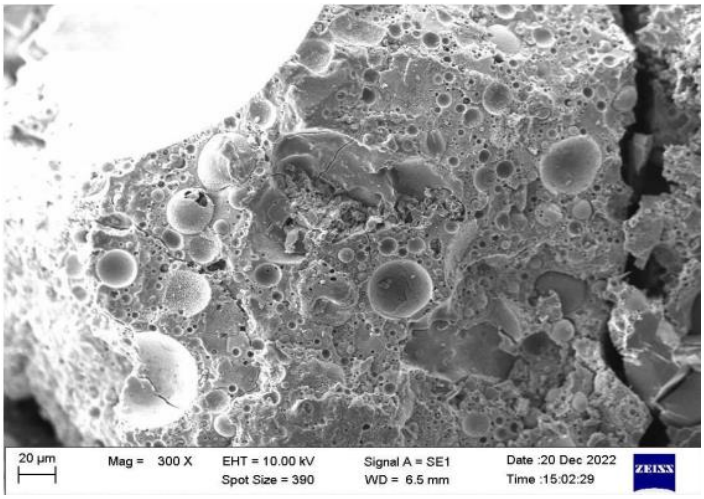


Fig. 21. SEM result of geopolymer concrete at elevated temperature curing of 115°C, showing less unreacted fly ash than room temperature curing specimens

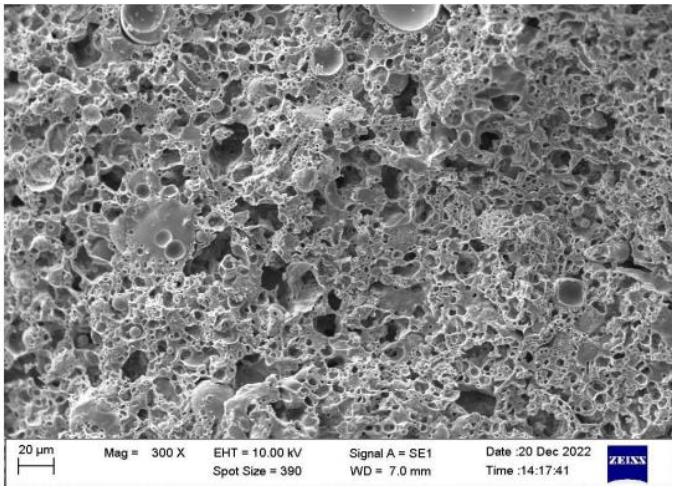


Fig. 22. SEM result of geopolymer concrete with elevated curing and burned at 600°C, showing increased porosity and microstructural changes after high-temperature exposure

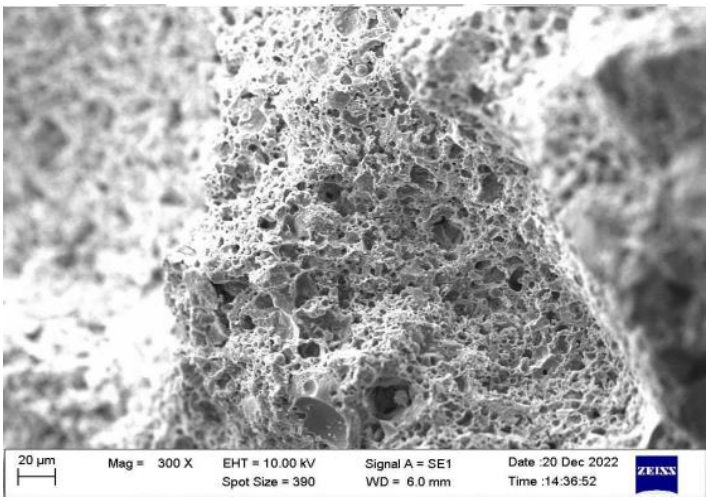


Fig. 23. SEM result of geopolymer concrete with elevated curing and burned at 800°C

Figure 21 shows SEM images of geopolymer concrete cured at 115°C for 24 hours. The structural condition in Figure 21 appears denser and smoother compared to Figure 20. Additionally, the number of unreacted fly ash particles, represented by spherical particles, is significantly reduced

compared to Figure 20. This observation suggests that an appropriate curing temperature, namely 115°C, is sufficient to induce further polymerization reactions in fly ash [29].

Figure 22 shows the SEM of geopolymer concrete after being burned at 600°C with elevated temperature curing at 115°C. After burning, there was an increase in porosity, pore size, and volume. This increase in porosity may be associated with structural changes occurring during high-temperature exposure, such as crystallization of geopolymer gel [35].

Figure 23 shows the SEM image of geopolymer concrete after burning at 800°C with elevated temperature curing at 115°C. Compared to the results at 600°C, the pore structure at 800°C is denser [16]. This behavior may be associated with sintering and densification processes occurring in geopolymer materials at elevated temperatures [34]. The permeable nano-pore structure of geopolymer concrete allows free water and water vapor to easily escape, preventing pore pressure buildup that can lead to spalling, unlike in normal concrete.

In conclusion, the curing method's polymerization likely causes fly ash to react, forming a stronger, denser structure that increases compressive strength. Concrete burned at 800°C exhibits a denser structure than that burned at 600°C. This is due to sintering and densification processes occurring at higher temperatures.

5. Conclusions

Based on the results obtained through this analysis, a few conclusions can be drawn. Firstly, it is evident that fire exposure has a negative impact on the performance of geopolymer concrete as a structural material, with the concrete samples experiencing a reduction of 65.86%, 70.84%, 70.94%, 71.75%, and 71.33% at the temperatures of 400°C, 500°C, 600°C, 700°C, and 800°C, respectively. Aside from that, firing also alters the physical and mechanical properties of the concrete samples, resulting in an average weight reduction of 5.85%, cracking at high temperatures of 600°C – 700°C, color changes from dark grey to brown, and deformities. Finally, the SEM results indicate an increase in concrete porosity after fire exposure.

The curing method also significantly affects the reduction in compressive strength. Elevated-temperature curing influenced the microstructure and thermal behavior of geopolymer concrete during fire exposure, making the samples more susceptible to adverse fire effects.

Compared to normal Portland cement concrete, the results show that geopolymer concrete fares better at high temperatures, with normal concrete samples experiencing an 81.42% reduction and geopolymer samples a 71.73% reduction in compressive strength at 800°C. The same applies to the effects on physical and mechanical conditions for both varieties: the normal concrete experienced a 12.33% reduction in weight, whereas the geopolymer concrete experienced a 5.85% reduction. The normal concrete sample also exhibited more significant spalling and cracking. Hence, from these differences, it can be concluded that geopolymer concrete is much more suited to high-heat and fire exposure than regular Portland cement concrete.

Temperature increases seemed to have no significant impact on the weight reduction for both varieties. At 400°C and 800°C, the geopolymer variety experiences reductions of 5.26% and 7.2%, respectively, while the normal variety experiences reductions of 11.66% and 12.33%, respectively. On the contrary, temperature increases have different impacts on the reduction of compressive strength amongst the two varieties. The geopolymer concrete does not experience a significant rise in reduction (65.87% at 400°C and 71.33% at 800°C); however, the normal concrete does (35.82% at 400°C and 81.42% at 800°C)

Through this analysis, several further considerations and suggestions can be made for future studies on this topic. Firstly, more studies into curing methods would greatly benefit our understanding of the relationship between the polymerization reaction and the strength of concrete. Aside from that, further analysis is needed to investigate the relationship between the Si/Al ratio and the strength of geopolymer concrete at high temperatures. Additional research is needed on the admixture for geopolymer concrete to determine an optimum mix that enhances heat and fire resistance.

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