Effect of heat curing on early strength of high-performance mortar containing ferronickel slag as cement replacement

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Abstract. High-performance mortar (HPM) is a new material in construction projects which requires a huge amount of cement on its production. As a consequence, the cost of this material will increase. This problem can be solved by utilizing alternative binders combined with the latest curing technology to obtain a low cost of HPM without loss of quality. This study aims to examine the effect of heat curing on the compressive strength of HPM containing FNS as cement replacement in early days (7 days). The FNS was ground using a ball mill to achieve a fineness similar or higher than cement. A low water-to-cement ratio of 0.35 was chosen in this research. The series of HPM mixtures containing FNS used in this study were 0%, 5%, 10%, 15%, 20% and 30%. Heat curing at 75 °C was used to assess the performance of the HPM compared to normal curing. The particle size distribution of binders was determined using a laser diffractometer. The results showed that the presence of FNS in the HPM had a positive effect on the compressive strength at 7 days after applying heat curing. The use of heat curing at 75 °C increased the strength of HPM at 7 days.

1. Introduction

Nowadays, high-quality materials are required for construction projects all over the world. The demand for steel material for all types of structures such as high-rise buildings, long-span bridges and tower is still high because of its high performance. However, the erections of structural steelwork, such as assembling the steel components and connection need high-skill builders. Besides this, steel structure is more expensive than other materials such as concrete, mortar, and wood, which implies high cost if used as the main material for the construction project. Therefore, other materials mentioned above are more promising than steel to be used as the main material for the construction project in the future.

Mortar has been studied by many researchers. This material can be upgraded to achieve high performance by applying heat curing. This technology gives a significant effect on strength improvement in early days [1]. Other researchers noticed that polymer concrete’s high strength is achieved at heat curing temperature of 75 °C compared to 50 °C and 100 °C [2]. The application of heat curing technology to mortar and concrete seems to be more expensive than normal curing, hence it will need an additional combination to compensate for the high cost of heat curing, and the high quality of the material is still maintained.

Ferronickel slag, one of the supplementary cementitious material, has been studied by many researchers. Utilizing this slag can decrease material construction cost since this slag is a by-product of nickel mining, which has no economic value. The production of ferronickel slag keeps increasing because the production of nickel matte generates the same amount with its by-product. Therefore, it will be useful if the slag is upgraded in mortar production in order to minimize the environmental degradation.
2. Material and method

2.1. Cement and ferronickel slag

In this study, the authors used an Ordinary Portland Cement (OPC type I) with moderate C₃A throughout all tests, since this cement increased the compressive strength of concrete for longer curing periods compared to OPC type I with higher C₃A [3]. The chemical compositions and particle size distribution of OPC I are shown in Table 1 and Figure 1.

Ferronickel slag (FNS) used in this research was a waste slag from FeNi IV Plant of Aneka Tambang Company (Indonesia). Besides FeNi IV, this company has three smelters (FeNi I, FeNi II, and FeNi III), which generates nickel matte and three slag types. FeNi IV produces solid-granulated ferronickel slag with less porosity. Before using the FNS in mortar, the slag was ground intensively using a ball mill with vertical rotation for four hours. According to literature, high energy is needed to grind the slag which has a toughness of 6-7 Mohs hardness [4]. Since the hardness of FNS is about 6.5 of Mohs scale which is comparable to copper slag [5], applying a long duration of grinding time (four hours) for FNS in the present work is chosen to achieve a particle size of FNS smaller than OPC. Both the chemical compositions and grain size of FNS are given in Table 1 and Figure 1.

| Constituents | OPC I | FNS |
|--------------|-------|-----|
| SiO₂         | 19.9  | 53.6|
| Al₂O₃        | 5.3   | 5.5 |
| CaO          | 64.1  | 5.2 |
| Fe₂O₃        | 3.0   | 12.7|
| MgO          | 2.4   | 20.9|
| SO₃          | 1.9   | 0.2 |
| C₃S          | 51    | -   |
| C₂S          | 24    | -   |
| C₃A          | 6     | -   |
| C₄AF         | 11    | -   |
| Blaine permeability (cm²/g) | 3350 | -   |

Figure 1. Particle size distribution of FNS and OPC I by laser diffraction

2.2. Sand

Sand used in this study was natural aggregate from Pohara, Sulawesi Tenggara. This sand is normally used for normal concrete. The physical properties of sand are shown in Table 2.
2.3. Superplasticizer
In this study, a polycarboxylate ether superplasticizer (PCE) (MasterGlenium Sky 8851) was used throughout all experiments. This superplasticizer is designed to obtain good workability, high early, and final strengths in hot weather concreting. In addition, MasterGlenium Sky 8851 has long side chains which separates the cement particles at the start of the mixing process to achieve the slump retention and prevent the hardening of the mix.

2.4. Mix design
This mix design of HPM was taken from the mix design of high-performance concrete [6] which excluded the coarse aggregate. A water-to-cementitious (cement+FNS) ratio of 0.35 was chosen for this research. The effect of FNS as supplementary cementitious material (SCM) was studied with the replacement levels of 0%, 5%, 10%, 15%, 20%, and 30%. The HPM compositions used in this study are shown in Table 3.

2.5. Heat curing
Heat curing was performed after one day curing at room temperature. The samples were put on the steel grid in the curing box which is filled with water with a distance of ±2 cm to the samples. The maximum temperature was set at 75 °C with a heating rate of 0.2 °C/min. It is always mentioned in the literature that heat curing accelerates the hydration heat [7,8]. However, some researchers found that heat curing increases the porosity because of the variance in the coefficient of thermal expansion of mortar components [9]. Other literature reported that heat curing at 240 °C increased the strength of reactive powder concrete (RPC) in early days (7 days) and decreased at longer curing periods (28 days) [10]. In addition, Heinz and Ludwig [11] noticed that heat curing at higher temperature increased the strength of ultra-high performance strength (UHPC) in early days (1 day) and also decreased the strength at 28 days of curing periods. The later phenomenon occurred for the heat curing at a temperature higher than 90 °C which is due to the temporary relaxation effect. So, in this study, a 75 °C was chosen to prevent the negative effect on the strength of HPM.

3. Results

3.1. Effect of FNS
In Figure 2, the results of the compressive strength of HPM are presented. In general, it can be seen that the strength of HPM is decreased as increasing the FNS content at 7 days of normal curing. For heat curing at 7 days, the strength of HPM containing a lower replacement level of FNS (5% and 10%) increased compared to the reference mixture. However, for the higher replacement level of FNS (15%, 20%, and 30%) the compressive strength of HPM decreased after applying heat curing.

From Figure 3, it seems that the use of FNS as cement replacement after applying normal curing gave a negative effect on strength enhancement compare to reference. For lower replacement levels
(5\% and 10\%), the strength of HPM decreased by about 1.4\% and 3.8\% respectively. This phenomenon also occurred for higher replacement levels (15\%, 20\%, and 30\%), which decreased by about 5.1\%, 15.1\%, and 26.8\% respectively. However, these results are still higher than reduction of the strength of FNS content in which the compressive strength of concrete is calculated based on actual cement content, as shown in Figure 3. The reactivity of FNS tends to be higher after applying heat curing. The compressive strength of HPM with a lower amount of FNS (5\% and 10\%) was about 67.5 MPa and 65.1 MPa respectively which increased by about 6.8\% and 3.1\% compared to the reference mixture. For higher replacement level, the compressive strength of HPM decreased, except for 20\% which was comparable to reference mixture.

Figure 2. The strength evolution of HPM containing FNS at 7 days

Figure 3. Enhancement in compressive strength at 7 days (FNS HPM vs reference HPM)

The effects of FNS obtained in these current results can be compared with the findings of several literature. Kim et al. [12] found that the compressive strength of concrete containing a lower amount of FNS (5\% and 10\%) is higher and similar than reference mixture under normal curing at 7 days. The negative effect of FNS obtained in this current finding is due to the fineness effect of FNS which is only somewhat higher than that of cement fineness as seen in Figure 1. Comparing this result presented with the result obtained by Huang et al. [13], the strength of HPM containing 30\% of FNS in this current finding is higher than that of the finding of Huang et al. [13], especially for three types of electric arc furnace ferronickel slag powder (EFS). However, it can be observed that this current result is somewhat lower than mortar made with two types of blast furnace ferronickel slag powder (BFS) as reported by Huang et al. [13]. This can be explained by the fact that BFS used by Huang et al. [13] contains about 24\% of calcium oxide.
(CaO) and about 32% of silica oxide (SiO$_2$) which is more reactive than FNS used in this study (5% of CaO and 54% of SiO$_2$). The positive effect of FNS is achieved by applying heat curing at 75 °C. It can be said that the FNS is more reactive under heat curing. In addition, although the amount of CaO in the FNS is relatively low and the fineness of FNS is slightly higher than OPC, heat curing can activate the silica content from FNS to react with calcium hydroxide (Ca(OH)$_2$) from OPC to generate gel calcium-silicate-hydrate (CSH gel).

3.2. Effect of heat curing
Figure 4 depicts the effect of heat curing on the strength improvement of HPM at 7 days. It is clear that the use of heat curing at 75 °C enhanced the compressive strength of HPM compared to that of normal curing. The highest of strength development was achieved for 20% FNS which increased by almost 20% compared to normal curing. The use of heat curing seems beneficial for the strength enhancement of HPM containing FNS because they are higher compared to reference mixture, as shown in Figure 4. This achievement might be due to the chemical effect of heat curing, which speeds up the heat hydration of binders (cement and FNS) to form gel calcium-silicate-hydrate (CSH gel). In addition to the heat hydration of binders, heat curing contributes to pozzolanic activity of FNS which releases hydroxyl ion to consumes calcium ion from OPC. This result corresponds with the finding of Li et al. [14], who found the positive effect of heat curing on the strength improvement of mortar containing FNS in comparison to that of mortar plain. Regarding the phase evolution, it is often mentioned in literatures that heat curing transforms the phase composition from the amorphous CSH to crystalline CSH and then at higher temperature tobermorite and jennite CSH are generated, filling the air voids, and in the end the higher strength at early days is achieved [10,15].

![Figure 4. The evolution of strength of HPM (heat curing vs normal curing)](image)

4. Conclusions
Within this paper, heat curing was applied in analyzing the early compressive strength of high-performance mortar containing ferronickel slag. To obtain a higher reactivity of FNS as cement replacement, the size of FNS was reduced using a ball mill. Based on the result obtained, some major outcomes are listed as follows:

1. The use of FNS as cement replacement after applying normal curing gave negative effect on strength enhancement compare to reference.
2. The positive effect of FNS as cement replacement on compressive strength of HPM was achieved under heat curing, especially for lower replacement level (5% and 10%). Nevertheless, the strength decreased as increasing FNS content, except for 20% which was similar than for the reference HPM.
3. By applying heat curing to the mixture, the strength of HPM is technically increased for all replacement level of FNS compared to normal curing. In addition, the use of heat curing seems beneficial for the strength improvement of HPM containing FNS because they are higher than for the HPM without FNS.

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