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Case study

## Performance evaluation of cement paste incorporating ferro-nickel slag powder under elevated temperatures

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## ABSTRACT

This study investigated the fire resistance performance in terms of physical and chemical properties of the cement paste incorporating an iron by-product (i.e., ferronickel slag; FNS) at elevated temperatures (200 °C, 400 °C, 600 °C, and 800 °C). The cement pastes partially replaced with FNS, ground granulated blast-furnace slag (GGBS), and pulverized fly ash (PFA) at 30%, 60%, and 30%, respectively, were fabricated to compare the performance with other pozzolanic binders. All the pastes were kept at the water to binder ratio (W/B) of 0.467. The specimen was cured for 28 days and exposed to set temperatures. After/before heating, compressive strength and mercury intrusion porosimetry (MIP) were measured to evaluate the fundamental properties. Simultaneously, a variation in phase composition was examined using X-ray diffraction (XRD) and thermogravimetry (TG). As a result, despite lower strength at room temperature for the blended paste, those specimens were always higher than ordinary Portland cement (OPC) one after heating. Among them, FNS modified paste ranked the highest value in the residual strength after 400 °C, indicating 30.7% at 800 °C, which is consistent with a change in porosity and average pore size. This may be attributed to the presence of hydrotalcite and ferric/ferrous hydroxide, which is observed in the XRD results of FNS incorporated paste even after exposure to high temperatures. However, the optimum replacement level of FNS powder should be verified to secure a better performance in the given and a more severe temperature environment.

## 1. Introduction

The demand for concrete structures has been growing in terms of structural stability, durability, and applicability for unique environments such as ironworks and plants exposed to high temperatures. Although concrete has been regarded as an excellent construction material with relatively high fire resistance efficiency, exposure to high temperature causes amounts of internal heat transfers, resulting in different behaviors of the cement matrix and aggregates due to the difference in thermal expansion coefficients [1,2]. In this situation, the restrained member and unbalanced thermal equilibrium lead to thermal stress occurrence, which reduces

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load-carrying capacity, resulting in further deterioration such as cracking, spalling, deterioration, or even structure collapse in severe cases [3,4]. In general, the strength loss is not noticeable in the temperature environment under 300 °C, and the degradation could even be recovered by rehydration over time [5]. However, since the major hydration products in the cement matrix, C-S-H gel and Portlandite ( $\text{Ca}(\text{OH})_2$ ; CH), decompose at above the temperature destroying the pore structure [6], the concrete becomes irreversible in strength [7,8].

Traditionally, the use of industrial wastes as a cementitious material in concrete is customary to increase the resistance to fire damage. Poon et al. [3] and Heikal et al. [9] investigated the influence of the replacement of pozzolanic materials, including ground granulated blast-furnace slag (GGBS), and pulverized fly ash (PFA) and silica fume (SF) on the residual compressive strength at elevated temperatures. They reported that the blended specimens show relatively higher strength until around 600 °C exposure than ordinary Portland cement (OPC) at replacement levels up to 40%, 15%, and 30% for GGBS, PFA, and SF, respectively, due to a reaction of the remaining binder with free lime. This similar effect was summarized by Cree et al. [10], but in their publication, the authors point out an unconcise evaluation method in the many earlier works, which could lead to an inconsistent result even at the identical condition. More recently, Babalola et al. [8] reviewed the residual compressive strength of normal and high strength concrete modified by pozzolanic materials at elevated temperatures compared to those at room temperature. They concluded that denser microstructure in the mixture might cause the deterioration of strength development at the high temperature due to its condensation of internal pressure within pores by lower thermal conductivity. Therefore, it is subject to debate whether using a pozzolanic material as a binder improves the resistance against high temperature even though benefits of the replacement in enhancing the concrete properties.

Nevertheless, with an increasing demand for developing cost- and  $\text{CO}_2$ -low concrete, there is still of great interest in using various industrial wastes in the concrete to enhance the performance at the elevated temperature. Mohammadhosseini et al. [11] conducted on residual mechanical properties of concrete incorporating carpet fiber and palm oil fuel ash after exposure to high temperature. In their study, the modified concrete exhibited a promising performance, but the increased residual strength is due to the addition of waste fiber rather than the replacement of the ash, where the binder produced low hydraulic and pozzolanic reactivity. This similar trend was also proved by the same research group [12,13]. On the one hand, Ma et al. [14] examined the performance of copper slag incorporated mortar, which is different types of iron waste glass (i.e., GGBS), at elevated temperatures. They mentioned that the waste addition in the mixture has no significant influence on both before/after strength, compared to OPC solely one. However, in Afshon and Sharifi [15]'s study, the modified copper slag in the particle size enhanced the mechanical properties of the mixed concrete, which showed a better fire resistance performance. Thus, it is worthwhile to investigate/utilize various industrial by-products in improving the resistance at high temperatures in addition to the conventional pozzolanic binders.

Ferro-nickel slag (FNS) is an industrial by-product of ferronickel production; it is obtained after raw materials such as nickel ore and bituminous coal are smelted at a high temperature and separated from ferronickel. For practical purposes, the research on the binder has been mainly focused on the use of aggregate in concrete manufacturing, particularly for fine aggregate [16,17]. While, some authors have attempted to create added value by applying it to the concrete as a cement substitute material [18,19]. Although FNS has low reactivity to water that it is not subject to hydration reaction [19,20], it could be used with ordinary Portland cement (OPC) and react with CH to form C-S-H gel, thereby contributing to long-term strength development [21]. Moreover, depending on the specific surface area, it could replace 10–40% of the total mass [19]. In that case, it could have a similar level of mechanical performance compared to 100% OPC. Early strength development is relatively low, as the conventional pozzolanic substitutes, but its low initial hydration heat offers advantages in reducing damage from drying shrinkage and thermal stress [21,22]. In addition, by generating hydrates such as hydrotalcite and magnesium silicate hydrate (M-S-H) in long-term hydration, it is expected to offer an advantage in securing durability as well as an appropriate level of strength [19]. In particular, it is expected to have an excellent performance to fire resistance because a formation of  $\text{MgCO}_3$  reacted between MgO in FNS and  $\text{CO}_2$  in the air [23], which may affect modification of pore structure in FNS-mixed concrete. Nevertheless, a few studies research the change in hydrate composition and pore structure at high temperatures.

The present study aims to evaluate the improvement of the fire resistance performance by FNS addition in a high-temperature environment. The cement paste at 30% of FNS replacement was manufactured. For comparison with specimens incorporating pozzolanic binder, additional experiments covered GGBS and PFA incorporated specimens with the replacement level of 60% and 30%, respectively. All the pastes were kept at 0.467 of water to binder ratio (W/B). The cement pastes are cured at room temperature for 28 days and then exposed to the elevated temperatures (200 °C, 400 °C, 600 °C, and 800 °C). Thereafter, it is measured the compressive strength and analyzed the change in hydrates composition and pore structure using X-ray diffraction (XRD), thermogravimetry (TG)

**Table 1**

Chemical and physical properties of binders used in this study.

		OPC	FNS	GGBS	PFA
Oxide(%)	CaO	66.9	0.6	47.18	6.41
	MgO	1.6	27.4	4.55	1.39
	$\text{Al}_2\text{O}_3$	3.9	2.2	13.13	21.6
	$\text{SiO}_2$	17.4	51	29.7	55.54
	$\text{Fe}_2\text{O}_3$	5.1	15.5	0.64	9.27
	$\text{SO}_3$	3.4	0.1	2.3	0.8
LOI (%)		2.4	<0.1	1	4.65
Blaine ( $\text{cm}^2/\text{g}$ )		3712	4660	4200	3851
Specific gravity		3.12	3.05	2.86	2.31

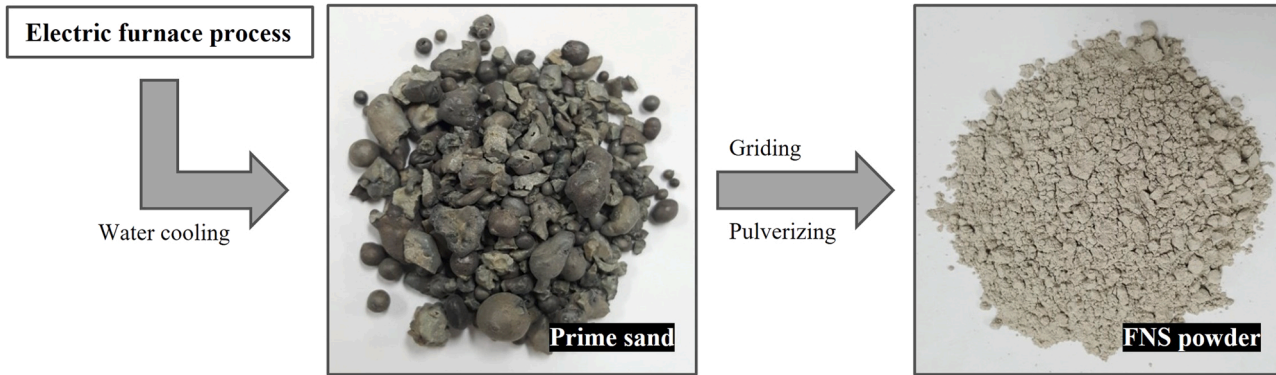


Fig. 1. Visual image of FNS waste powder before/after milling.

analysis, and mercury intrusion porosimetry (MIP).

## 2. Experimental works

### 2.1. Materials

In manufacturing cement paste, this study used OPC cement with a fineness of 3712 cm<sup>2</sup>/g and specific gravity of 3.12. For the binder, FNS, GGBS, and PFA are used, and the physical and chemical properties of each binder are listed in Table 1. Except for FNS, which binder is not specified as a standard, OPC, GGBS, and PFA were satisfied with KS L 5201, KS L 5405, and KS F 2563. FNS was produced by a domestic company in which the prime sand after a rapid cooling process with sprayed water was ground/pulverized to achieve a specified fineness. Fig. 1 is the visual image of FNS before/after milling. Each binder displays an X-ray diffraction (XRD) pattern, as shown in Fig. 2, and the primary compounds consisting of FNS are found to be Fayalite(Fe<sub>2</sub>(SiO<sub>4</sub>)) and Forsterite (Mg<sub>2</sub>(SiO<sub>4</sub>)). The Mg-bearing constituent typically has low solubility at ambient temperature to form magnesium silicate hydrates (M-S-H) [24]. In comparison, GGBS and PFA have a wide halo pattern in the XRD result, which means the amorphous nature of the binders.

### 2.2. Mix proportion and sample preparation

For the cement paste specimen, regardless of binder type, W/B was set at 0.467, and the replacement ratio of FNS, GGBS, and PFA was 30%, 60%, and 30% by weight of the total binder, respectively. The replacement level for each binder was determined based on the fact that the residual mechanical properties were affected by those at ambient temperature [8]. According to Malik et al. (2021) [7], those level for GGBS and PFA was reasonable for achieving better performance after/before exposure to high temperature. However, the FNS replacement ratio was only considered the maximum value for higher performance for practical purposes [19], due to a lack of information about fire resistance. All the mix design includes no chemical admixtures to avoid any unintended chemical reactions. The details of mix proportions are given in Table 2. After mixing consisting of 3 min of dry and 2 min of wet process, it was cast in the cubic mold (50 × 50 × 50 mm) to be stored in the laboratory for 24 h at 20 ± 2 °C and RH 50 ± 5%. Then, the specimen demolded was cured in a humid chamber (RH 95%) at 20 °C for 28 days to ensure adequate hydration degree.

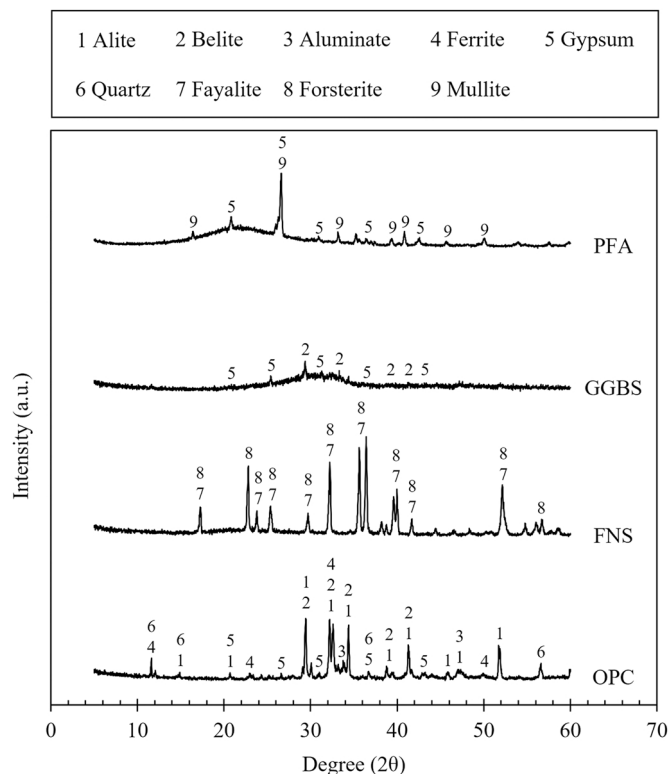


Fig. 2. XRD pattern of binders used in this study.

**Table 2**  
Mix proportion of cement paste.

	Weight ratio					Water
	OPC	FNS	GGBS	PFA		
Control	1.0	–	–	–	–	0.467
F 30	0.7	0.3	–	–	–	
G 60	0.4	–	0.6	–	–	
P 30	0.7	–	–	0.3	–	

### 2.3. Heating and cooling regime

The cement paste was placed on an electric furnace and exposed the elevated temperatures (200 °C, 400 °C, 600 °C, and 800 °C) at a heating rate of 10 °C/min, as shown in Fig. 3. The temperature was increased to the set temperature and then was maintained for 2 h to allow uniform heat distribution throughout the specimen. After that, the specimen went through a natural cooling in the electric furnace until reaching room temperature at around 20 °C, which is the so-called unstressed method for measuring residual mechanical properties at the steady-state condition of temperature [15]. The time-temperature history is shown in Fig. 4. The described heating/cooling method was performed by following the previous studies [13,14].

### 2.4. Test procedures

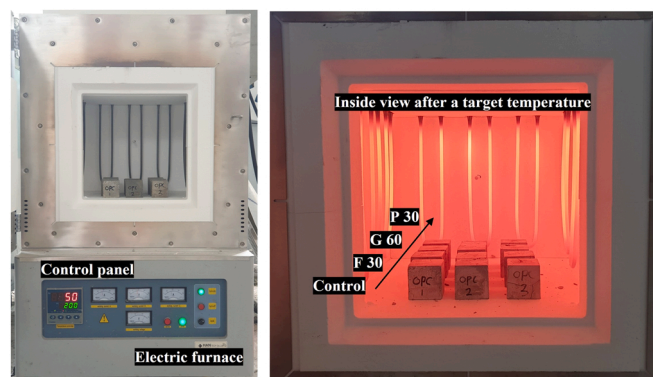
The compressive strength of the cement pastes was measured after cooling to ambient temperature from each target one to obtain a ratio of residual compressive strength. The measurement was carried out in accordance with KS F 2405, and the average value of three replications for each target temperature and the mix was used. Residual compressive strength ratio is calculated as the ratio of compressive strength of the cement paste at 28 days to the strength of the target temperature.

Examining the pore structure of the cement paste exposed to high temperatures was performed by MIP test. A sample of about 1 cm<sup>3</sup> was taken from the specimen after measuring the compressive strength. The sample was immersed in the alcohol-based solvent (i.e., isopropanol) for 1 h to remove the remaining water in the cement matrix, and in turn, it was dried in a vacuum desiccator at 50 °C for 6 h to evaporate water and solvent inside or on the surface of the sample [25]. This hydration halting method is also adopted for pretreatment of the powder sample in XRD and TG tests. The pore size distribution of the specimen was measured using Autopore IV 9500 (Micromeritics Instrument Corp.), where the pressure is gradually increased from 0.2 MPa to 227.5 MPa for detecting small and large pores. The pore size according to the applied pressure can be calculated using the following equation.

$$d = \frac{-4 \gamma \cos\theta}{P} \quad (1)$$

where  $d$  is the pore size (m),  $\gamma$  is the surface tension of mercury (N/m),  $\theta$  is the contact angle of mercury (°), and  $P$  is the applied pressure (MPa).

Simultaneously, XRD and TG analysis was conducted to analyze the change in phase composition of the specimen exposed to the identical environment. After completing hydration stopping for paste sample, a powder sample was obtained with a sieve of 150 μm. In order to prevent carbonation or further hydration of the sample, XRD analysis was performed immediately after collecting the dust sample. An identical sample was also used for TG analysis. For XRD analysis, SmartLab (Rigaku Corp.) instrument was used to achieve an XRD pattern at a range of 5–60° of 2θ and a scan rate of 4°/min. In addition, TG analysis was performed using approximately 30–40 mg of the sample at a condition including a heating range of 50–800 °C and a heating rate of 10 °C/min. The equipment was SDT Q 600(TA Instruments), and heating was proceeded in an N<sub>2</sub> atmosphere to prevent carbonation during the experiment. By



**Fig. 3.** Paste specimen placed in an electrical furnace.

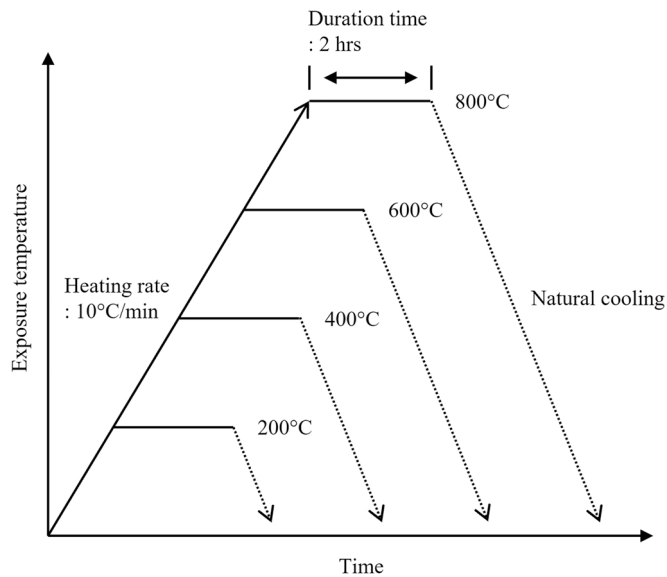


Fig. 4. Time-temperature history conducted in the present study.

differentiating the TG result for the temperature, a differential TG (DTG) curve was obtained, and then the CH and BW contents in the specimen were calculated using the following equations [25].

$$BW = \frac{W_{50} - W_{550}}{W_{550}} \quad (2)$$

$$BW = \frac{W_{CH,i} - W_{CH,f}}{W_{550}} \times \frac{74}{18} \quad (3)$$

where  $W_n$  is the mass (%) at  $n^\circ\text{C}$ ,  $W_{CH,i}$  is the mass (%) at the initial temperature of decomposition,  $W_{CH,f}$  is the mass (%) at the final temperature of decomposition, and  $\frac{74}{18}$  is the molar mass ratio of CH to Water.

### 3. Results and discussion

#### 3.1. Residual compressive strength

This study measured the compressive strength of the paste specimen cured at  $20^\circ\text{C}$  for 28 days to determine a variation in the residual strength at elevated temperatures. The result is shown in Table 3 and shows that the strength is dependent on the types of binder in the cement paste. The compressive strength of OPC paste displays the highest value at 54.47 MPa, followed by the specimen mixed with FNS, GGBS, and PFA at 48.06, 50.61, and 52.72 MPa, respectively. Despite the pozzolanic reaction in the hydration process, the strength enhancement in the GGBS and PFA mixture was not distinct but similar to Control, which trend was in line with most previous studies [4,26]. The lowest strength value for F 30 may presumably be due to low  $\text{CaO}/\text{SiO}_2$  in the FNS powder, resulting in no participation in the direct hydration reaction [19]. As indicated in Fig. 1, the main compounds of FNS include Fayalite and Forsternite with low reactivity, so that the strength development is contributed mainly by ion exchange in C-S-H gel or AFm hydrate rather than the hydration reaction [19,27]. Therefore, replacing FNS powder with cement would not be applicable for achieving higher strength in the initial hydration process than OPC. Nevertheless, the room condition strength is about 88% of Control, and also, there is still a possibility for further reaction over time, thereby improving fire resistance.

Fig. 5 displays the residual compressive strength ratio at a temperature-increasing environment from room temperature ( $20^\circ\text{C}$ ) to  $800^\circ\text{C}$ . It is confirmed that the residual compressive strength decreases with increased temperature, regardless of the mix design. At

**Table 3**  
Compressive strength of paste specimens cured for 28 days.

	Compressive strength (MPa)
Control	54.47 ± 3.04
F 30	48.06 ± 3.16
G 60	50.61 ± 1.66
P 30	52.72 ± 3.53

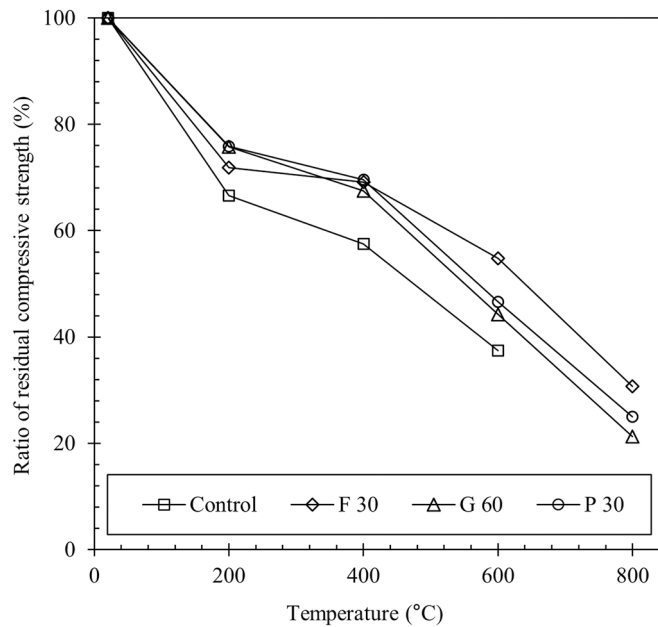


Fig. 5. Ratio of residual compressive strength of paste specimens at elevated temperatures.

the beginning of the test, a reduction in the strength of the specimen containing binders was lower than OPC, showing 71.9%, 75.7%, and 75.9% of relative strength for F 30, G 60, and P 30, respectively, during which Control showed the lowest ratio of residual strength (66.6%). This reduction can be due to the removal of various types of pore water in the cement matrix at the temperature range, leading to micro-crack and thus strength loss [28]. Poon et al. (2001) [3] and Shumye et al. (2019) [4] mentioned that the decreased strength in OPC could be compensated by the addition of pozzolanic additives with the cement due to further reaction of the remaining grains forming Tobermorite in the cement matrix. The effect of the FNS replacement on residual strength within 200 °C was not reported elsewhere, but it might be due to the formation of Fe-bearing hydroxide in the hydration process [14]. This trend is also shown in the temperature increase from 200 °C to 400 °C, where the strength reduction ratio of Control was 42.5%, followed by G 60 (32.5%), F 30 (30.9%), and P 30 (30.4%).

After 400 °C exposure, a sharp decrease in the strength is observed at all mixes. The residual strength ratio of Control at 600 °C is 37.4%, and the blended pastes are reduced by around 50%. Afterward, as shown in Fig. 6, Control displays severe cracking that compressive strength could not be measured, whereas F 30, G 60, and P 30 shows at 30.7%, 21.3%, and 25.0% in the residual strength ratio, respectively. It is well addressed in the literature [5,10] that the amount of CH and C-S-H gel begins to decompose within this temperature range, resulting in cracking in the microstructure and dramatically decreasing strength. However, the strength reduction for the paste incorporating FNS is relatively low compared to the other mixes. According to a study by Kim et al. (2019) [19], although porosity decreases when replacing the FNS powder with OPC, the difference was insignificant, except for FNS with a low specific surface area. Also, Lee et al. (2020) [29] reported that 30% FNS powder replacement increases porosity compared to the OPC. Both studies may indicate that FNS replacement contributes to the modification of pore structure, so the thermal conductivity of the mixture changes. Moreover, Ma et al. (2018) [14] stated that self-curing of Fe-bearing slag affects more strength improvement before/after exposure to the elevated temperature. This enhancement at fire resistance is identified in the present result that the paste modified by FNS shows the highest residual strength ratio, even after 800 °C exposure.

Fig. 7 shows the MIP results of the cement paste after the heating and cooling process up to 800 °C. The porosity and average pore diameter obtained from the results are indicated in Table 4. For total porosity at 28 days, the binder replacement in cement paste is revealed to have an insignificant effect in modification of pore structure, displaying nearly no correlation to the compressive strength at an identical curing condition. For example, GGBS incorporated specimen at 28 days of curing displays the lowest porosity of 27.18%, followed by control (28.81%), P 30 (29.35%), and F 30 (30.12%). However, the total volume is much affected by the temperature increase.

According to the MIP result, the total intruded volume of the mercury increases with the increase in heating temperature, regardless of the binder types. Additionally, the average pore diameter increased, modifying the average diameter at 28-days of 12.9–46.2 nm to 926.1–1487.6 nm after exposure to 800 °C (Table 4). Presumably, it results from coarsening effect in the cement matrix [30], indicating that shrinkage occurs with the rise of the temperature in the cement matrix and thus cracking. Poon et al. (2001) [3] revealed the deleterious effect in the cement paste blended with pozzolanic materials at above 600 °C. Memon et al. (2019) [5] also reported that the microstructural coarsening is observed even at lower temperature exposure (250 °C), beyond which severe degradation of the cement matrix occurs mainly due to decomposition of C-S-H gel. This phenomenon is in line with the MIP results in the present works.

The modification of pore structure from the decomposition of hydrates at above 400 °C could affect thermal transfer in the cement

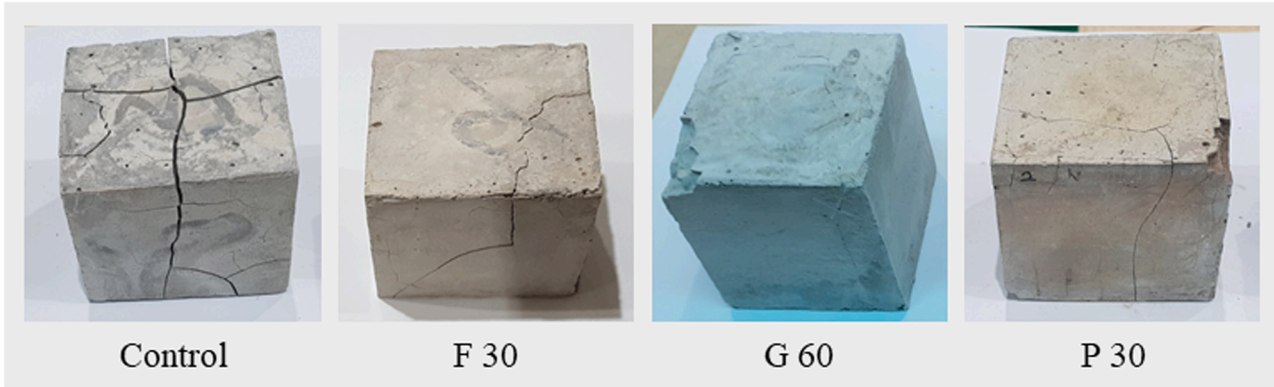


Fig. 6. Visual examination of paste specimens after exposed to 800°C.3.2 Pore size distribution.



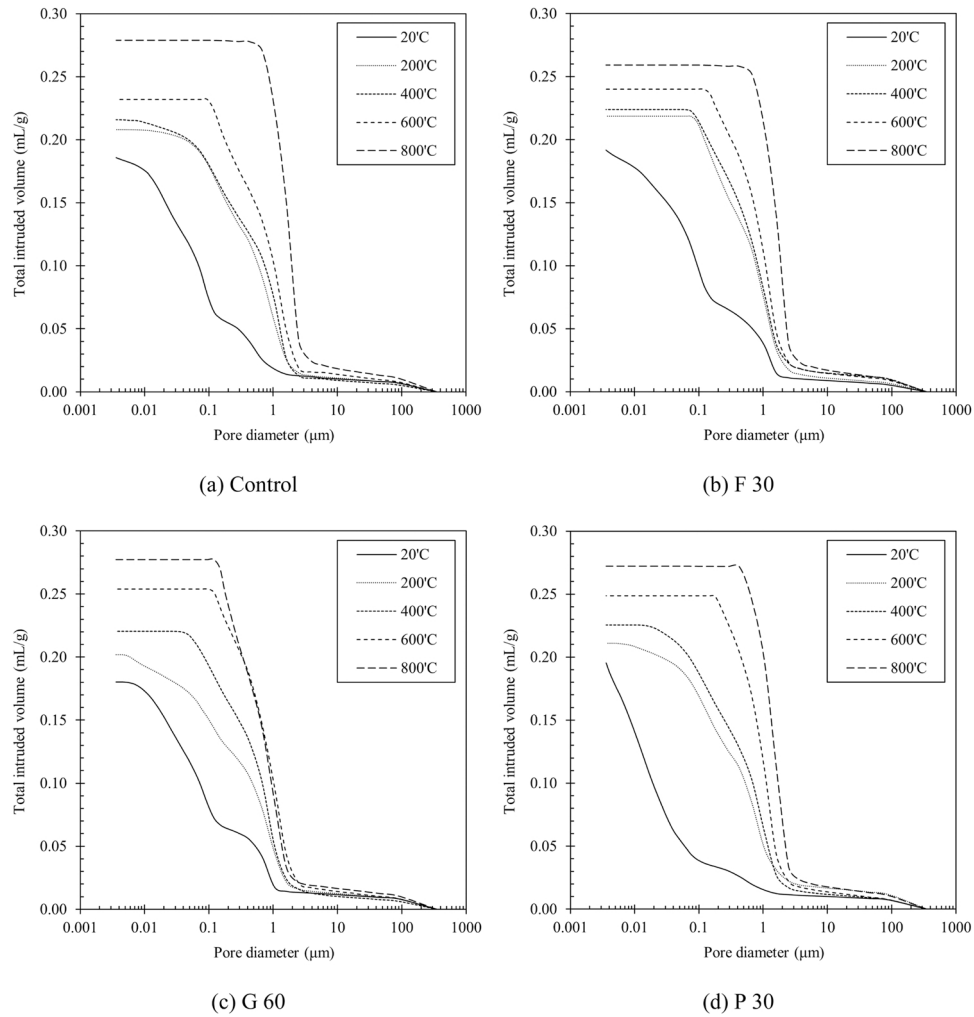


Fig. 7. Poe size distribution of paste specimens at elevated temperatures.

**Table 4**  
Porosity and average pore diameter of paste specimens obtained from MIP result.

		Exposure temperature (°C)				
		20	200	400	600	800
Control	Porosity (%)	28.81	33.46	35.74	40.35	48.98
	Average pore diameter (nm)	46.2	184.5	535.4	839.5	1487.6
F 30	Porosity (%)	30.12	34.34	36.33	39.75	44.08
	Average pore diameter (nm)	35.5	157.0	382.1	597.4	926.1
G 60	Porosity (%)	27.18	31.36	34.72	40.22	44.87
	Average pore diameter (nm)	12.9	69.0	254.3	796.8	1459.7
P 30	Porosity (%)	29.35	32.51	36.66	41.51	45.90
	Average pore diameter (nm)	23.7	115.5	172.9	703.2	1275.1

matrix. Particular at similar porosity in the temperature rising environment, the average size of pores is one of the influencing factors in thermal conductivity. Lee et al. (2020) [29] proved that a smaller average diameter or porosity generally slows thermal transfer in the cement matrix. Memon et al. (2019) [5] reviewed that the addition of pozzolanic binder results in a reduction in average pore diameter with an increase of temperature, but consequently leading to crack widening and pore coarsening. On the other hand, the FNS incorporated specimen displays the lowest porosity and average pore diameter at the heating environment of above 400 °C in this study. According to Kim et al. (2019) [], adding FNS powder in a mixture can modify the pore distribution, shifting to lower pores due to a formation of gel-like hydrotalcite in the cement matrix. Moreover, In the Afshoon and Sharifi (2020) [15]'s publication, a certain replacement level of Fe-bearing material produced a lower porosity than OPC. These observations may indicate that refinement of pore structure is affected by the Fe<sub>2</sub>O<sub>3</sub> and MgO in the FNS powder, but this would require further verification by analyzing the change in hydrates composition.

### 3.2. Hydration products

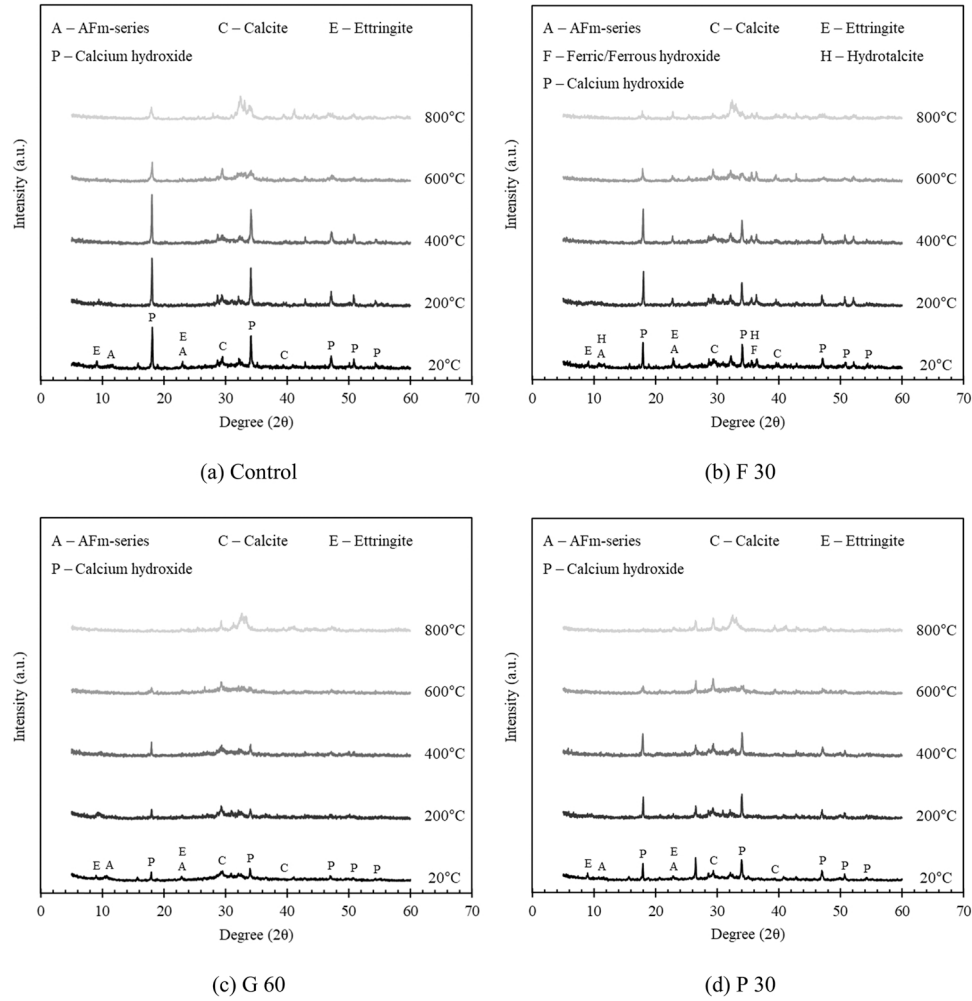
XRD analysis was conducted after exposure of 20 °C, 200 °C, 400 °C, 600 °C, and 800 °C to check a variation of hydrates composition in the cement paste, as indicated in Fig. 8. Regardless of the mix, the major hydrates in the specimen at 28 days are CH, Ettringite, calcium carbonate (CC), and AFm series, and some peaks of unhydrated powder such as C<sub>3</sub>S and C<sub>2</sub>S are observed. While the cement paste modified by FNS powder produces ferric/ferrous hydroxide (Fe(OH)<sub>3</sub>/Fe(OH)<sub>2</sub>) and hydrotalcite (Mg<sub>6</sub>Al<sub>2</sub>(CO<sub>3</sub>)(OH)<sub>16.4</sub> H<sub>2</sub>O), which is consistent with the existing literature [14,19]. This may indicate that FNS powder in the mixture contributes to secure appropriate strength with its low reactivity compared to the OPC and pozzolanic binders.

From 20–200 °C of exposure, it is observed that the peak intensity corresponding to CH showed a similar level for all the mixes. In the temperature range, CaO generated from the decomposition of C-S-H gel reacts with the residual water in the cement paste to form CH during the cooling process [31,32], which is closely related to the strength degradation of cement paste in the present work. This behavior lasts until the temperature of 400 °C, above which the peak for CH almost decreases/disappears. According to Malik et al. (2021) [7], the rehydration of CH can occur in the blended system with pozzolanic binders, reducing a crack formation but accompanying strength loss. Also, Babaoala et al. (2021) [8] pointed out that although the reaction of the remaining reactive binder may be beneficial to secure a residual strength below 400 °C, the strength will be remarkably dropped at the higher temperature. This variation can be confirmed by quantifying the CH value in the specimen from the TG-DTG analysis performed at the identical condition, as given in Fig. 9 and Table 5. For example, the CH content of 28-day Control, F 30, G 60, and P 30 are 20.44%, 13.37%, 4.70%, and 8.60%, respectively, and subsequently, reaches the maximum value at 400 °C, above which the CH content decreases with the temperature increase for all the mixes.

Meanwhile, FNS incorporated cement paste displays only a slight variation in peaks of hydrotalcite and ferric/ferrous hydroxide at the high-temperature environment. Although the peak related to the decomposition of hydrotalcite and ferric/ferrous hydroxide is not clearly detected in the DTG curves due to overlapping with decalcification of CC, those hydrates are presumed to have an affirmative influence on strength development after the heating and cooling process. Ma et al. (2018) [14] observed the presence of hydrotalcite after 1200 °C of exposure and proved that the Fayalite, which is one of the clinkers in FNS powder used in the present works, is likely to form ferric/ferrous hydroxide at around 600 °C under alkaline environment. This phenomenon would affect the modification of pore structure in the heating and cooling process, resulting in enhancement of the residual strength. Therefore, the use of FNS powder is expected to offer high fire resistance to the concrete exposed to high temperatures.

## 4. Conclusions

This study evaluated the influence of FNS replacement with cement on fire resistance under high-temperature environments in terms of microstructural and fundamental properties. The main aim was to ascertain and investigate the usability of FNS powder as a cementitious material in enhancing the performance at elevated temperatures, which was compared with the cement paste incorporating the conventional pozzolanic binder. The cement pastes with 30%, 60%, and 30% substitution of OPC by FNS, GGBS, and PFA were manufactured to determine the residual compressive strength, pore distribution, and phase composition. Conclusions drawn from the results in the present works are as follows:



**Fig. 8.** XRD patterns of paste specimens at elevated temperatures up to 800 °C.

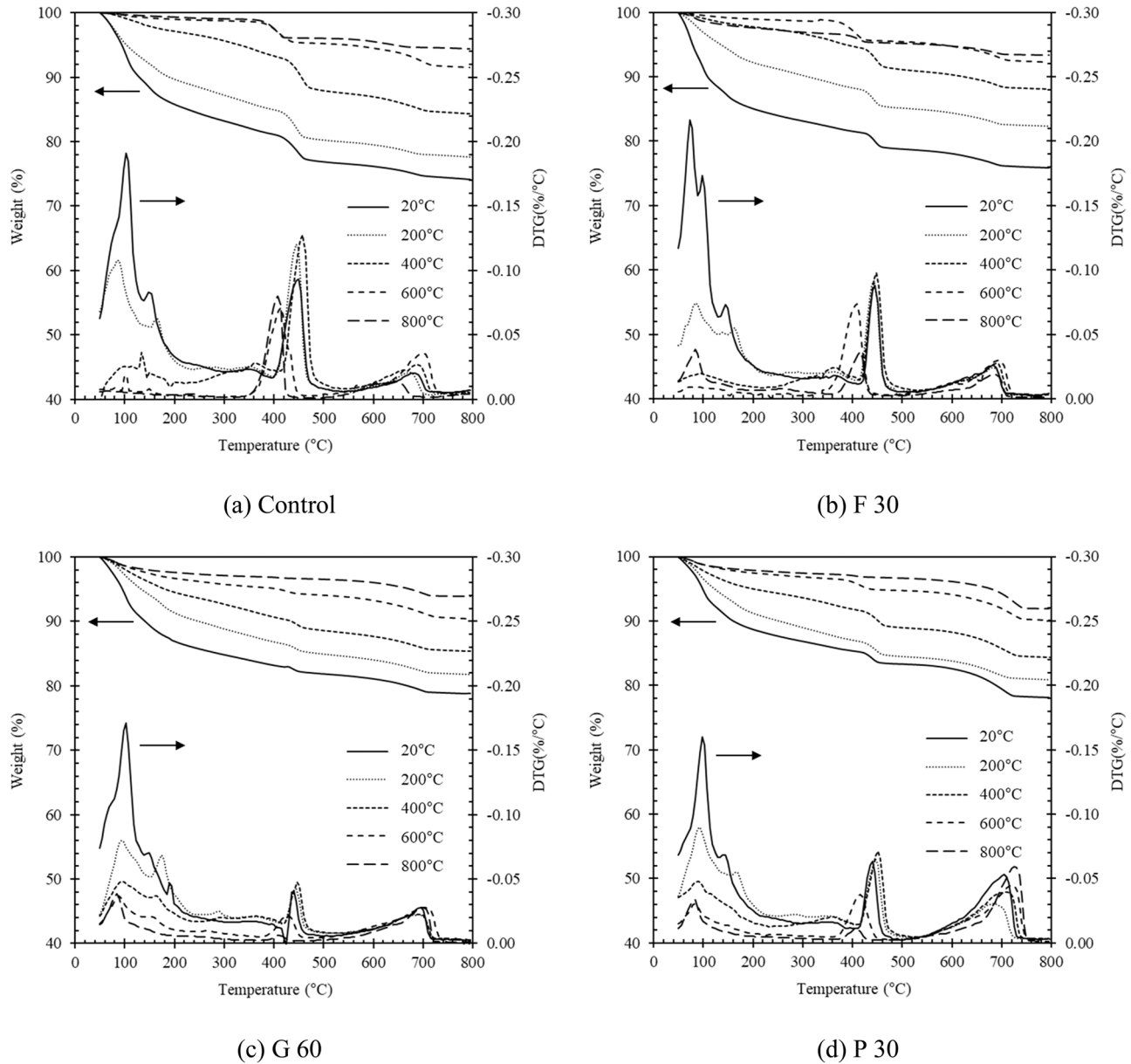


Fig. 9. TG and DTG curves of paste specimens at elevated temperatures up to 800 °C.

**Table 5**  
CH and BW content of paste specimens obtained from TG-DTG result (% mass).

		Exposure temperature (°C)					
		20	200	400	600	800	
Control	BW	23.88	20.53	13.06	5.49	4.49	
	CH	19.18	20.44	22.87	13.77	6.73	
F 30	BW	21.90	15.63	9.65	5.28	5.20	
	CH	11.15	13.37	15.19	13.72	6.07	
G 60	BW	18.93	15.98	12.36	6.75	4.00	
	CH	4.70	7.54	8.37	4.88	1.44	
P 30	BW	17.42	16.19	11.72	5.92	3.82	
	CH	8.60	10.27	11.91	7.63	2.23	

- 1) Compressive strength for the blended paste at room temperature indicates that FNS can be an alternative as a cementitious material in mortar and concrete. However, the replacement ratio must be carefully adjusted in determining mix design. To secure comparative or even better mechanical properties at early ages, high volume replacement would be avoided due to the low reactivity of FNS powder.
- 2) The residual strength after exposure to high temperatures improved with the binder replacement, and among them, FNS powder was more outstanding. Particularly at above 400 °C, the FNS incorporation produced lower average pore diameter, linked with the residual strength. Although cracks on the surface for the FNS mixture were observed after 800 °C, it can be mitigated with increasing replacement ratio within optimum levels that satisfy better mechanical properties.
- 3) XRD and TG-DTG analysis revealed the presence of other types of hydrates (i.e., hydrotalcite and ferric/ferrous hydroxide) in FNS modified specimen at high-temperature environments. Unlike C-S-H gel and CH, after 400 °C, there was still existed in the mixture, which may produce a better fire resistance due to a modification of pore structure. However, a higher alkaline environment to promote their formation accompanies lower FNS replacement and thus reduced economic benefit.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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