

## Review Article

# Characterization of Portland Cement Incorporated with FNS

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The potential use of ferronickel slag (FNS) as supplementary cementitious material has been widely researched in recent years. Although much research was carried out on utilizing FNS as a binder, its advantages and disadvantages are still not clear. To properly use FNS as a cement replacement, this paper summarizes the following. (1) Changes expected on the oxide composition of FNS powder are due to the forming ores, fluxing stone, and cooling method. (2) The decreasing of the hydration heat evolution rate was detected by hydration heat evolution test and this is due to the low content of CaO and Al<sub>2</sub>O<sub>3</sub> component in FNS. (3) It was found that the incorporation of FNS forms a dense pore structure more than cement mix and this is due to the secondary hydration reactions. (4) Hydration characteristics of FNS were assessed by pozzolanic reactions unexpectedly detected and incorporation of FNS creates C-S-H gel and hydrotalcite. (5) The development of strength was tested by compressive strength, splitting tensile strength, and flexural strength. From the results, the reduction of compressive strength was detected at an early age but substantially increasing at the long-term curing ages. However, splitting tensile strength and flexural strength of concrete have shown various trends. (6) There is an improvement in the resistance to chloride penetration and sulfate attack while susceptible to carbonation. This is induced by the lowered pH in pore solution due to the reduction of Ca(OH)<sub>2</sub> by substituting FNS binder. Finally, (8) ternary blended mixtures with conventional cementitious materials are an option to properly use FNS as a binder.

## 1. Introduction

Ordinary Portland cement (OPC) has been widely used in various parts of the world until recently. However, technological advances and environmental problems have led to the increased use of other supplementary cementitious materials. Significantly, the environmental load on CO<sub>2</sub> emission, which arose from the cement production, is 4–5% out of the entire output of human beings, and it has become a considerable problem of construction [1]. Hence, Portland cement mixed with other materials, such as ground granulated blast furnace slag (GGBS) from pig iron smelting or fly ash from coal-fired power plants (PFA), have increased popularity. But, these traditional admixtures already cannot be easily obtained in many places due to the surge in use. Consequently, finding new construction materials is an important issue not only for the replacement of cement but also for complementation of conventional admixtures. From

this point of view, research on the direction in which ferronickel slag (FNS) can be used as a substitute for cement is actively conducted.

Ferronickel slag (FNS) is a by-product obtained from the primary industry of smelting of laterite ore in an electric arc furnace at a high temperature with a reducing agent for the production of ferronickel. It is assumed that 1 ton of ferronickel may generate about 14 tons of FNS [2–4]. In particular, 30 million tons of FNS is produced in China [5] and 2 million tons in South Korea annually [6].

The utilization of FNS in concrete has been studied as aggregate by using pelletized type [6]. Because of its characteristics of low absorption rate, dense structure, and high hardness, FNS is considered to be usable as a fine aggregate for concrete [7, 8] and road construction [9]. Recently, the strength properties of concrete [10] and alkali-silica reactivity due to the high content of amorphous silica in FNS [2, 11] have been studied. Also, durability characteristics of

mortar [12] and concrete [13] incorporating slag aggregate with traditional supplementary cementitious materials were examined.

Likewise, the physical properties of FNS are suitable to use as an alternative and in concrete [11]. Nevertheless, due to a significant silica amount, FNS has shown reactivity when used with cement or/and alkali in geopolymers [14]. As a result, most FNS are landfilled [6, 15] due to the potential reactivity and unexpected hazardous effect. And the disposal of FNS has been pointed out concerning heavy metal reaching on the landfill area [16] and health issues to the neighbors [17]. Thus, using the FNS wastes in concrete would be one solution to reduce the problem of a landfill and save energy in construction [6].

Though suspicious of its applicability, many studies about FNS as a binder reported good physical performance and reactivity. According to the literature [3], the replacement of cement with FNS increases the degree of polymerization of silica chains in C-S-H gel and improves the resistance of concrete to chloride ion penetration. Pozzolanic reaction of FNS was also observed in some studies [18, 19], in which, in other words, the arguments about soundness reactivity in FNS aggregate is in fact advantage of using FNS as binder since the reactivity is necessary for hydration [6]. Lately, to utilize ferronickel slag as a substitute material for cement, microhydration heat, flow, compressive strength, and drying shrinkage variations were investigated [20], which means that it can potentially perform as cementitious materials. Lately, the proper replacement ratio of FNS to replace OPC was also suggested at 20%, depending on fineness [21]. Therefore, the utilization of FNS can be beneficial to reduce cement production costs and less energy-consuming.

As stated above, recent studies show that there is a potential to utilize FNS as construction materials. However, the use of industrial by-products as cementitious materials may reveal different properties compared to conventional materials [22]. Moreover, its advantages and disadvantages as a cement replacement are not clearly determined, despite many research projects conducted in the field. Therefore, in order to properly use FNS, this paper summarizes recent research about using FNS as cementitious materials.

## 2. Characteristics of FNS as a Binder

**2.1. Properties of FNS Powder.** The properties of FNS powder obtained from researches are tabulated in Table 1. FNS can be categorized into two categories. For example, FNS used in [15, 18] mainly consisted of  $\text{SiO}_2$  and  $\text{Fe}_2\text{O}_3$  while FNS used in other researches was generally composed of  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{MgO}$ . This can be explained because the composition of slag materials changes depending on the ores, fluxing stone, and cooling method. Generally, nickel slag generated from laterite ore contains a high amount of  $\text{Fe}_2\text{O}_3$  and low  $\text{MgO}$ , whereas garnierite ore contains low  $\text{Fe}_2\text{O}_3$  and high  $\text{MgO}$  [4]. Its minerals consist of crystalline phases such as enstatite, forsterite, fayalite, diopside, and spinel phase [11, 18, 23]. Generally, slag can be classified into their basicity index [6]. Nkinamubanzi et al. [24] suggest that the

potential reactivity of slag powder can be anticipated by calculating the simplest basicity coefficient of the raw materials from chemical composition. The basicity coefficient ( $\text{CaO}/\text{SiO}_2$ ) of slag greater than 1 indicates higher reactivity since the formation of hydration products is possible under the alkali condition. Based on the suggested equation, the basicity ratio of FNS is seen around 0.01–0.66; thus, it can be assumed that FNS has low hydraulic reactivity.

Nowadays, ferronickel slag is usually categorized as electric furnace ferronickel slag and blast furnace ferronickel slag depending on the production process. The type of FNS used in references is also specified in Table 1. Figure 1 shows the shape of the electric arc furnace ferronickel slag (EFS) and blast furnace ferronickel slag (BFS). As shown in Figures 1(a) and 1(b), both EFS and BFS particles are irregular and exhibit light grey color, thus hard to distinguish. From the literature [3], EFS mainly consisted of  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{MgO}$ , while BFS are  $\text{CaO}$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$ . Moreover, the  $\text{CaO}$  content in the EFS powders (1.01%–8.24%) is much lower than the BFS (22.50%–25.19%). Thus, types of FNS should be distinguished since the composition of these two types of FNS is significantly different. Moreover, in general, fineness is related to the operating condition and purpose of the application. Thus, the fineness of FNS used in research varied from 3,400 to 26,300, while the density of FNS ranged from 2.87 to 3.18, respectively. Moreover, in general, fineness is related to the operating condition and purpose of the application. Thus, the fineness of FNS used in research varied from 3,400 to 26,300 while the density of FNS ranged from 2.87 to 3.18, respectively.

**2.2. Effect of FNS Properties of FNS Powder.** The hydration heat evolution is an exothermal chemical reaction based on the mineralogical composition of the cement composites. The reactivity of binders in the cement matrix can be estimated by observing the hydration heat evolution. The exothermic rate and cumulative hydration heat of cement mix with FNS were analysed using a TAM-Air isothermal calorimeter at a constant temperature of 25°C, according to ASTM C1702 [26]. The literature results are shown in Figure 2. Three electric arc furnace FNS powders (EFS1, EFS2, and EFS3) and two blast furnace FNS powders (BFS1 and BFS2) were used in this literature. The hydration process of FNS can be divided into three steps, which is similar to that of ordinary Portland cement. However, the second exothermic peak in the composite binders is obviously lower. As shown in Figure 1(b), the cumulative hydration heat curves of the binders containing the EFS powders are nearly identical, and the total heat released is much lower than the binders containing the BFS powders. This result may be arisen by the low content of active components, such as  $\text{CaO}$  and  $\text{Al}_2\text{O}_3$ , in the EFS powders. Therefore, the replacement of cement by FNS results in a decreased hydration heat evolution rate and a decreased second peak value compared to cement. Consequently, the use of FNS can reduce the amount of heat generation, which is relevant to the risk of thermal cracking in concrete and has important implications for using this material at the construction site.

TABLE 1: Chemical and physical properties of FNS as a binder.

Oxides	[3]	[6]	[15, 18]	[22]	[23]	[25]
SiO <sub>2</sub>	29.95–50.48	40.46–40.81	41.18	37.47	48.23	51.0
Al <sub>2</sub> O <sub>3</sub>	3.08–26.31	2.65–3.64	5.98	21.37	3.59	2.20
Fe <sub>2</sub> O <sub>3</sub>	1.55–14.36	6.87–9.07	40.02	1.72	15.76	15.5
MgO	8.93–32.61	40.44–43.43	7.79	10.53	23.01	27.4
SO <sub>3</sub>	0.04–1.31	0.26–0.53	0.64	0.32	0.50	0.1
CaO	1.01–25.19	3.61–6.60	4.12	24.82	6.28	0.6
Na <sub>2</sub> O	0.12–0.32	0.02–0.04	0.09	—	—	—
K <sub>2</sub> O	0.07–0.40	0.05–0.08	0.37	—	0.09	—
Cr <sub>2</sub> O <sub>3</sub>	1.37–2.47	0.73–0.95	2.75	—	—	—
NiO	0.02–0.19	0.02–0.05	0.13	—	—	—
LOI	—	—	-3.44	0.68	—	—
<i>Physical characteristics</i>						
Fineness (cm <sup>2</sup> /g)	3,910–4,610	4,660–26,300	3,985	—	3,400	4,666
Density (g/cm <sup>3</sup> )	2.87–2.97	3.02–3.05	3.18	—	3.14	3.05
Source (type)	China (electric arc furnace, blast furnace)	South Korea (electric arc furnace)	Greece (electric arc furnace)	China (—)	South Korea (electric arc furnace)	South Korea (—)

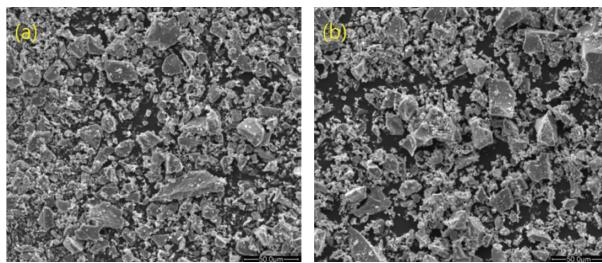


FIGURE 1: Morphology of FNS: (a) EFS and (b) BFS [3].

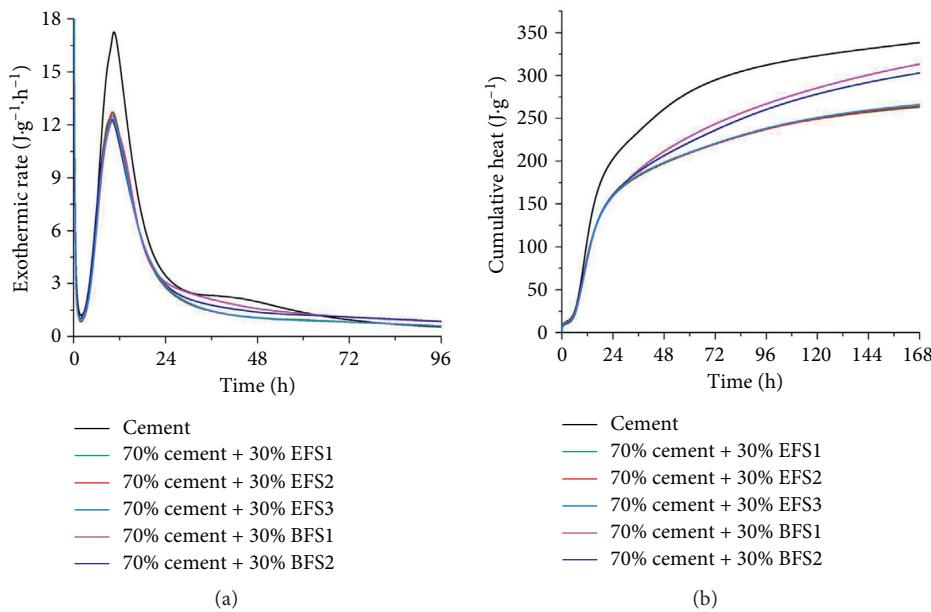


FIGURE 2: Effects of FNS on cement hydration kinetics. (a) Exothermic rate and (b) cumulative heat [3].

**2.3. Effect on Pore Structure.** Hydration reactions are attributed to the pore structure, and porosity generally decreases with age in the curing condition for cementitious materials [27]. For an evaluation of porosity in the cement matrix, many test methods, such as X-ray tomography, nitrogen adsorption, and nuclear magnetic resonance (NMR), have been applied. However, the mercury intrusion porosimetry (MIP) is the most conventionally used test to identify the pore structure of the cement matrix. Literature [3] applied MIP to the hardened FNS paste and divided the pore structure into four ranges: gel micropores ( $<4.5\text{ nm}$ ), mesoporous ( $4.5\text{--}50\text{ nm}$ ), middle capillary pores ( $50\text{--}100\text{ nm}$ ), and large capillary pores ( $>100\text{ nm}$ ). Then, by using a replacement ration of 30% in the cement paste with a blast furnace FNS, a similar range of large capillary pores volume was observed compared to OPC paste. Thus, it was suggested that it contributed to an improvement in the densification of the pore structure [6]. On the other hand, [28] classified the pore structure as macropore ( $>10\text{ nm}$ ); large capillary ( $0.5\text{--}10\text{ nm}$ ); small capillary ( $0.01\text{--}0.5\text{ nm}$ ); and gel ( $<0.01\text{ nm}$ ). Based on their classification, they suggested that the high fineness of FNS made the pore structure denser by ball bearing effect and presence of hydrotalcite. In addition, [25] also studied the MIP test results of 30% FNS paste at different curing ages. Results obtained at the curing age of 28 days and 90 days had a porosity of 30.12% and 29.13%, respectively. From the test results, the authors stated that the secondary hydration reaction of FNS creates C-S-H gel and hydrotalcite; subsequently, it induces the reduction of macropores. Thus, it was confirmed that the incorporation of FNS forms a dense pore structure and new hydration products due to the secondary reactions.

**2.4. Effect of FNS on Fresh State.** The concrete mix should have enough workability to facilitate the pouring and casting work at the construction site. The determination of the normal mortar flow was carried out according to ASTM C1437 [29]. Table 2 presents the fresh concrete properties of blended mix with FNS. The FNS containing cement demanded relatively less water than OPC, and the authors suggested that less water demand was attributed to the delayed hydration of slag. The flow tests confirmed the above results and showed that FNS addition improves the mortar workability. It was found that the replacement of cement with the less reactive admixtures leads to reduced amounts of hydration products formed during the early hydration stages, thus resulting in higher workability of the mortar.

The setting times of mixtures in literature [18, 30] were determined following the European Standard EN 196-3 [31] and Australian Standards [32] while [6] followed a standard test method [33]. All blended cement showed relatively longer setting times, rather than OPC. And the setting time generally increased with the increment of the percentage of the admixtures. The initial and final setting times for the highest FNS substituted specimen were found to be up to 140 min longer than those of OPC. The addition of FNS is then expected to delay the hydration process and increase

setting times, a fact that was confirmed by the results of the flow tests.

### 3. Physical Properties of FNS Mortar and Concrete

**3.1. Compressive Strength.** In the hardened state, for mortar and concrete containing supplement cementitious materials, compressive strength primarily depends on the replacement ratio, water-to-binder ratio, amount of cementitious materials, curing type, and curing age. The compressive strength results at 28 days of curing age for different FNS content mortar and concrete were collected from research papers and are presented in Figure 3. It clearly shows that compressive strength for FNS mortar and concrete was strongly dependent on FNS content; an increased replacement of cement by FNS resulted in a reduction in the compressive strength for FNS mortars. The blended cement containing 30% FNS substitution presented the lowest compressive strength in all previous research. In particular, [6] showed a strongly reduced compressive strength in a mix with 30% FNS, only 30.17 MPa, while the lower substitution rates of 5 and 10% accounted for 34.6–36.24 MPa, respectively. However, it is crucial to consider that the FNS used in their study had different fineness; for example, the fineness accounted for  $4,660\text{ cm}^2/\text{g}$  at 30% replacement while  $8,600\text{ cm}^2/\text{g}$  at 10% and  $26,300\text{ cm}^2/\text{g}$  at 5%.

Furthermore, due to the replacement of clinker in cement by supplementary cementitious materials, the mixture further extends that curing age should be accompanied [34]. To evaluate the relationship between the development of compressive strength and curing ages, [18, 25] monitored the compressive strength at a later age with FNS contents varying as 5, 10, 15, 20, and 30%, as given in Figure 4. As shown in Figure 4, all FNS mortars developed relatively lower strength than OPC at all curing ages. However, the curve of 5% FNS from 28 days to 91 days shows an almost identical curve with OPC. Thus, it can be assumed that FNS showed less reactivity and retarded development of compressive strength. Moreover, at later ages, the gap between OPC and FNS mortars and concrete was gradually reduced. For example, the compressive strength of FNS mortars at 91 days was 62.8, 60.1, 59.1, and 58.2 MPa for 5, 10, 15, and 20% FNS, respectively, while OPC reached 63.5 MPa. Reference [25] found that the strength activity of 30% FNS mortar at 28 and 91 days was 79 and 86% while 95 and 100% for concrete, respectively. This result indicates that the reactivity increases over curing. Thus, it is evident that compressive strength for FNS mortar and concrete is strongly dependent on curing ages, which imply latent hydraulic or pozzolanic reaction.

**3.2. Diverse Strength.** Although the advantage of reduced water demand in the FNS mix was reported, low water-to-binder ratio induced delayed setting time and low early age strength. However, the enhancing effect of FNS concrete in strength development was reported by [6], as shown in Figure 5. These strength values were more or less in a limited range to OPC, depending on the fineness of FNS. As for the

TABLE 2: Summary of properties of FNS cement at the fresh state.

Reference (specimen)	Water-to-binder ratio	FNS content (%)	Water demand (%)	Flow (%)	Setting time (minute)	
					Initial	Final
[6] (mortar)	0.5	0	—	—	392	541
[6] (mortar)	0.5	5	—	—	433	557
[6] (mortar)	0.5	10	—	—	485	612
[6] (mortar)	0.5	30	—	—	493	680
[18] (paste)	0.25	0	27.8	97.5	145	185
[18] (paste)	0.25	5	27.6	100.2	150	195
[18] (paste)	0.25	10	27.0	104.7	160	200
[18] (paste)	0.25	15	26.5	107.9	170	215
[18] (paste)	0.25	20	26.1	110.5	175	220
[30] (paste)	0.5	0	30.0	—	130	190
[30] (paste)	0.5	20	29.0	—	130	200
[30] (paste)	0.5	30	28.0	—	130	200
[30] (paste)	0.5	40	27.5	—	140	200
[30] (paste)	0.5	50	27.0	—	130	200
[30] (paste)	0.5	65	27.0	—	150	230

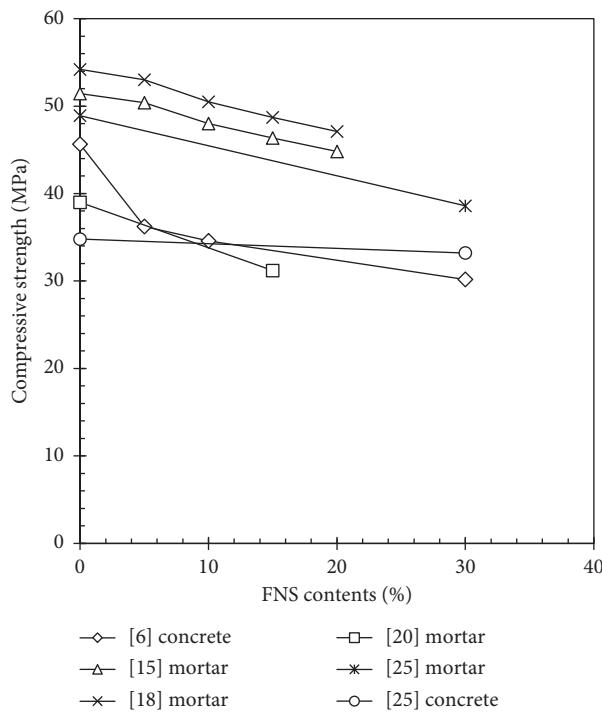


FIGURE 3: Compressive strength at 28 days of curing ages.

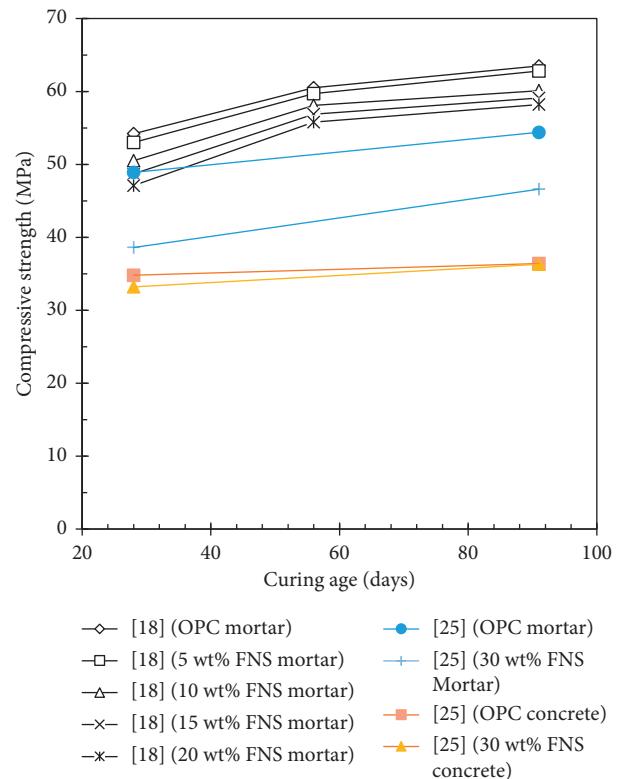


FIGURE 4: Compressive strength at different ages.

flexural and splitting tensile strength, an increase in the fineness of FNS increased the strengths. On the contrary, the FNS concrete benefited against OPC ones in producing the shear strength; all mixes for FNS increased the shear strength by about 14.9–16.1% points to the original value of 7.85 MPa. This study suggested that due to limited hydraulic reactivity, a large margin of FNS could be used in filling-up voids and pores in cement paste and even at the interfacial region between aggregate and paste. Thus, the strength development of the FNS mortar and concrete significantly altered by a combination of replacement ratio and fineness.

## 4. Durability of FNS Mortar and Concrete

**4.1. Influence on Physical Properties of FNS Mix.** After hardening, even though concrete is well designed, it can expand and crack. The main reasons for this unsoundness are caused by the MgO hydrates or strains induced by shrinkage. Due to the high content of MgO in FNS, a soundness test is necessary for using FNS as a binder. Moreover, investigation of the risk of drying shrinkage can confirm the reduction effect of FNS on the hydration heat

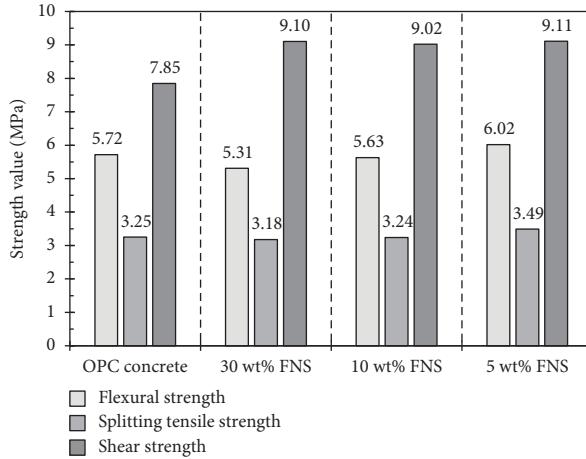


FIGURE 5: Strength characteristics of FNS concrete at flexural, splitting tensile, and shear strengths [6].

generation and water demand, which has been stated in some literature [3]. The autoclave expansion and drying shrinkage test were evaluated by [6, 30]. The autoclave expansion test, especially, is designed for measuring the potentially deleterious expansion by free MgO (periclase). According to [30], the autoclave expansion was not observed. Due to the reason that the MgO in FNS is in the form of crystalline, forsterite rather than free MgO, the autoclave expansion was not shown in FNS mortar. Reference [6] stated that the incorporation of FNS showed distinctively low drying shrinkage compared to OPC. The authors also added that high amount replacement of FNS instead of OPC could reduce microcracks in mass concrete structures, resulting in reduced maintenance cost.

**4.2. Resistance to Chemical Degradation.** To assess the resistance of FNS concrete against chloride ion penetrability, many researchers conducted rapid chloride penetration resistance (RCPT) [35]. Reference [3] reported that the pozzolanic reaction due to the addition of FNS dramatically improves the resistance of the concrete to chloride ion penetration. The studies conducted by [6] also confirmed the high resistivity of FNS in chloride attack. According to [6], the denser pore structure in FNS concrete restricts pore connectivity for external chloride ions, and then the corrosion risk would decrease.

Additionally, reference [6] observed that a high replacement ratio of low fineness FNS appears to be the most resistive after sulfate attack. During hydration, the unhydrated FNS clinkers might further have formed hydrotalcite consuming ettringite, one of the problematic hydrates in concrete structure due to volume expansion if sulfate attack is applied. This improvement of sulfate attack resistivity happens as a factor of the previous stated latent hydraulic and pozzolanic reactivity of FNS.

However, a high replacement of cement by cementitious materials may induce carbonation. Reference [6] investigated the carbonation depth of FNS mortar and stated that the FNS binder had a more dangerous aspect of carbonation

than OPC. According to the literature, the principal reason is the lowered pH in pore solution due to the reduction of Ca(OH)<sub>2</sub> by substituting the FNS binder. Also, low CaO content in the FNS compound was attributed to the extreme condition of calcium carbonate formation accompanied by high SiO<sub>2</sub> content, which requires Ca(OH)<sub>2</sub> to consume.

**4.3. Ternary Blended Cement Containing FNS.** To compensate for the disadvantages of the FNS binder, [18, 20, 23, 36] investigated ternary binders. It was found that ternary binders present relatively lower strength at all ages compared to OPC though the latter increased at later curing ages. The authors suggested that the reduction of strength development is attributed to the pozzolanic reaction at later ages. Reference [20] examined the characteristics of ternary mortar, including FNS with GGBS and PFA, replaced at 15% of cement weight. That study has shown that similar flow value and drying shrinkage were expected compared to binary mix with 100% replacement of FNS, while lower values are seen compared to OPC. Reference [18] investigated mixtures containing up to 20% of cement weight with FNS and/or natural pozzolans. They also concluded that delayed hydration and pozzolanic reaction appeared with the formation of secondary calcium silicate hydrate gel in the binary and ternary mix with FNS. Reference [23] studied the chemical reaction and performance of ternary blended binders by mixing FNS and PFA. It was confirmed that C-S-H gel was formed more than only PFA was mixed by the pozzolanic reaction of FNS and PFA. Reference [36] also states that the ternary mix using FNS and GGBS contributed to the dense pore structure. Likewise, ternary binders with conventional cementitious materials and FNS can optimize the properties of the FNS mix.

**4.4. Summary and Future Research.** A summary of the test results of incorporating FNS as a binder is displayed in Table 3. The fresh concrete properties of FNS blends demanded relatively less water than OPC, and the flow tests confirmed FNS addition improves the mortar workability. In the case of setting time, the initial setting was delayed at least 3% to a maximum 26% while the final setting was increased at least 3% to a maximum 26%. The setting time results showed a large difference when compared between references, but a typical one shows that the hardening process is delayed when FNS is mixed.

As a result of measuring the compressive strength, it showed a tendency to decrease compared to OPC concrete varying from 1% to 33%, while there was a case where it increased depending on the fineness or curing age. Although FNS incorporation in the cement mix resulted in a decreased compressive strength compared to OPC, the difference was not significant.

As for diverse strength, tensile and splitting tensile strength values were more or less in a limited range to OPC while enhancing shear strength. Based on the strength development, the FNS mix has a high potential for structural concrete, considering that it accompanies a further reinforcement to compensate for the weakness.

TABLE 3: Summary of results for the incorporation of FNS in Portland cement as a binder.

Experiment	[3]	[6]	[15, 18]	[25]	[30]
Flow	—	—	↑	—	—
Water demand	—	—	↑	—	↑
Setting time	—	↑Initial (10–26%) (3–26%)	↑Final (3–21%) (5–19%)	—	↑Initial (8–15%) (5–21%)
Compressive strength	↓ (1.4–6.2%) or ↑ (0.8–4.9%)	↓(21%)	↓ (1–8%)	↓(14%) or ↑(100%)	↓(7–33%)
Flexural strength	—	Various	—	—	—
Splitting tensile strength	—	Various	—	—	—
Shear strength	—	Enhanced	—	—	—
Expansion	—	↓	↑(but moderate)	—	Moderate
Shrinkage	—	↓	—	—	—
Chloride resistance	Enhanced	Enhanced	—	—	—
Sulfate resistance	—	Various	—	—	—
Carbonation	—	↓	—	—	—

When it comes to durability, due to denser pore structure formation, the risk of penetration of external ions such as chlorides and sulfates will decrease. Especially for the case of sulfate attack, the high substitution of FNS is most resistive regarding consuming ettringite, which is one of the problematic hydrates if sulfate attack is applied. As seen in Table 3, carbonation was found to be a more dangerous aspect. And this is induced by the lowered pH in pore solution by replacing the FNS binder.

From the summary, the use of FNS has the potential to be a supplementary cementitious material and beneficial for the environment. It is evident that finding new cementitious materials is an urgent issue in the construction industry due to the demand for cement expected to increase. Currently, the utilization of FNS has been studied increasingly as a binder. Concerning the soundness reactivity, there is still caution of its application, but studies about FNS reported favorable environmental and physical performance. The leaching test conducted from [15] indicated that leachable heavy metals in FNS were substantially below the regulatory thresholds. Reference [30] reported that there is no soundness effect on the expansion.

The research that currently exists with respect to FNS use has reported that it has the potential to perform as cementitious materials. Cement with environmentally friendly materials such as FNS may become beneficial to be more employed. The benefits of cementitious materials application are not only constrained to the properties of concrete but also a significant reduction in economic and environmental costs [37]. Thus, FNS can be used as a binder with a positive effect on the environment. Notwithstanding the advantages of using industrial by-products, however, a study on the long-term durability and performance of FNS blends is not sufficient. As suggested in Table 3, recent research is insufficient for external environment resistance of concrete, such as freeze-thaw resistance and high alkali environments. Moreover, as shown in Table 1, the type of FNS used in references is not well documented. The difference in sources and manufacturing process produces a different chemical

composition, although it has similar morphology. It is also important that MgO contained in FNS should not be confused as soundness because it is crystalline phases such as enstatite, forsterite, fayalite, diopside, and spinel phase [11, 18, 23] that are different from brucite ( $Mg(OH)_2$ ) which causes expansion. In other words, as CaO is divided by free CaO (lime), MgO must be divided by Free MgO. It should not be evaluated as suspicious without consideration of the form of oxide not only for utilizing FNS but also for improving the utility of industrial by-products as construction materials. Consequently, further research must be carried out to safely use and prevent inadequate properties of FNS.

## 5. Conclusion

This paper summarized the effects of FNS use on mortar and concrete properties, as shown in Table 3. And several insights have been gained through the conducted published literature:

- (1) The composition of FNS powder changes depending on the ores, fluxing stone, and cooling method. Its minerals mainly consist of crystalline phases such as enstatite, forsterite, fayalite, diopside, and spinel phase due to the nickel ore.
- (2) Based on the basicity coefficient equation, FNS has low hydraulic reactivity. Thus, the use of FNS can reduce the amount of heat generation that is relevant to the risk of thermal cracking in concrete. Also, the addition of FNS increases setting times and workability by delaying the hydration process.
- (3) The replacement of cement by FNS results in an overall reduction in the compressive strength for FNS mortars and concrete. However, at later ages, the strength was gradually increased due to increased activity of FNS over curing.
- (4) Limited hydraulic reactivity of FNS plays a role in a cement matrix as filling-up voids and pores in

- cement paste and even at the interfacial region between aggregate and paste.
- (5) Due to the presence of MgO in FNS in the form of crystalline rather than free MgO, no negative expansion was detected in the FNS mix. Furthermore, incorporation of FNS showed distinctively low drying shrinkage compared to mix with OPC only.
  - (6) The addition of FNS improves the resistance of concrete to chloride ion penetration and sulfate attack while it might be more vulnerable to carbonation due to the reduction of Ca(OH)<sub>2</sub> hydrates and a consequent reduction of pH.
  - (7) Ternary mix with conventional binders and FNS showed similar properties. Moreover, more C-S-H gel was formed in the ternary mix. The formation of additional C-S-H gel implies that the ternary mix may improve the properties of blended mixtures with FNS.
  - (8) Related to the FNS mix's performance, there is a lack of research for long-term durability and severe external resistance such as freeze-thaw resistance and a high alkaline environment. To properly use the FNS in the construction industry, further research should conduct.
  - (9) The oxide composition in FNS strongly depends on the sources and manufacturing process method. Therefore, the categorization of the FNS according to the chemical composition of the FNS should be conducted.
  - (10) MgO contained in FNS should not be confused as soundness because it is crystalline phases that are different from brucite (Mg(OH)<sub>2</sub>) which causes expansion.

## Data Availability

All data have been disclosed in this manuscript.

## Conflicts of Interest

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

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