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Research Article

Economy, Energy, and Environment Impact on the Use of Ferronickel Slag Waste for Construction Project in Indonesia

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Abstract

This research intends to investigate the economic, energy and environmental aspects of mortar and concrete manufactured with ferronickel slag (FNS) as a substitute for cement and aggregate because many infrastructure projects in Indonesia use waste materials, particularly FNS, as one of the construction components. Results indicate that incorporating FNS powder as one material in construction projects also has indirect benefits such as generating employment, and fostering local community economic growth. The grinding of FNS will provide business opportunities for Micro, Small and Medium-sized Enterprises (MSMEs). The use of FNS as sand replacement affords an economy advantage in concrete production which also benefits in the construction sector. In addition, utilizing by-products (FNS 1 and FNS 2) in mortar production has a beneficial effect on lowering the LCC. However, adding FNS in place of sand does not reduce the LCC of concrete constructed with FNS. The usage of FNS in place of cement appears to help reduce mortar's energy consumption. However, using FNS in place of sand throughout the concrete-making process has minimal impact on energy usage. There is an environmental benefit to using FNS 1 and FNS 2 in the mortar production process. When concrete is built using FNS as a sand substitute, the CO_2 emission does not show the same favourable outcomes as mortar made with FNS powder. Although it doesn't significantly reduce carbon emissions, FNS sand significantly improves concrete's performance.

Keywords

Estimate Cost, Ferronickel Slag Waste, LCC, Energy Consumption, CO_2 Emission

1. Introduction

Lately, the main option for construction projects globally has been concrete and mortar, replacing other building materials. The two ingredients mainly required to make concrete and mortar are cement and fine aggregate (sand). Over several decades, the amount of cement produced worldwide has increased steadily, reaching 2.8 billion tonnes and it is predicted to rise to over 4 billion tonnes annually [1]. Cement output doubled the total production in 1990 and increased by about 300% from production levels in the 1970s [2, 3]. Significant expansion is anticipated in the Middle East and Northern Africa, as well as in nations like China and India (WBCSD)/International, 2009). An appreciable rise in the

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cement industry's overall energy consumption and CO_2 emissions is correlated with this notable surge in cement output [4].

Ordinary Portland cement (OPC) has been a popular choice for building materials in many countries throughout the world [5]. The demand for cement in Indonesia is also rather strong, particularly during President Joko Widodo's administration (2014–2019), when building toll road infrastructure was a key initiative [6]. The most environmentally harmful and polluting industry is the cement sector. Cement plants are responsible for between 5 and 7% of the world's CO_2 emissions. The environment is negatively impacted by every step of the production process. Massive machinery releases harmful gasses and particles into the atmosphere during the grinding and clinker-burning processes used to produce cement. It takes a lot of energy in this process also. The overall gross added value of cement production is roughly equivalent to 50% of the energy costs. Additionally, 400 kg of limestone and 200 kg of combustion waste are released into the atmosphere during the production of one ton of cement, resulting in 600–900 kg CO_2 emissions. Globally speaking, the production of cement exceeds 4 billion tons. The Earth's atmosphere becomes contaminated by about 3 billion tons of greenhouse gases as a result. Increasing the energy efficiency of companies that use a lot of energy, like cement plants, can help them compete more successfully in the world market [6].

About 20% to 30% of the volume of concrete is made up of sand (fine aggregate), one of the elements in addition to coarse aggregate, cement, and water. An estimated 6.25 billion tons of sand are needed annually to provide enough concrete for construction projects worldwide. This implies a significant depletion of natural resources, which will worsen the ecosystem. In addition, there is a shortage of resources, which limits the extraction of natural resources and has a negative impact on the advancement of society [7, 8]. Using industrial waste to produce concrete is an alternate method of protecting the environment when natural resources become more scarce in the near future [9].

Preserving natural resources and protecting human health are the primary goals of sustainable development, with the latter being achieved through preventative measures [10]. Reusing waste materials to substitute cement or aggregate in civil construction is a feasible alternative in this case. The manufacturer finds it more and more challenging to store waste materials in stockpiles, both financially and environmentally. As a result, this market should not simply be evaluated based on its financial contribution. The benefits increase when waste material from industry is used in civil buildings, for instance, as they take the place of natural resources [11].

Utilizing tried-and-true economic analysis principles, Life Cycle Cost (LCC) is a valuable method for assessing the long-term performance of alternative investment options [12]. It is an economic process that takes into account residual value, construction, operation, maintenance, replacement, and rehabilitation expenses to determine which design option is most cost-effective over a given period [13]. LCC is a measurement technique used in the valuation process that seeks to ascertain the worth of an activity's benefits from an all-encompassing standpoint [14].

In cement production, about 24% of the electricity used derives from the grinding of raw materials, while clinker calcination still consumes a higher amount of energy [15]. Thus, from this perspective, the advancement of technology for grinding raw materials will have a direct impact on the growth of the cement industry. Meanwhile, aggregate production energy consumption is influenced by several factors, including geological variability, gravel homogeneity, grain size, production scale, climate, equipment maintenance and technology, site organization, and geography [16]. Ten million tons of aggregates, 1500–2000 million tons of cement, and 1000 million tones of water are used in concrete plants [17, 18]. In addition, 1.65 tons of limestone and 0.6 tons of clay are needed for every ton of cement used [19]. Additionally, a significant quantity of fossil fuels is needed [18]. In other words, the most energy and carbon dioxide are released during the manufacturing of concrete when cement is used [20]. As a result, almost 8% of global CO_2 emissions are attributable to concrete [21]. Due to the clinkerization process of cement, which uses furnaces with temperatures between 1350 and 1400 ℃, the majority of these emissions are linked to its manufacturing [20].

As many infrastructures project in Indonesia applies waste material, especially ferronickel slag (FNS) as one of the construction materials, therefore, this research aims to study the economy, energy and environmental perspective of mortar and concrete made with FNS as cement and aggregate replacement.

2. Research Methods

2.1. Data

In Indonesia, ferronickel slag (FNS) has been used in construction projects as land reclamation, subgrade replacement material, aggregate substitution, and cement replacement. However, it is problematic to obtain data from infrastructure projects in Indonesia that apply FNS as a construction material. Therefore, the authors used the data from previous works of literature for analyzing economy, energy, and environmental impact of FNS waste used as an aggregate substitution, and cement replacement. Table 1 presents the mix design mortar using FNS as cement replacement with the proportions of 0%, 5%, 10%, 15%, and 20% [22]. The mix design of concrete with FNS as aggregate replacement is seen in Table 2 [9].

Table 1. *Mix design of mortar containing FNS.*

Material	0%	5%	10%	15%	20%
OPC	864.2	821.0	777.8	734.6	691.3
FNS	0.0	43.2	86.4	129.6	172.8
Fine aggregate	1108.9	1108.9	1108.9	1108.9	1108.9
Water	302.3	302.2	302.1	302.1	302.0
Superplasticizer	4.3	4.3	4.3	4.3	4.3

Table 2. *Mix design of concrete made with FNS.*

Material	Ref	10%	20%	30%	40%	50%
OPC	449.0	449.1	449.2	449.3	449.4	449.5
Sand	576.0	518.6	461.1	403.6	346.1	288.5
FNS aggregate	0.0	57.6	115.2	172.9	230.6	288.4
Coarse aggregate	1117.0	1117.5	1117.9	1118.4	1118.8	1119.4
Water	157.0	157.4	157.7	158.1	158.5	158.9
Superplasticizer	9.9	9.9	9.9	9.9	9.9	9.9

2.2. Methodology

In this study, FNS used as cement replacement was treatment in two ways, which were ground in 1 hour (FNS 1) and 2 hours (FNS 2) to obtain two grades of fineness. Whereas, FNS coarse was directly used as fine aggregate replacement because these two materials tend to have the same particle size. The application of different methods will have an impact on material prices, energy consumptions, and carbon dioxide emissions.

The first step is economy analysis. The concrete and mortar price are calculated based on local price of the material constituents in USD. Afterwards, the economy impacts of concrete or mortar products will be determined. The LCC approach, which adheres to the ASTM standard for the life cycle costing of investments related to buildings, is the most suitable technique for assessing the economic effects of building products [23]. According to the following equation, the total life cycle costs (LCC) of a concrete product (CLCC) in this case study are equal to the sum of the present values of the initial cost (CFirst) and future costs (CFuture) minus the residual value (RV):

$$C_{LCC} = C_{first} + C_{future} - RV \quad (1)$$

The building service life (BSL) is 60 years, the building lifespan (BLS) is 25 years, the price of casting concrete with a concrete pump is approximated 55 USD without discount rate, and the social cost per ton of CO_2 emissions was 12 USD. CP is equal to concrete price in m3.

$$RV = \frac{BSL-BLS}{BSL} \times CP \quad (2)$$

Of the energy used to produce cement, roughly 10% goes toward grinding granulated blast furnace slag [24]. As FNS has a similar hardness to copper slag (6–7 on the Mohs scale [25], it requires more energy to grind. The total energy consumption (TEC) of concrete and mortar was calculated based on equation 3:

$$TEC = Sum(EEm \times Mm) \quad (3)$$

The energy saving can be obtained based on equation 4:

$$ES = (100 - TEC_{i\%})/(TEC_{ref}) \times 100) \quad (4)$$

Where:

TEC = total energy consumption (MJ/m^3)

$TEC_{i\%}$ = total energy consumption of FNS percentage (MJ/m^3)

TEC_{ref} = total energy consumption of 0% FNS (MJ/m^3)

EEm = embodied energy per material (MJ), see Table

Mm = Mass of the material (kg/m^3)

Environmental analysis is then determined based on CO_2 emission approach. The production process of each constituent materials emits CO_2 emissions. The total CO_2 emissions (COE) of concrete and mortar was calculated based on equation 5:

$$COE = Sum(COEm \times Mm) \quad (5)$$

Where:
COE = total CO_2 emission ($kgCO_2/m^3$)
COEm = CO_2 emission per material (kg), see Table 3.

Table 3. CO_2 emissions and embodied energy of mortar and concrete ingredients (per 1 kg).

Ingredients	Embodied energy (MJ)		CO_2 emissions (kg)	
	Mortar	Concrete	Mortar	Concrete
OPC	5.5	5.5	0.833	0.833
FNS	1.6/2.1	0	0.411/0.632	0
Fine aggregate	0.08	0.08	0.021	0.021
Coarse aggregate	-	0.3	-	0.056
Water	0.2	0.2	0.0008	0.0008
Superplasticizer	11.5	11.5	0.6	0.6
Processing	0.24	0.1	0.04	0.035

3. Results and Discussion

3.1. Economy Analysis

Figure 1 depicts the mortar prices per cubic metre in US$ according to the unit price of constituent materials. It seems that the mortar price decreased as increasing FNS content. The mortar prices with FNS 1 are lower than mortar with FNS 2. The effect of longer grinding times is higher on the mortar unit prices, which can be seen in mortar prices made with FNS 2. The lower price of mortar with FNS 1 and FNS 2 is 113 US$ and 115 US$, respectively, which is obtained for mortar containing 20% FNS powder. In general, utilizing FNS as cement replacement in mortar presents a competitive price for the infrastructure sector. Incorporating FNS powder as one material in construction projects also has indirect benefits as generating employment, and fostering local community economic growth, in addition to other social factors. In addition, the grinding of FNS will provide business opportunities for Micro, Small and Medium-sized Enterprises (MSMEs). This finding corresponds with the finding of Silgado (2024) [26], who obtained the competitive price of concrete utilizing rice husk ash as cement replacement.

The concrete price utilizing FNS as sand replacement is given in Figure 2. The concrete price was reduced by increasing the proportion of FNS sand. The higher decrease in concrete price is about 126 US$ for 50% FNS, while other replacement levels were lower than reference concrete. The concrete with 50% FNS reduces the price by about 3.6% in comparison to that of the reference concrete.

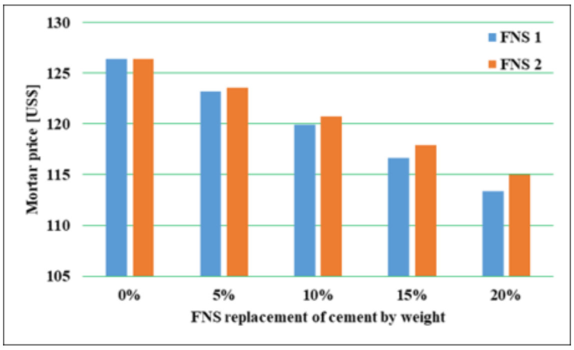

Figure 1. Estimate cost of the mortar.

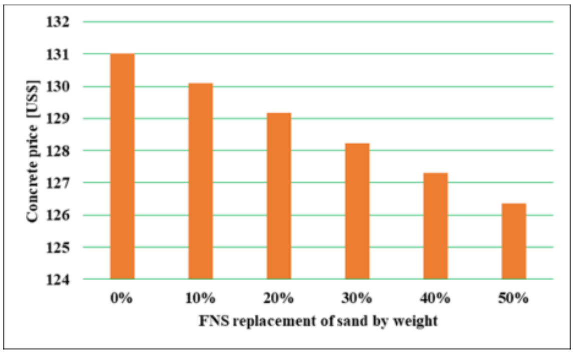

Figure 2. Estimate cost of the concrete.

The use of FNS as sand replacement affords an economy advantage in concrete production which is also beneficial in the construction sector. In addition, there are further secondary benefits of using FNS aggregates in the construction industry. As the concrete quality also depends on the aggregate quality, generating FNS aggregate in several gradations and particle sizes can create new jobs in local community to boost economic growth. In literature, the benefit cost of concrete using steel slag aggregate is also achieved [27]. The use of FNS as sand replacement can reduce the supply of raw material, especially fine aggregate. This can assure the sustainability of the infrastructure sector in the future.

The estimate of LCC of mortar made with FNS 1 and FNS 2 is displayed in Figure 3. The LCC of mortar with FNS 1 and FNS 2 decreased with increasing FNS proportion. This results mean that there is a positive impact of using by products (FNS 1 and FNS 2) in mortar production for decreasing the LCC. The decrease in the LCC obtained in this study is caused by the low price in processing of FNS powder compared to the processing of cement, leading to a decrease the concrete price in m3 which is equal to the present values of the initial cost. The economic criteria in this instance are determined by adding the FNS powder which potentially decreased the LCC of mortar. In this present study, there are five alternatives of mortar based on FNS content and fineness levels, which can be proposed for construction projects Therefore, the government can support new policies in the construction sector by promoting FNS as an alternative replacement for cement, which is economically beneficial and provides opportunities for employment in the construction sector and small and medium businesses.

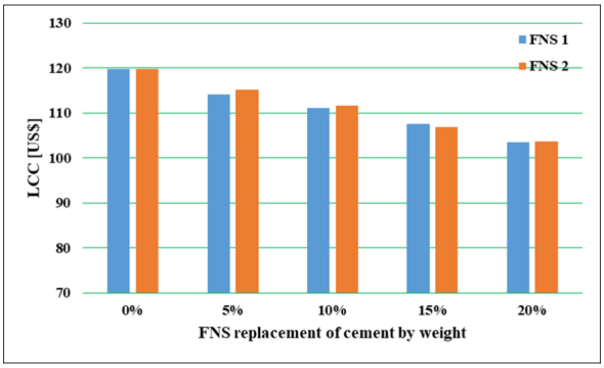

Figure 3*. Estimate of the life cycle cost of mortar made with FNS 1 and FNS 2.*

The positive results of LCC for mortar with FNS powder are not the case for the LCC of concrete made with FNS as sand replacement as seen in Figure 4. There are no significant differences among the LCC of concrete mixes containing FNS. Utilizing FNS as sand replacement does not contribute to decreasing the LCC of concrete made with FNS. This may also be caused by the proportion of sand replacement with FNS only being a maximum of 50%. The use of FNS as a sand substitute up to 100% may have a significant effect on reducing the LCC. This is essentials to be proven in further research.

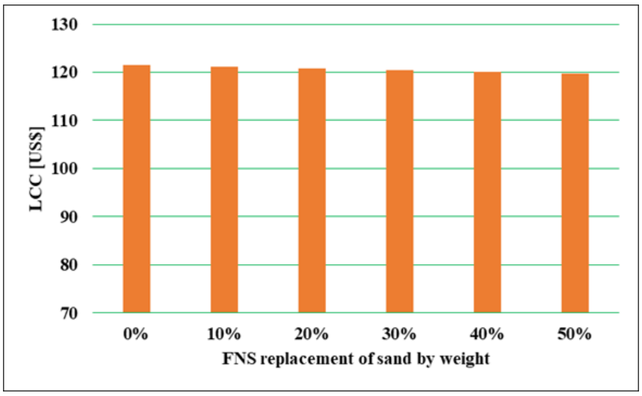

Figure 4*. Estimate of the life cycle cost of concrete made with FNS.*

3.2. Energy Consumption Analysis

Figure 5 shows the energy consumption of the mortar mixes with different amounts of cement replacement by FNS 1. The energy consumption decreased as the FNS 1 proportion increased. It can be observed that mortar with 0% FNS 1, 5% FNS 1, 10% FNS 1, 15% FNS 1, and 20% FNS 1 required about 5500 MJ/m3, 5330 MJ/m3, 5161 MJ/m3, 4993 MJ/m3, and 4824 MJ/m3, respectively. The reduction in energy consumption of mortar production is caused by the embodied energy to produce FNS 1, which is about 1.6 MJ per kg, in comparison to the embodied energy to produce cement, which is 5.5 MJ per kg. The embodied energy required by FNS is less because it is only for the grinding process. While the calcination and grinding of clinker requires more embodied energy throughout the cement production process [2].

Figure 5 displays how much energy is saved when producing mortar using FNS 1. With a rise in the FNS 1 proportion, mortar's energy savings rose. The energy saving obtained for mortar containing FNS 1 with the proportions of 5%, 10%, 15%, and 20% are about 3%, 6%, 9%, and 12%, respectively as seen in Figure 5.

In comparison to the energy consumption and energy saving of mortar using FNS 1, it can be seen in Figure 6 that the energy consumption of mortar made with FNS 2 also decreased. It can be observed that the decrease in energy consumption due to the increase in FNS 2 use in mortar production is smaller in comparison to that of mortar made with FNS 1. A similar result is also achieved for the results of energy saving of mortar with FNS 2, which obtained energy saving of about 2.6% (5% FNS 2), 5.3% (10% FNS 2), 8% (15% FNS 2), and 10.7% (20% FNS 2). Grinding FNS 2 in a longer time is the main reason for this result.

In the literatures, energy consumption in cement production can be minimized by applying optimization of the kiln process [28] and efficiency in the grinding process [15]. However, energy consumption in cement production is still large because two main processes cannot be avoided, which are grinding and clinker calcination. So, by implementing FNS as a partial replacement for cement, energy consumption in material production can be further reduced.

The energy consumption of concrete made with FNS as sand replacement is shown in Figure 7. It is seen that there is no effect of FNS as sand replacement on the reduction in energy consumption of concrete. The energy saving is also shown without the effect of FNS as sand replacement as depicted in Figure 7. The production of FNS is without embodied energy as seen in Table 3, which is the main reason for the results obtained as seen in Figure 7.

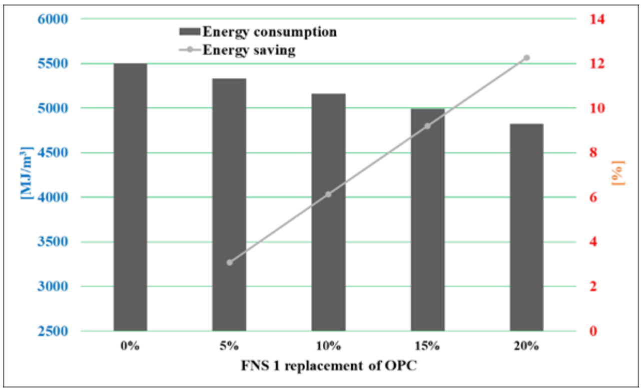

Figure 5. *Energy consumption and energy saving for mortar with FNS 1.*

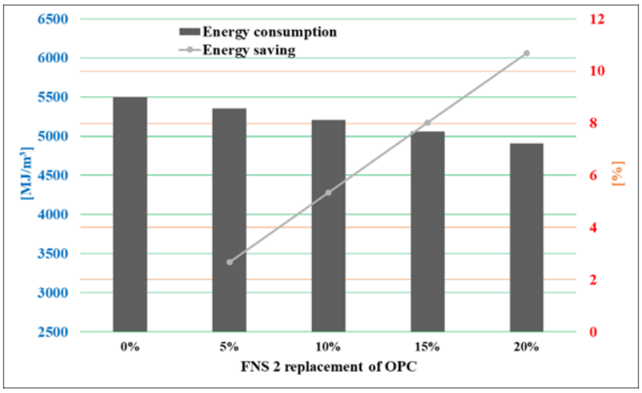

Figure 6. *Energy consumption and energy saving for mortar with FNS 2.*

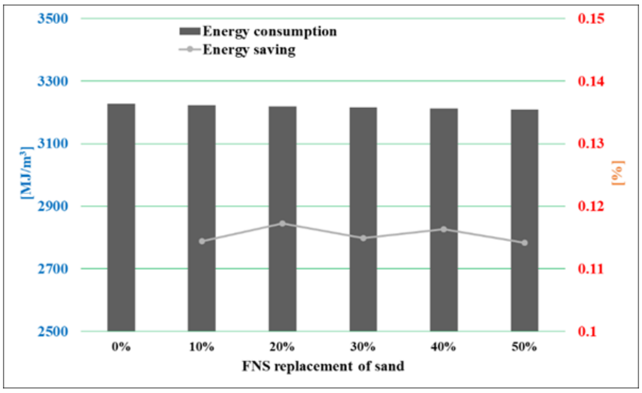

Figure 7. *Energy consumption and energy saving for concrete with FNS.*

3.3. Environmental Analysis

Furthermore, the amount of CO_2 emissions can be determined using the data from the literature (Table 3). The use of FNS in place of cement in the production of mortar appears to improve air quality. Figure 8 illustrates this behavior. For mortar mixes with FNS 1 and FNS 2, the amount of CO_2 emission dropped as the FNS percentage increased. It can be seen that 20% FNS 1 substitution resulted in the lowest CO_2 emission (764 kg/m^3), while the CO_2 emission for mortar with FNS 2 is about 802 kg/m3. In literature, this finding corresponds to other findings [29], as the ecological benefit is obtained for RPC using copper slag powder as cement replacement. Another outcome also obtained similar results to this present result as the concrete using 40% fly ash and 50% blast furnace slag as a cement replacement reduced the CO_2 emission [30].

As observed in Figure 9, the CO_2 emission of concrete prepared with FNS as sand replacement does not exhibit the same beneficial effects as the CO_2 emission of mortar with FNS powder. The low consumption of CO_2 emission of fine aggregate production is the main reason for the low effect of FNS in reducing the CO_2 emission of concrete. Although there is a small contribution of FNS as sand replacement in reducing carbon emission, the environmental damage in the future can be minimalized.

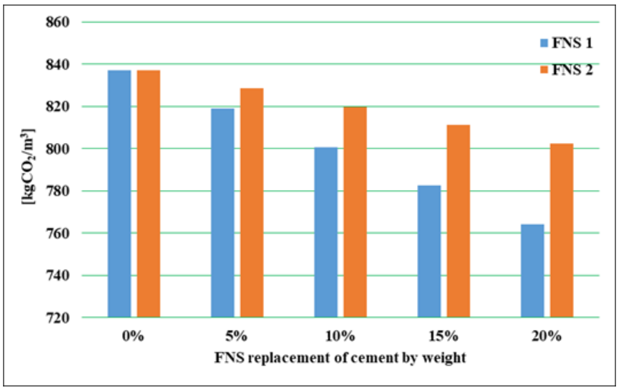

Figure 8. *CO_2 emission for mortar mixes with varying amount of FNS powder.*

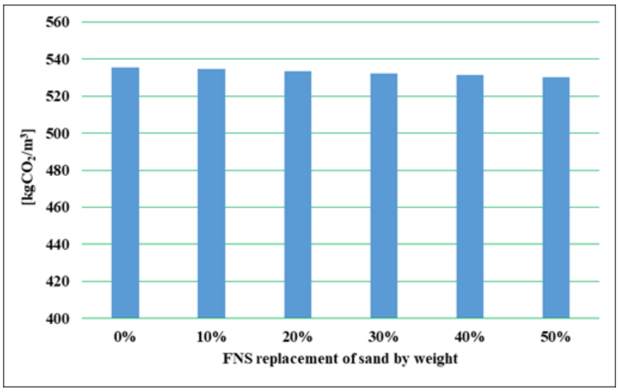

Figure 9. *CO_2 emission for concrete mixes with varying amount of FNS sand.*

4. Conclusions

FNS is a by-products from the nickel smelting industry which can be used as cement replacement and sand replacement in the production of construction materials. This paper investigated the use of FNS as cement replacement in mortar with the proportion of 0% FNS to 20% FNS in steps of 5%, which was ground to reach two levels of fineness as to achieve the requirements as a cement replacement material. Besides, FNS coarse also is directly used as sand replacement in concrete production with the replacement level of 0%, 10%, 20%, 30%, 40%, and 50%.

Based on the fact that data from infrastructure projects in Indonesia that use FNS as a building material is difficult to collect. Therefore, in order to analyze the economic, energy and environmental effects of using FNS waste as a substitute for aggregate and cement, the writers collected data from earlier literature. The first step in analyzing the data is compressive strength performance. The material prices and LCC, which are economy perspective, are then examined. The last step is energy investigation and environment evaluation.

As a result, using by-products (FNS 1 and FNS 2) in mortar production has a beneficial effect on lowering the LCC. By endorsing FNS as a cost-effective substitute for cement, which creates job possibilities in the construction industry and for small and medium-sized enterprises, the government can encourage new regulations in this field. On the other hand, the LCC of concrete built with FNS is not decreased by replacing sand with FNS. The use of FNS as cement replacement seems beneficial in decreasing energy consumption of mortar. While applying FNS as sand replacement in concrete production is only little effect in lowering energy consumption. Using FNS 1 and FNS 2 in the production of mortar has an environmental benefit. Compared to mortar made with FNS powder, the CO_2 emission of concrete prepared using FNS as a sand substitute does not show the same positive results. While FNS sand plays a minor role in lowering carbon emissions, the environmental destruction in the future can be minimalized.

Abbreviations

FNS	Ferronickel Slag
LCC	Life Cycle Cost

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Author Contributions

Irmawatty Paula Tamburaka: Conceptualization, Methodology, Formal analysis, writing original draft

Romy Suryaningrat Edwin: Formal analysis, Writing review editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] M. Schneider, M. Romer, M. Tschudin, H. Bolio, Sustainable cement production-present and future, Cem. Concr. Res. 41 (2011) 642–650. https://doi.org/10.1016/j.cemconres.2011.03.019

[2] B. Bakhtyar, T. Kacemi, M. A. Nawaz, A review on carbon emissions in Malaysian cement industry, Int. J. Energy Econ. Policy. 7 (2017) 282–286.

[3] Q. Qian Zhu, CO_2 abatement in the cement industry, 2011. https://doi.org/10.1007/978-94-010-2608-6_14

[4] 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

[5] A. K. Dikshit, S. Gupta, S. K. Chaturvedi, L. P. Singh, Usage of lime sludge waste from paper industry for production of Portland cement Clinker: Sustainable expansion of Indian cement industry, Case Stud. Chem. Environ. Eng. 9 (2024) 100557. https://doi.org/10.1016/j.cscee.2023.100557

[6] A. Rokhmad, Configuration and the role of community leaders in the conflict of natural resources of limestone mining for the cement industry in Rembang Indonesia, Int. J. Energy Econ. Policy. 10 (2020) 521–528. https://doi.org/10.32479/ijeep.8321

[7] P. Mehra, R. C. Gupta, B. S. Thomas, Properties of concrete containing jarosite as a partial substitute for fine aggregate, J. Clean. Prod. 120 (2016) 241–248. https://doi.org/10.1016/j.jclepro.2016.01.015

[8] Q. Wang, D. Wang, S. Zhuang, The soundness of steel slag with different free CaO and MgO contents, Constr. Build. Mater. 151 (2017) 138–146. https://doi.org/10.1016/j.conbuildmat.2017.06.077

[9] R. S. Edwin, E. Ngii, R. Talanipa, F. Masud, R. Sriyani, Effect of nickel slag as a sand replacement in strength and workability of concrete, IOP Conf. Ser. Mater. Sci. Eng. 615 (2019). https://doi.org/10.1088/1757-899X/615/1/012014

[10] A. Allesch, P. H. Brunner, Assessment methods for solid waste management: A literature review, Waste Manag. Res. 32 (2014) 461–473. https://doi.org/10.1177/0734242X14535653

[11] D. R. R. Gonçalves, W. C. Fontes, J. C. Mendes, G. J. B. Silva, R. A. F. Peixoto, Evaluation of the economic feasibility of a processing plant for steelmaking slag, Waste Manag. Res. 34 (2016) 107–112. https://doi.org/10.1177/0734242X15615955

[12] S. Ozbay, K., Parker, N. A., Jawad, D. & Hussain, Guidelines for Life Cycle Cost Analysis. Report for Federal Highway Administration, 2003.

[13] C. Alexandra, S. & Ferreira Real, Contribution of Life-Cycle Cost Analysis to Design Sustainability in Construction (in Portuguese), Inst. Super. Técnico, Univ. Técnica Lisboa. (2010).

[14] Q. Maulana, B. Soesanto, L. R. Utomo, I. Rachman, T. Matsumoto, Life Cycle Assessment and Cost Benefit Analysis of Municipal Waste Management Strategies, J. Environ. Sci. Sustain. Dev. 4 (2021) 69–96. https://doi.org/10.7454/jessd.v4i1.1107

[15] R. Meng, Q. Zhao, M. Wu, Q. Long, M. Zhou, A survey and analysis on electricity consumption of raw material mill system in china cement industry between 2014 and 2019, Sustain. 13 (2021) 1–11. https://doi.org/10.3390/su13031126

[16] M. Ozcelik, Energy consumption analysis for natural aggregate processing and its results (Atabey, isparta, turkey), Min. Miner. Depos. 12 (2018) 80–86. https://doi.org/10.15407/mining12.03.080

[17] F. Belaïd, How does concrete and cement industry transformation contribute to mitigating climate change challenges?, Resour. Conserv. Recycl. Adv. 15 (2022) 200084. https://doi.org/10.1016/j.rcradv.2022.200084

[18] C. Muñoz Sanguinetti, F. Quiroz Ortiz, Análisis de Ciclo de Vida en la determinación de la energía contenida y la huella de carbono en el proceso de fabricación del hormigón premezclado. Caso estudio planta productora Región del Bío Bío, Chile., Rev. Hábitat Sustentable. 4 (2014) 16–25. http://remaderas.ubiobio.cl/ojs/index.php/arquitec/article/viewArticle/906

[19] L. Beressa, B. V. Saradhi, Life Cycle Assessment of Ethiopian Cement Manufacturing: A Potential Improvement on the Use of Fossil Fuel in Mugher Cement Factory, Appl. Environ. Res. 43 (2021) 100–112. https://doi.org/10.35762/AER.2021.43.4.8

[20] J. Lvel, R. Watson, B. Abbassi, Z. S. Abu-Hamatteh, Life cycle analysis of concrete and asphalt used in road pavements, Environ. Eng. Res. 25 (2020) 52–61. https://doi.org/10.4491/eer.2018.399

[21] R. S. Edwin, M. Kimsan, I. P. Tamburaka, B. Pramono, A. Azis, P. Van den Heede, N. De Belie, E. Gruyaert, Effect of Ferronickel Slag as Cementitious Material on Strength of Mortar, Key Eng. Mater. 931 (2022) 213–218. https://doi.org/10.4028/p-n4v7se

[22] R. Edwin, Romy. S, Kimsan. M, Pramono. B, Masud. F, Sriyani, Effect of ferronickel slag in concrete and mortar, Mag. Civ. Eng. 109 (2022). https://doi.org/10.34910/MCE.109.9

[23] ASTM, Standard Practice for Measuring Life-Cycle Costs of Buildings and Building ASTM, Am. Stand. Test. Mater. (2017).

[24] C. Shi, J. Qian, High performance cementing materials from industrial slags - A review, Resour. Conserv. Recycl. 29 (2000) 195–207. https://doi.org/10.1016/S0921-3449(99)00060-9

[25] K. Murari, R. Siddique, K. K. Jain, Use of waste copper slag, a sustainable material, J. Mater. Cycles Waste Manag. 17 (2014) 13–26. https://doi.org/10.1007/s10163-014-0254-x

[26] S. S. Suárez Silgado, L. Calderón Valdiviezo, C. Betancourt Quiroga, Life cycle analysis and economic evaluation of cement and concrete mixes with rice husk ash: application to the Colombian context, Mater. Constr. 74 (2024). https://doi.org/10.3989/mc.2024.350723

[27] L. C. B. Costa, M. A. Nogueira, L. C. Ferreira, F. P. da F. Elói, J. M. F. de Carvalho, R. A. F. Peixoto, Eco-efficient steel slag concretes: an alternative to achieve circular economy, Rev. IBRACON Estruturas e Mater. 15 (2022) 1–17. https://doi.org/10.1590/s1983-41952022000200001

[28] B. Afkhami, B. Akbarian, N. Beheshti A., A. H. Kakaee, B. Shabani, Energy consumption assessment in a cement production plant, Sustain. Energy Technol. Assessments. 10 (2015) 84–89. https://doi.org/10.1016/j.seta.2015.03.003

[29] R. S. Edwin, E. Gruyaert, N. De Belie, Influence of intensive vacuum mixing and heat treatment on compressive strength and microstructure of reactive powder concrete incorporating secondary copper slag as supplementary cementitious material, Constr. Build. Mater. 155 (2017) 400–412. https://doi.org/10.1016/j.conbuildmat.2017.08.036

[30] A. Maury-Ramírez, N. De Belie, Environmental and Economic Assessment of Eco-Concrete for Residential Buildings: A Case Study of Santiago de Cali (Colombia), Sustain. 15 (2023). https://doi.org/10.3390/su151512032