Effect of Ferronickel Slag as Cementitious Material on Strength of Mortar

Romy Suryaningrat Edwin[1,a], Masykur Kimsan[1,b], Irmawatty Paula Tamburaka[2,c], Bambang Pramono[3,d], Asminar Azis[4,e], Philip Van den Heede[5,f], Nele De Belie[5,g], Elke Gruyaert[6,h]

[1]Department of Civil Engineering, Halu Oleo University, Kendari, Indonesia

[2]Department of Economics Development Studies, Halu Oleo University, Kendari, Indonesia

[3]Department of Information Technology, Halu Oleo University, Kendari, Indonesia

[4]Department of Electrical Engineering, Halu Oleo University, Kendari, Indonesia

[5]Ghent University, Magnel-Vandepitte Laboratory for Structural Engineering and Building Materials, Belgium

[6]KU Leuven, Department of Civil Engineering, Materials and Constructions, Ghent Technology Campus, B-9000 Ghent, Belgium

[a]romy.edwin@uho.ac.id, [b]masykur.kimsan@uho.ac.id, [c]irmatamburaka19@gmail.com, [d]bambang.pramono@uho.ac.id, [e]asminar2000@gmail.com, [f]Philip.VandenHeede@UGent.be, [g]Nele.DeBelie@UGent.be, [h]elke.gruyaert@kuleuven.be

Keywords: Ferronickel slag, flowability, flexural strength, compressive strength

Abstract. In this work, the performance of mortar made with ferronickel slag (FNS) as cement replacement was investigated. The granulated FNS was ground to obtain a fineness higher than cement. To assess the performance of FNS in fresh and hardened mortar, the workability, flexural, and compressive strength were experimentally assessed. Based on the results obtained, the fluidity of mortar increased with increasing FNS content. It was found that FNS did not promote the compressive strength of mortar in the early days of curing, but at longer curing times the FNS starts to react. Although there is a decrease in flexural strength of mortar containing FNS, this result tends to be better than the compressive strength performance. The presence of FNS in mortar increased the porosity.

1. Introduction

Since the mid 90's, concrete has become the main material for construction projects because of its advantages such as low cost, ease of application and low maintenance compared to other materials. The worldwide demand of concrete is rising for mega-infrastructure, especially high rise buildings, dams, and long span bridges. Beside aggregates, a concrete mix contains cement as a glue to bind the aggregates through its hydration. Cement production contributes to about 5 to 8% of anthropogenic CO_2 emissions globally [1], which is mostly generated from clinker production. In cement manufacturing, the production of 1 ton cement comes with a CO_2 emission of about 1 ton. As annual global cement production will increase to 3680 Mt (low estimate) or 4380 Mt (high estimate) in 2050 [2], this potentially will accelerate the relentless advance of climate change.

At the same time, environmental degradation caused by the dumping of large amounts of mining waste keeps increasing uncontrollably. Ferronickel slag (FNS), a by-product from ferronickel matte, also contributes to environmental damage. FNS contains harmful elements, which pollute water and soil in the mining area, causing serious health problems to humans. Therefore, utilization of the ferronickel slag in concrete production could be a sustainable solution.

2. Experimental Work

2.1. Material Properties and Mix Design

The materials used in this work were purchased from a Belgian Company, except for the Ferronickel Slag (FNS) which was obtained from Indonesia. FNS is a solid waste obtained from the smelting process of ferronickel alloy. Upon exiting the smelting furnace, the ferronickel matte is transferred to the next treatment, during which the slag undergoes a fast cooling process. Water is used during the air cooling process to granulate the slag. The grain size of FNS used in this study varied from 0.075 mm to 0.4 mm as result of the cooling process of Smelter Feni 4, Aneka Tambang Company, Indonesia. Based on the aforementioned particle size, this slag can directly be used as sand replacement in concrete or mortar. However, in current research, the slag is utilized as cement replacement, so that a size reduction is required to meet the standards of a cementitious material. The oxide composition of the Portland cement and slag is presented in Table 1. It is the result of an XRF analysis. The amount of silicon dioxide of FNS is moderate, indicating medium pozzolanic activity.

Table 1. Chemical compositions of binders determined by XRF [wt%]

Constituents	Cem I 52.5 N	FNS
CaO	67.00	5.16
SiO_2	18.20	53.60
SO_3	3.83	0.22
Al_2O_3	3.59	5.55
Fe_2O_3	2.83	12.70
MgO	2.08	20.90
K_2O	1.09	0.14
P_2O_5	0.40	-
TiO_2	0.23	-
Na_2O	0.20	-
SrO	0.17	-
Cl	0.14	-
ZnO	0.10	-
Cr_2O_3	-	1.20
MnO	-	0.50
NiO	-	0.06

The mix design of mortar used in this work is based on EN-196-1 [3] as seen in Table 2. To evaluate the strength performance of FNS applied in mortar relative to a reference mixture, two series of mixtures (10% and 20% by weight) were manufactured.

Table 2. Compositions of mortar mixtures with FNS (in g)

Mix Series	Cem I 52.5 N	FNS	Standard sand	Water
0%	450	0	1350	225
10%	405	45	1350	225
20%	360	90	1350	225

2.2. Physical Properties of Binders and Standard Sand

To obtain a particle size of FNS similar to or higher than cement, a long duration milling process (40 minutes) was applied. Next, the particle size and specific surface area (SSA) of the slag was measured using laser diffraction (Malvern Mastersizer 2000E) with size range 0.1 to 1000 microns, which was compared to the particle size and SSA of cement used in this study, as seen in Table 3. It seems that the particle size of FNS is lower than that of cement. Furthermore, the hardness of FNS seems to be lower than for copper slag since previous work by the authors [4] has shown that a particle size d_{50} of 37.72 µm for copper slag was only achieved after applying a long duration (1 hour) grinding process. The specific gravity of cement and FNS is also tabulated in Table 3.

Table 3. Particle size, SSA, and specific gravity of binders

Materials	Particle size d_{50} (µm)	SSA (cm^2/g)	Specific gravity (g/cm^3)
Cem I	15.907	3240	3.10
FNS	7.717	6270	3.15

The sand used in this study was standard sand cf. EN 1097-6, 1097-3 and EN 196-1. The physical properties of standard sand is shown in Table 4.

Table 4. Physical properties of standard sand

Particle size distribution (mm)	Oven-dried density (g/cm^3)	Loose bulk density (g/cm^3)
0.08 – 2.00	2.65	1.64

2.3. Flowability, Flexural and Compressive Strength

To measure the effect of FNS on the fresh state properties, the slump flow was tested cf. EN 1015-3:2006 [5]. After 7 and 28 days of normal curing at 20 ± 2 ºC, the specimens (40x40x160 mm prims) were also evaluated in terms of their flexural and compressive strength performance cf. [3].

2.4. Mercury Intrusion Porosimetry

To investigate the effect of FNS on the porosity, mercury intrusion porosimetry (MIP) was performed on the mortar specimens. After performing compressive strength tests, the samples were crushed and submerged in isopropanol for one hour to stop the reactions. Before starting the measurement, the specimens were put in liquid nitrogen for 15 minutes and transferred into a freeze-dryer. After 2 weeks, the constant mass was obtained and the samples were put into a dilatometer for MIP measurement (Thermo Scientific). The first step of MIP occurred at low pressure (140 kPa) to continue immediately with a high pressure step (200 MPa). The result of porosity is the average of two measurements.

3. Results and Discussion

3.1. Workability of Mortar

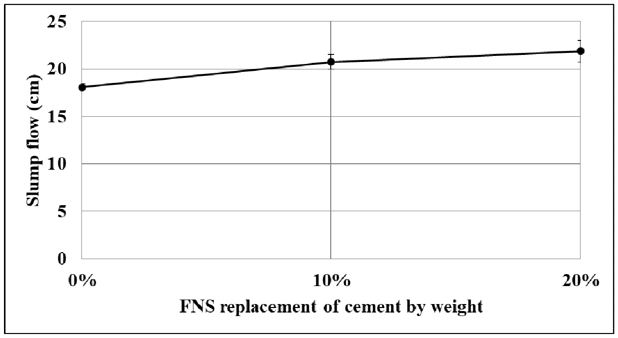

Fig. 1. Slump flow of fresh mortar containing FNS

Slump flow results of mortar are summarized in Fig. 1. The slump flow of mortar increased with increasing FNS content. This result is expected as the void ratio of mortar containing FNS will have been changed and will thus influence the fresh mortar consistency. This finding confirms the result of Katsiotis et al. [6], who found increased workability with increasing FNS content. It should be noted that despite the higher workability no segregation was observed. This result could be of value for the construction sector because it implies that concrete or mortar with FNS would be relatively easy to mix, transport and cast. Hence, it may reduce the labor and production cost.

3.2. Compressive Strength

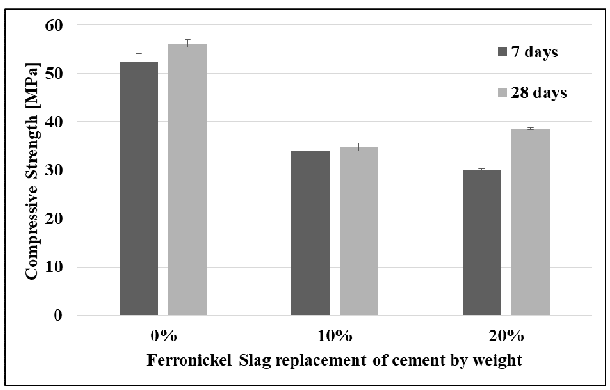

Fig. 2. Compressive strength evolution of mortar containing FNS (error bars represent standard errors, the average values represent three replicates)

The results of the mortar prisms after compressive strength investigation are seen in Fig. 2. For reference mortar, 52 MPa was achieved after 7 days of curing, while 56 MPa was obtained after curing for 28 days. For mortar with FNS, the decrease in compressive strength compared to the reference mortar occurred for all curing times. Moreover, the strength reduction transcends the proportion of slag as observed in Figure 2. Normally, the compressive strength of mortar at 28 days containing 10% and 20% of FNS should, in relation to the cement reduction, achieve about 50 MPa and 44 MPa, respectively. In fact, the results obtained were only about 34 MPa and 38 MPa for mortar containing 10% and 20% of FNS, respectively. It seems that FNS as cement replacement did not contribute to the compressive strength of mortar. It is mentioned in literature that the fineness effect plays a vital role in compressive strength development of FNS concrete [7]. Kim et al. [7] found that only concrete including 10% of FNS with a SSA of 8600 cm^2/g (2.6 times finer than cement) achieved a similar strength to the reference concrete. This means the use of FNS with a fineness lower than 2.6 times the cement fineness resulted in a compressive strength lower than the reference concrete.

Therefore, the result presented is expected as the fineness of FNS used in this study is only 2 times finer than cement. For 28 days of curing, the strength of mortar with 20% FNS is slightly higher than that of the 10% FNS. This indicates that there is FNS reactivity at 28 days, especially for 20% FNS. This result is in correspondence with the finding of Rahman et al. [8], who found a low reactivity of ferronickel slag at early days.

3.3. Flexural Strength

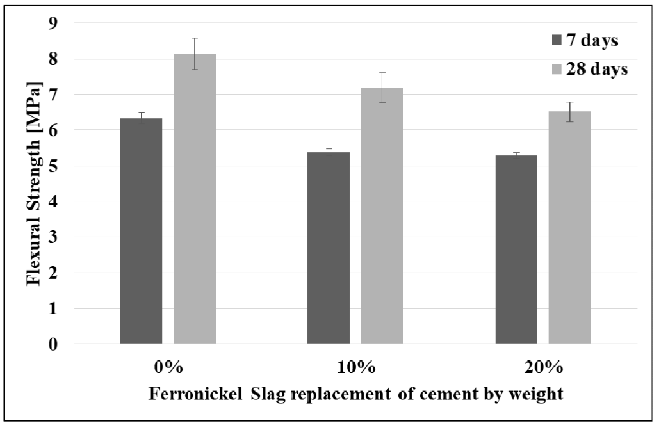

Fig. 3. Flexural strength evolution of mortar containing FNS (error bars represent standard errors, the average values represent three replicates)

The flexural strength evolution of mortar is shown in Fig. 3. The highest flexural strength was achieved by the control mixture. It decreases with a higher replacement level of cement by FNS. At early curing age, the flexural strength of mortar reduced from 6.3 MPa for the reference mixture to 5.4 MPa and 5.3 MPa for 10% and 20% FNS, respectively. For longer curing times, the flexural strength of the samples containing 10% and 20% FNS decreased from 8.1 MPa for the reference mixture to 7.2 MPa and 6.5 MPa, respectively. It seems that the use of FNS did not enhance the flexural strength of mortar. However, the decrease in flexural strength tends to be lower than that of the compressive strength results as described in the previous section. In general, the reactivity of FNS tends to be low in the early days of curing. Further research is needed to determine the reactivity of FNS for longer curing periods.

3.4. Porosity

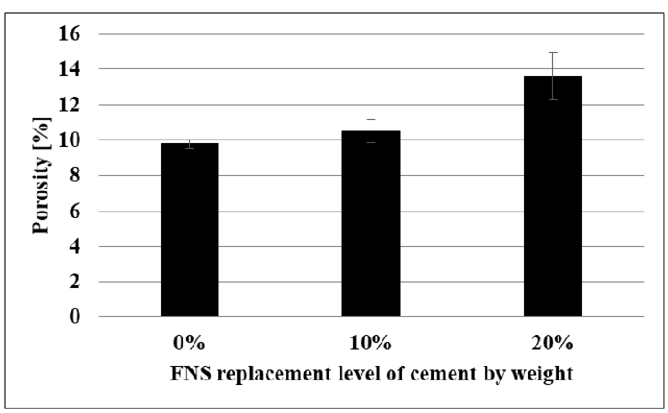

Fig. 4. Porosity of mortar containing FNS at 28 days determined by MIP

The effect of FNS replacement on the porosity of mortar is seen in Fig. 4. It is clear that the porosity of mortar increased with increasing FNS content. It seems that FNS addition had no contribution to porosity reduction. The low reactivity of FNS at early days might be the reasons for this phenomenon, as many hydration products are not yet produced to fill the capillary pores. This result confirms the result of compressive strength of FNS mortar as discussed in the previous section. However, this phenomenon might be temporary as porosity may be reduced by later age pozzolanic reactions as found by Huang et al. [9], so that further investigation is needed to see the effect of FNS on the porosity reduction for longer curing times.

4. Conclusions

An investigation of the effects of FNS as cement replacement in mortar is presented. The following conclusions can be made:

1. The fluidity of fresh mortar increased with increasing FNS content. This is caused by the change in void ratio of mortar containing FNS, which will influence the fresh mortar consistency.
2. The use of FNS as cement replacement did not enhance the flexural and compressive strength of mortar. However, a longer observation is necessary to see what strength performance can be achieved after reaction of the FNS.
3. The addition of FNS increased the porosity.

Acknowledgement
The authors would like to thank the Vlir-Uos, Belgium for providing the financial support to this research project (The South Initiative 2020-2021) with contract number: ID2020SIN281A101. Philip Van den Heede is a postdoctoral researcher financed by the Research Foundation - Flanders (FWO) (project No. G062720N) and gratefully acknowledges its support.

References

[1] W.B.C. for S.D. (WBCSD)/International, E.A. (IEA), Cement Technology Roadmap 2009 - Carbon emissions reductions up to 2050, 2009.
[2] A. Hasanbeigi, L. Price, E. Lin, Emerging energy-efficiency and CO 2 emission-reduction technologies for cement and concrete production: A technical review, Renew. Sustain. Energy Rev. 16 (2012) 6220–6238. https://doi.org/10.1016/j.rser.2012.07.019.
[3] EN-196-1, Methods of testing cement — Part 1: Determination of strength, 2007.
[4] R.S. Edwin, M. De Schepper, E. Gruyaert, N. De Belie, Effect of secondary copper slag as cementitious material in ultra-high performance mortar, Constr. Build. Mater. 119 (2016) 31–44. https://doi.org/10.1016/j.conbuildmat.2016.05.007.
[5] EN-1015-3, Methods of test for mortar for masonry - Part 3: Determination consistence of fresh mortar (by flow table). CEN, Brussels, 2006.
[6] N.S. Katsiotis, P.E. Tsakiridis, D. Velissariou, M.S. Katsiotis, S.M. Alhassan, M. Beazi, Utilization of Ferronickel Slag as Additive in Portland Cement: A Hydration Leaching Study, 6 (2015) 177–189. https://doi.org/10.1007/s12649-015-9346-7.
[7] H. Kim, C.H. Lee, K.Y. Ann, Feasibility of ferronickel slag powder for cementitious binder in concrete mix, Constr. Build. Mater. 207 (2019) 693–705. https://doi.org/10.1016/j.conbuildmat.2019.02.166.
[8] M.A. Rahman, P.K. Sarker, F. Uddin, A. Shaikh, A.K. Saha, Soundness and compressive strength of Portland cement blended with ground granulated ferronickel slag, Constr. Build. Mater. 140 (2017) 194–202. https://doi.org/10.1016/j.conbuildmat.2017.02.023.
[9] Y. Huang, Q. Wang, M. Shi, Characteristics and reactivity of ferronickel slag powder, Constr. Build. Mater. 156 (2017) 773–789. https://doi.org/10.1016/j.conbuildmat.2017.09.038.

Authors' background

Your Name	Title*	Research Field	Personal website
Romy S Edwin	associate professor	Civil and Material Engineering	
Masykur Kimsan	assistant professor	Civil Engineering	
Irmawatty Paula Tamburaka	associate professor	Economy and Environment	
Bambang Pramono	assistant professor	Information Technology	
Asminar Azis	PhD candidate	Electrical Engineering	
Philip Van den Heede	postdoctoral researcher	Structural engineering and building materials	
Nele De Belie	full professor	Durability of cementitious materials	
Elke Gruyaert	full professor	Concrete Technology and Concrete Durability	

*This form helps us to understand your paper better, the form itself will not be published.

*Title can be chosen from: master student, PhD candidate, assistant professor, lecture, senior lecture, associate professor, full professor