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A systematic review of ferronickel slag in cement-based materials as binder and aggregate

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Abstract – This review analyses studies regarding the use of ferronickel slag (FNS) as a partial replacement for binder and partial or total replacement for fine aggregate in cement-based materials in a systematic way. To this effect, the chemical composition of FNS was described, as well as its effect on pastes, mortars and concretes regarding fresh and hardened state properties such as compressive, split tensile and flexural strengths and modulus of elasticity. Setting times and chloride ion related durability was also analysed. Generally, it was found that fine aggregate FNS in partial replacements tends to improve the mechanical properties, while reducing workability. FNS as a binder reduced the compressive strength in most samples, but at certain proportions and situations might still be of interest for use in civil construction. Chloride ion penetration was in most cases reduced with the presence of FNS in the mix.
Keywords: Binder. Cement-based materials. Ferronickel slag. Fine aggregate.

Uma revisão sistemática da escória de ferro-níquel em materiais à base de cimento como aglomerante e agregado

Resumo – Esta revisão analisa estudos sobre a utilização da escória de ferro-níquel (FNS) como substituto parcial do aglomerante e substituto parcial ou total do agregado miúdo em materiais à base de cimento de forma sistemática. Para tal, a composição química da FNS foi descrita, bem como seu efeito em pastas, argamassas e concretos em relação às propriedades no estado fresco e endurecido, como resistência à compressão, compressão diametral e flexão e módulo de elasticidade. Tempos de pega e a durabilidade em relação à íons cloreto também foram analisados. Em geral, observou-se que a utilização da FNS como agregado miúdo em substituições parciais tende a melhorar as propriedades mecânicas, no entanto, reduzindo a trabalhabilidade. A FNS como aglomerante reduziu a resistência à compressão na maioria das amostras, mas em certos teores e situações ainda pode ser de interesse para o uso na construção

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civil. A penetração de íons cloreto foi majoritariamente reduzida com a presença de FNS na mistura.
Palavras-chave: Aglomerante. Agregado miúdo. Escória de ferro-níquel. Materiais à base de cimento.

Una revisión sistemática de la escoria de hierro-níquel en materiales a base de cemento como aglomerante y árido

Resumen – Esta revisión analiza sistemáticamente los estudios sobre el uso de la escoria de hierro-níquel (FNS) como sustituto parcial del aglomerante y como sustituto parcial o total del árido fino en materiales a base de cemento. Para ello, se describe la composición química de la FNS, así como su efecto en pastas, morteros y hormigones con respecto a propiedades en estado fresco y endurecido, tales como resistencia a la compresión, compresión diametral, resistencia a la flexión y módulo de elasticidad. También se analizan los tiempos de fraguado y la durabilidad frente a los iones cloruro. En general, se observó que el uso de FNS como árido fino en sustituciones parciales tiende a mejorar las propiedades mecánicas, aunque reduce la trabajabilidad. El uso de FNS como ligante redujo la resistencia a la compresión en la mayoría de las muestras; sin embargo, en ciertas proporciones y condiciones, su aplicación aún puede ser de interés para la construcción civil. La penetración de iones cloruro se redujo mayoritariamente con la presencia de FNS en la mezcla.
Palabras clave: Aglomerante. Árido fino. Escoria de hierro-níquel. Materiales a base de cemento.

Introduction

Ferronickel slag (FNS), an industrial by-product of the ferronickel industry, originating mainly from electric arc furnaces, is a material predominantly composed of SiO2, MgO and Fe2O3, and its amorphous content can exceed 50% (KOMNITSAS; ZAHARAKI; BARTZAS, 2013). Blast furnaces are also used in parts of eastern China to produce ferronickel alloy (LIU; ZHANG; SUN, 2021), and the resulting slags from this method generally have a much higher content of CaO than other ferronickel slags (LI et al., 2022; HAN et al., 2021; SUN; FENG; CHEN, 2019). Ferronickel slag is produced in large quantities, of about 14 tons of slag for 1 ton of ferronickel alloy (SAHA; SARKER, 2016), due to the low content of nickel on the ore, about 1-2% (SAHA; KHAN; SARKER, 2018).

Cement production is of, approximately, 4 billion tons per year globally, representing about 8% of the total anthropogenic CO2 emissions (HABERT et al., 2020). Supplementary cementitious materials, usually by-products and waste from various industrial activities, have been used and studied for decades to provide added value to them, reducing energy consumption (CHEN et al., 2020) and improving certain properties of mortars and concrete.

Most of the FNS is still deposited in the open, highlighting the need for providing a destination to this waste, which can be harmful to the environment when exposed to acidic rain or in a seawater environment, also occupying farmland area (LIU et al., 2020).

Interest in FNS has been growing since the 20th century. Fig. 1 shows the number of publications according to the year, carried out on 12/06/2022 at sciencedirect.com using the keywords "ferronickel slag". It is possible to see an important increase in interest in the subject of reuse of this waste material. Studies are more focused on the use of FNS as a supplementary material in cementitious composites. This research found that in 2000-2009 40 manuscripts were published, then from the 2010-2019 196 manuscripts were published in the topic. This is evidence that the interest in FNS more than doubled in comparison to the period of 2000-2010 (490% more publications than the last decade). From 2020, this topic gains more attention, when there were found 190 publications, more than 90% of the number of publications found in the 2010 decade.

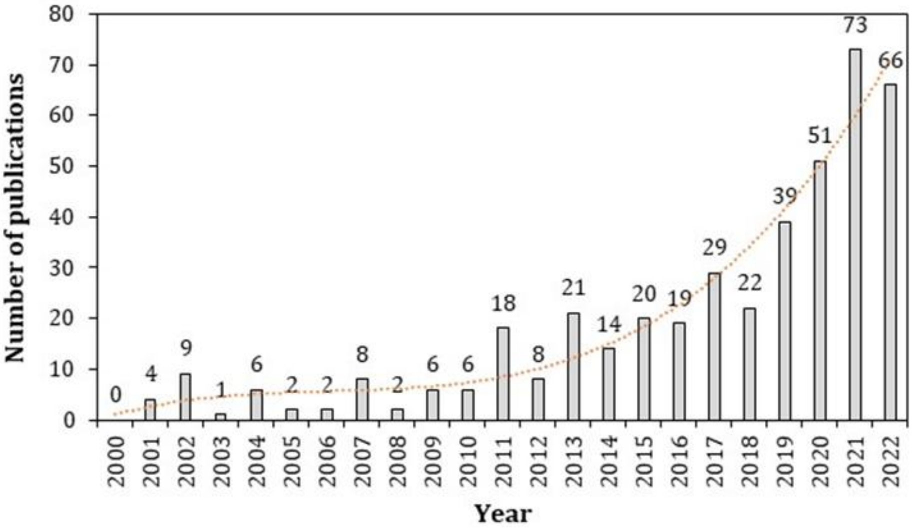

Fig. 1 – Recent publication with FNS in subject. Research carried out on 12/06/2022 at sciencedirect.com using the keywords "ferronickel slag".

Recent studies have shown that FNS may be used as supplementary material for cementitious composites after fine grinding. Katsiotis et al. (2015) FNS sample with a specific surface of 3985 cm²/g presented 40.71 wt% of reactive silica, with pozzolanicity of 5.9 MPa in mortars of slag with Ca(OH)2 and standard sand. As an admixture to 20 wt%, FNS seemed to delay the hydration, but the authors note that at longer ages the pozzolanic reaction of the slag apparently contributed to the compressive strength, with the gap between the values of the reference sample and the FNS specimens reducing by 90 days.

Relating to the penetration of chloride ions and sulfates, FNS blended cements contributed to a denser pore structure, as explained by Kim, Lee and Ann (2019), reducing the risk of corrosion. Therefore, its use was most recommended in cases where chloride or sulphate penetration is a concern, due to its resistivity against chemical degradation, even if not at all recommended when early age strength development is necessary.

In terms of rheology[6], Zhou and Shi (2021) found that pastes containing 30% FNS, at both 4200 cm²/g and 5500 cm²/g, presented significantly lower values of yield stress and plastic viscosity than the reference sample, indicating improved workability. The authors explained this effect due to reduced friction caused by the glass and fine particles in the grounded FNS. An important observation, however, is that the coarser FNS had a better rheological performance than the sample with a higher surface area, meaning that finer FNS samples will have a decreased workability when comparing to coarser ones. That, according to the authors, is due to the increase of contact between the particles.

Similarly, the mining of natural sand for the production of fine aggregate in concrete has caused a decrease in the availability of this resource and environmental problems, either by affecting the local fauna and flora, as well as through the emission of greenhouse gases through extraction and transport (GAVRILETEA, 2017). FNS has physical properties that justify its use

[6] The study of how materials deform and flow under applied forces.

as a substitute for sand, including low water absorption, high density and appropriate hardness (SAHA; KHAN; SARKER, 2018).

Regarding the workability of FNS when used as a fine aggregate, Shoya et al. (1999) performed technological tests in the fresh concrete in order to evaluate its self-compactability, with 50% and 100% replacement of sand. They found that the workability was reduced in FNS samples when comparing to the reference sample, although still able to be classified as self-compacting concrete. Explanations for this effect include poor gradation and high angularity of the ferronickel slag aggregate.

Saha and Sarker (2017a) found that concretes with 50% FNS fine aggregate had a higher slump than the reference, although the 100% FNS had a lower slump than both the 50% FNS and 100% sand samples. These are due to a decrease in surface area caused by the former, in which less water is necessary and a higher slump is achieved, and the angular shape of the particles, which explains the lower slump of the latter.

Research significance

Review articles provide a useful way to summarize research on a particular topic, offering both qualitative and quantitative insights (PALMATIER; HOUSTON; HULLAND, 2018; SHORT, 2009). They offer a general overview of a technique or material and are especially effective at highlighting trends and evolutions in science and technology. Another type of review article is the systematic review, which presents a quantitative analysis of data compiled on a particular topic. Systematic reviews are useful in showing the main impacts of technology, methodology, or material studies (WINDLE, 2010). For building materials such as carbon nanotubes (SILVESTRO; GLEIZE, 2020), inorganic solid wastes (PAIVA et al., 2021), recycled fibers (MERLI et al., 2020), inorganic short fibers (AHMAD; KHAN; SMARZEWSKI, 2021), and recycled plastics (GU; OZBAKKALOGLU, 2016), systematic reviews have been presented. A systematic review of ferronickel slag in cementitious composites can be an effective way to evaluate this type of waste material.

This study aims to review the physical-chemical composition and properties of ferronickel slag to guide its application as a fine aggregate and binder in the civil construction industry. The study analyzed 39 selected articles from major bibliographical research databases.

Methods

The process of literature review adopted was based on the systematic search flow phases (FERENHOF; FERNANDES, 2016), consisting of the search protocol, analysis, synthesis and writing, as adapted by Silvestro and Gleize (2020). The parameters are shown in Fig. 2.

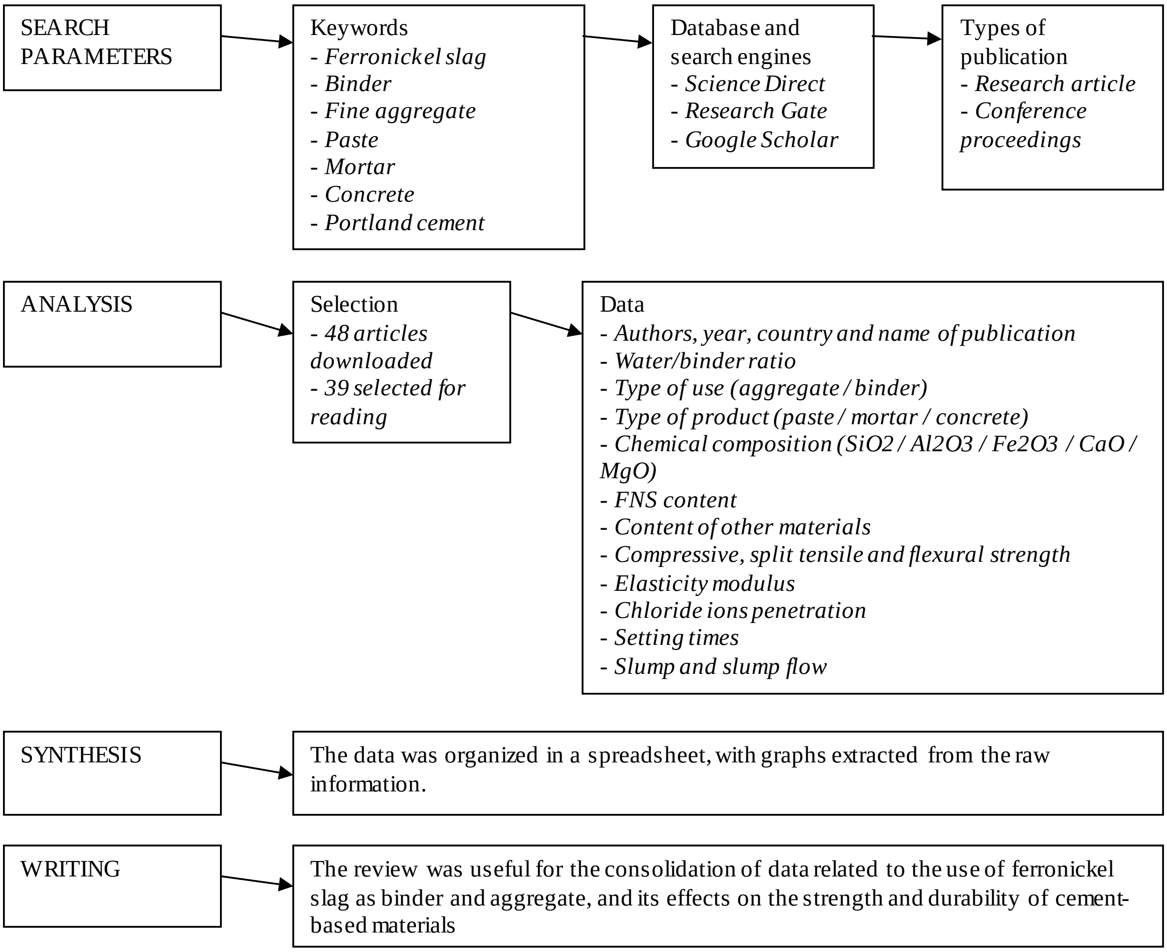

Fig. 2. Stages of systematic literature review

This article presents a review of 39 scientific papers and articles published in journals. Those are related to the use of ferronickel slag as fine aggregate or supplementary cementitious material, in terms of fresh and hardened state properties for cementitious composites. There are many research articles about the use of FNS as geopolymers, alkali activation and in asphalts, however they were excluded due to the fact alkali activated and bituminous composites present unique and very different properties and hydration mechanisms of setting, hydration and interaction with FNS. A list of the articles used is presented in Table 1. A comparison of the countries of origin is in Fig. 3.

Table 1 – List of articles used in this systematic review

Reference	Origin	Publication
SHOYA et al., 1999	Japan	Exploiting Wastes in Concrete
SAKOI et al., 2013	Japan	Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies
CHOI; CHOI, 2015	South Korea	Construction and Building Materials
LEMONIS et al., 2015	Greece	Construction and Building Materials
KATSIOTIS et al., 2015	Greece	Waste and Biomass Valorization
SAHA; SARKER, 2016	Australia	Construction and Building Materials
WANG; HUANG; WANG, 2017	China	Journal of Thermal Analysis and Calorimetry
HUANG; WANG; SHI, 2017	China	Construction and Building Materials

SAHA; SARKER, 2017a	Australia	Journal of Cleaner Production
RAHMAN et al., 2017	Australia	Construction and Building Materials
SAHA; SARKER, 2017b	Australia	Procedia Engineering
SAHA; SARKER, 2018a	Australia	International Journal of Concrete Structures and Materials
SAHA; SARKER, 2018b	Australia	Magazine of Concrete Research
CHO et al., 2018	South Korea	Advances in Civil Engineering
KIM; LEE; ANN, 2019	South Korea	Construction and Building Materials
SAHA et al., 2019	Australia	Construction and Building Materials
LI et al., 2019	China	Cement and Concrete Composites
SUN; FENG; CHEN, 2019	China	Construction and Building Materials
NGUYEN et al., 2019	Australia	Journal of Materials in Civil Engineering
LEE et al., 2019	South Korea	KSCE Journal of Civil Engineering
LIU et al., 2020	China	Journal of Hazardous Materials
SAHA; SARKER, 2020	Australia	Journal of Building Engineering
LIU et al., 2020	China	Construction and Building Materials
NURUZZAMAN et al., 2020	Australia	Journal of Building Engineering
QI et al., 2020	China	Construction and Building Materials
CHEN et al., 2020	China	Construction and Building Materials
GU et al., 2020	China	Construction and Building Materials
ZHAI et al., 2020	China	Construction and Building Materials
BAE; LEE; CHOI, 2021	South Korea	Materials
YANG et al., 2021	South Korea	Case Studies in Construction Materials
NGUYEN et al., 2021	Australia	Cement and Concrete Research
BOUASRIA et al., 2021	France	Journal of Building Engineering
MAŁEK et al., 2021	Poland	Materials
BAO et al., 2021	China	Journal of Cleaner Production
HAN et al., 2021	China	Thermochimica Acta
ZHOU; SHI, 2021	China	Journal of Thermal Analysis and Calorimetry
PETROUNIAS et al., 2022	Greece	Applied Sciences
NURUZZAMAN; KURI; SARKER, 2022	Australia	Construction and Building Materials
LI et al., 2022	China	Construction and Building Materials

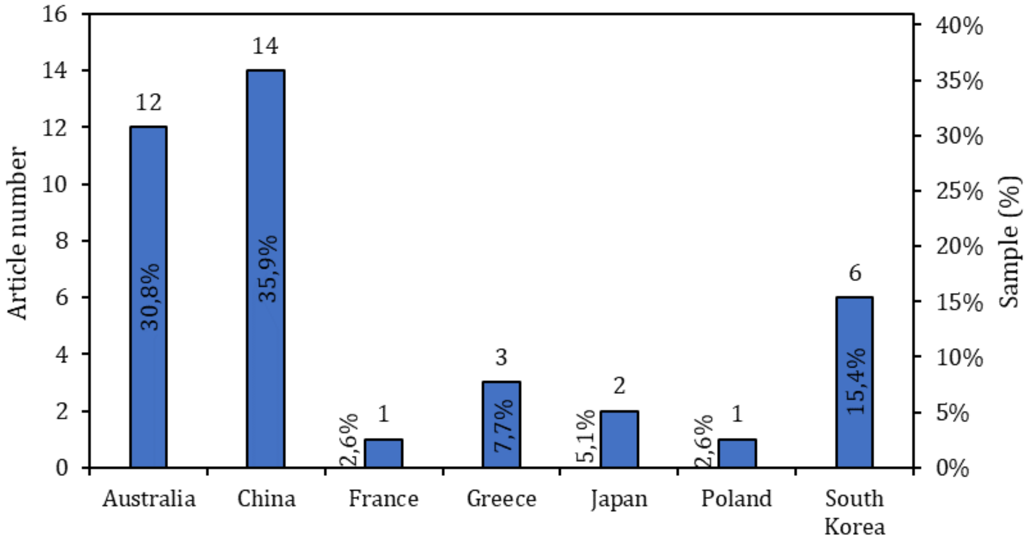

Fig. 3 - Origin of the articles

The usage and characteristics of the materials produced in each article, including overlaps, were analysed, and compiled in Table 2. Nuruzzaman, Kuri and Sarker (2022) studied the dual use of ferronickel slag as fine aggregate and supplementary binder, as did Saha and Sarker (2020).

Table 2 - Characteristics of the articles

Characteristics	Number of articles
Usage	
Use as aggregate	22
Use as binder	19
Cementitious matrix	
Concrete	22
Mortar	16
Paste	9

Results and discussion

Fig. 4 presents the chemical evaluation by oxide of the FNS found in the articles. The first aspect analysed was the chemical composition of the ferronickel slags, in terms of its main constituents – in this work, considered to be SiO2 (Fig. 4 (a)), Al2O3 (Fig. 4 (b)), Fe2O3(Fig. 4 (c)), CaO (Fig. 4 (d))and MgO (Fig. 4 (e)). Silica is the most prevalent, averaging 44% of the composition of all samples, followed by MgO, with 23%; Fe2O3 with 11%; CaO with 10% and Al2O3 under 8%. FNS samples that had a greater amount of CaO in its chemical composition, of above 15%, when used as a partial binder, generally produced mortars and concretes with increases in some mechanical properties, when comparing to the reference, in limited contents. Liu et al. (2020) found, for the same FNS content of 30%, increases ranging from 3% to 7% on concretes, depending on the cement used as the main binder. Also for concretes with 30% replacement rate, Qi et al. (2020) found 2% to 4% increases in compressive strength depending on the cement, while Chen et al. (2020) found a 9% increase.

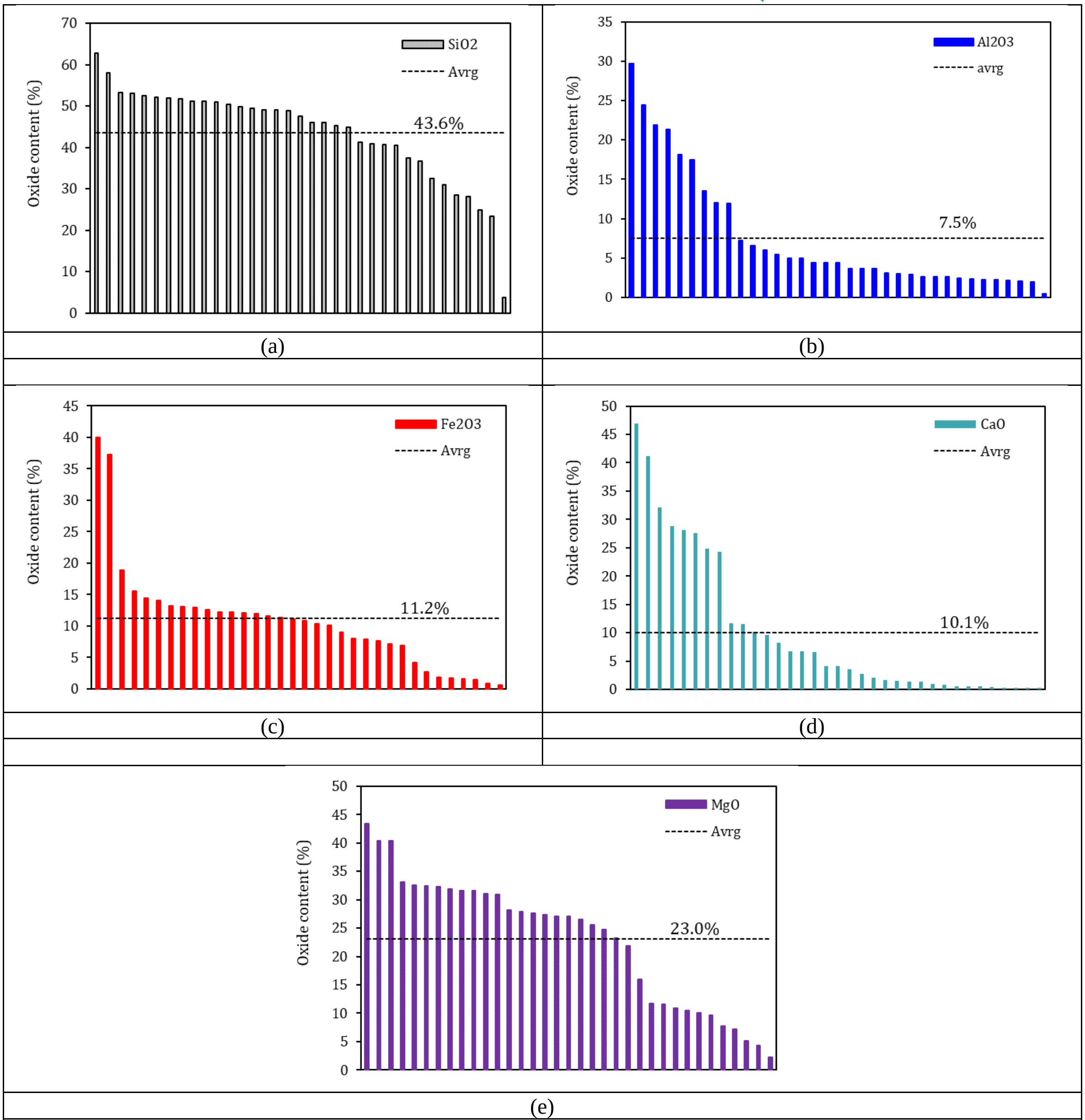

Fig. 4 – Data found for main chemical compound in FNS: SiO2 in (a); Al2O3 in (b); Fe2O3 in (c); CaO in (d) and MgO in (e). The bars correspond to data found in 35 manuscripts and the doted line the average values oxide.

Li et al. (2022) found that, with finely grounded FNS, passing on 5µm sieves, there was a 5% increase of compressive strength with 30% of FNS replacement in mortars. On the other hand, Rahman et al. (2017) found a 20% decrease in the values for compressive strength when using 30% of FNS in mortars. None of the FNS samples used as binder, studied in this review, with low contents of CaO - under 15% - produced mortars and concretes with higher compressive strength than the reference, at replacement rates of above 5%.

Averaging a quarter of the composition of the slag, the high content of MgO is a concern for the use of FNS as an aggregate due to harmful expansion associated with the component. Choi and Choi (2015) noted, however, that both air and water-cooled FNS samples did not appear to have peaks of free magnesia observed in XRD and, thus, no expansion due to it should occur. Bao et al. (2021) made a similar consideration regarding the absence of the periclase phase of Mg. When it comes to its use as a binder, the Brazilian standards NBR 16697:2018 requires that Portland cements classified as CP V have less than 6,5% of MgO in mass.

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Most of the cementitious matrices produced in the articles reviewed have a water/binder ratio greater than 0,40, as detailed in Fig 5.

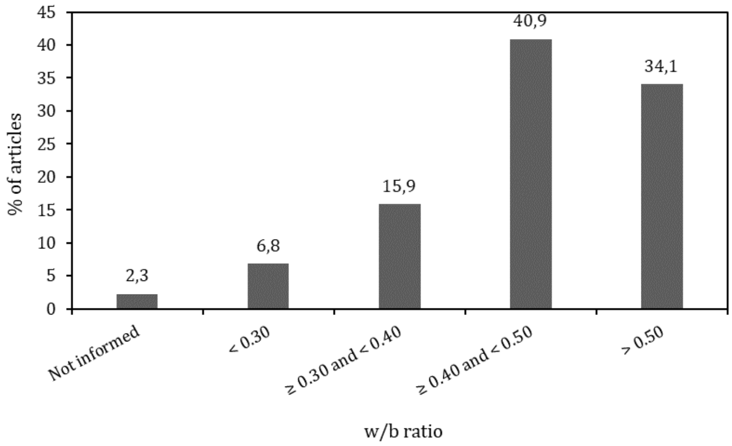


Fig. 5 –Water to binder ratio of the manuscript research (this result was obtained with a sample of 44, which means that more than one water to binder ratio can be presented in the same manuscript).

The informed Blaine[7] values of the FNS used as a partial binder ranged from 3420 cm²·g-1 to 8600 cm²·g-1, averaging 4700 cm²·g-1. A single outlier sample studied by Kim, Lee and Ann (2019) had a Blaine value of above 26000 cm²·g-1 providing an insight on the effect of very fine grinding on the mechanical properties of FNS cement.

In terms of fresh state properties, Nuruzzaman, Kuri and Sarker (2022) found that samples using grounded FNS as 30% replacement for binder presented a slump flow of 750mm, lower than that of the sample with fly ash, which had a slump flow of 785mm, and the V-funnel tests at 5 minutes resulted in 9 and 7 seconds of passing time, respectively. When replacing the fine aggregate with FNS at 30% and 50%, in samples also using the grounded FNS as partial binder, the respective results were 770mm and 700mm of slump flow, with V-funnel times of 8 and 13 seconds. Thus, according to the author, despite the sample containing 30% FNS binder and 50% FNS fine aggregate presenting lower workability and also slight segregation or piling of aggregate, all of those samples can be considered as self-compacting concrete by EFNARC standards. The authors attribute the piling of aggregate in the sample mentioned to the angularity of the FNS fine aggregate, as it was used in a high percentage of 50%.

When performing a rheological test in fresh pastes containing FNS as a partial binder replacement, Zhou and Shi (2021) found, by using the Bingham model, that the sample containing 30% FNS at a 4200 cm²/g surface area has the lowest values for yield stress and plastic viscosity. It was followed by the sample with 30% FNS at 5500 cm²/g, and then by the reference sample, which had the worst performance. According to the authors, this is explained by the reduction of friction between the particles in the composite binder, compared to the reference. The results also support that coarser grounded FNS as binder replacement will have the best impact in rheological terms, as there is an increase of direct contacts between particles in finer grounded FNS, hindering the slide of the particles.

Shoya et al. (1999) found that the use of 50% fine aggregate FNS concrete decreased the slump flow values (695mm) and increased the V funnel time (17s) compared to the reference (respectively, 700mm and 14s). This effect was even more pronounced at 100% replacement (respectively, 690mm and 21s). According to the author, however, that did not affect its suitability for producing self-compacting high-performance concretes.

[7] A measure of the specific surface area of a powdered material, expressed in m²/kg, determined by the air permeability method.

Setting in cementitious matrices is a principal parameter for fresh and utilization of the mixture. This property is highly sensible to admixtures, mineral addition and climate change (MAILVAGANAM, 2019), so it is very important to understand its behaviour with FNS presence.

Ferronickel slag as a binder delayed the hardening process of fresh mortar for Kim, Lee and Ann (KIM; LEE; ANN, 2019) in a proportional manner. The higher both the replacement rate and size of the FNS, the longer it took the initial set to begin, which was explained by the low reactivity of the FNS. 30% FNS mortar began to set 101 minutes later than the reference. Katsiotis et al. (2015) also found a similar pattern of setting times when studying blended FNS-cement pastes. Such a straightforward pattern was not found in Rahman et al. (2017) and Bouasria et al. (2021) samples, where the FNS content did not seem to be a determinant factor (Table 3).

Table 3 - Setting times of cementitious matrices with FNS

Authors	Year	Type of use	Matrix	FNS (%)	Other potential SCMs	Setting times (min)	
						Initial	Final
Katsiotis et al.	2015	Binder	Paste	REF		145	185
				5		150	195
				10		160	200
				15		170	215
				20		175	220
Rahman et al.	2017	Binder	Paste	REF		131	191
				20		131	200
				30		131	200
				40		140	200
				50		130	200
				65		150	230
Kim, Lee and Ann	2019	Binder	Mortar	REF		392	541
				5		433	557
				10		485	612
				30		493	680
Bouasria et al.	2021	Binder	Mortar	REF		233	320
				10		225	310
				15		213	326
				30		235	334
				5	*5% CREPIDULA*	219	325
				10	*10% CREPIDULA*	208	328
				15	*15% CREPIDULA*	211	356
				20	*20% CREPIDULA*	215	369
				30	*30% CREPIDULA*	222	395

The following is an analysis of the effects of incorporating FNS on the mechanical properties of cementitous matrices. The compressive, flexural, and split tensile strength (MPa) of the mortars and concretes were compiled in graphs, as was the modulus of elasticity (GPa). Table 4 shows the number of articles that dealt with each property, based on its use as aggregate or binder. Many studied multiple factors, and some researched both types of FNS incorporation.

Table 4 - Properties researched

Property by type of use	Number of articles
Aggregate	**21**
Compressive strength	19

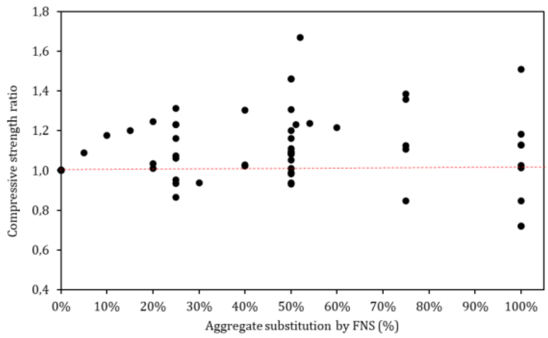
Flexural strength	5
Split tensile strength	8
Modulus of elasticity	4
Binder	**19**
Compressive strength	17
Flexural strength	3
Split tensile strength	5
Modulus of elasticity	4

Fig. 6 shows the increase or decrease of compressive strength of each sample that used FNS as aggregate in relation to the reference. Of all samples in all studies regarding FNS as fine aggregate, about three-quarters had higher compressive strength than the respective reference sample. The highest reported increase of compressive strength was that of Petrounias et al. (2022), which was of 67% on a 52% FNS fine aggregate content on concrete. The authors explain it due to the compact texture of the concrete specimens containing slags, and the unevenly distributed porosity of the natural aggregates. Concurring, Nuruzzaman, Kuri and Sarker (2022) attribute the increase in compressive strength in the mixtures containing FNS as sand substitute to the enhancement of particle size distribution of the aggregate. On the other hand, Saha and Sarker (2017a) found 28% less strength in compressive strength in comparison with the reference concrete, using 100% of fine aggregate replaced by FNS. The average change in compressive strength was an increase of 11%.

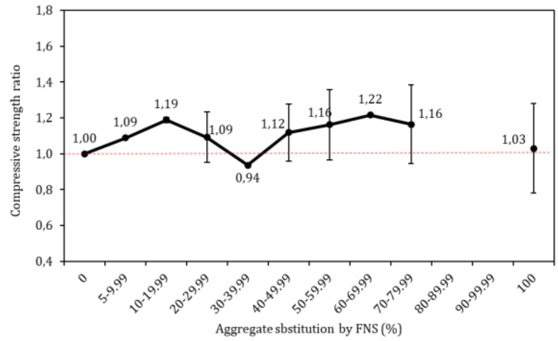
Regarding the modulus of elasticity, as showed in Fig. 7, about 64% of the samples had their values increased compared to the reference series. The highest value found was of 11% higher than the reference, on the Saha and Sarker (2017a) sample on a 50% replacement, which the authors attribute to the continuous grading of the fine aggregates in the combination of FNS and natural sand. The lowest value was found by Nuruzzaman, Kuri and Sarker (2022) at 10% lower than the reference, using 30% of FNS content.

Additionally, 60% of samples containing FNS resulted in higher values of split tensile strength (Fig. 8), with the highest increase being that of Malek et al. (2021), which replaced 25% of the fine aggregate with the FNS and achieved 43% more split tensile strength than the reference sample. Apart from that, Sun, Feng and Chen (2019) found that samples containing both three-quarters and a full replacement of ferronickel slag saw its split tensile strength reduced by 13%, the highest decrease recorded among the studies analysed in this review.

On the matter of flexural strength (Fig. 9), a clear majority of 72% of the 18 samples showed increases. At a two-thirds increase, the Malek et al. (2021) sample containing a quarter of FNS was once again the best-performing sample, similarly opposing the Sun, Feng and Chen (2019) sample containing 100% slag as fine aggregate.



(a)



(b)

Fig. 6 – 28D compressive strength ratio of cementitious composites with FNS as aggregate with different contents compared to the REF series. Raw data in (a) and average in (b)

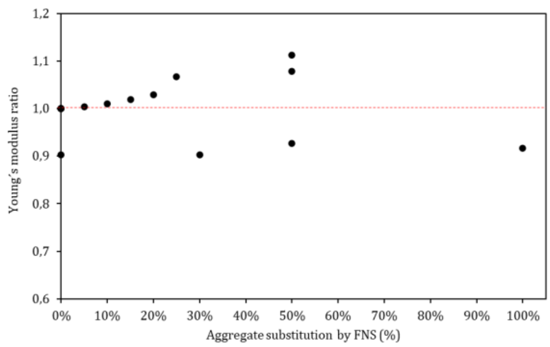


Fig. 7 - 28D Young's modulus ratio of cementitious composites with FNS as aggregate with different contents compared to the REF series

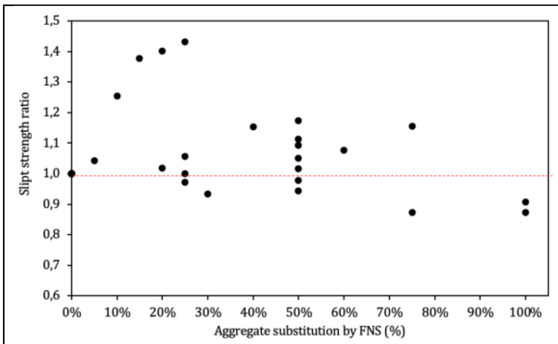


Fig. 7 – 28D split strength ratio of cementitious composite with FNS as aggregate substitution compared to the REF series

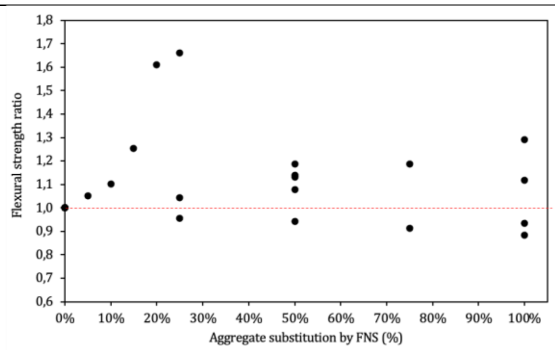


Fig. 8 - 28D flexural strength ratio of cementitious composite with FNS as aggregate substitution compared to the REF series

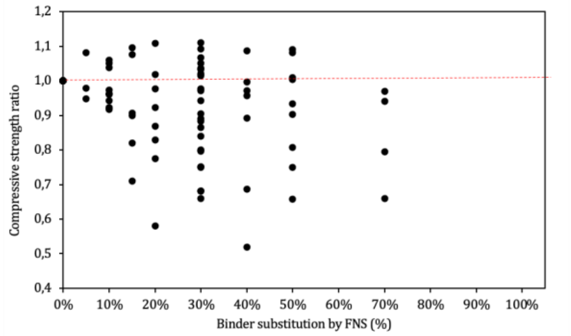
A different scenario emerged when FNS is properly ground and used as a partial replacement for binder in cement-based materials. Regarding compressive strength (Fig. 10), of the 70 FNS samples analysed in 17 articles, only 21 (three in ten) had higher values of compressive strength at 28 days than the reference. According to Lemonis et al. (2015), strength development in early ages is governed by the hydration of cement, with no apparent contribution of supplementary cementitious materials such as FNS. Kim, Lee and Ann (2019) explain that FNS restricts the formation of CS-type hydration products, due to the chemical composition of the ferronickel slag (generally, with higher content of SiO2 and lower content of CaO).

On average, the change in compressive strength was a 10% decrease. Both Qi et al. (2020), with 20% FNS as binder and C30 cement, and Li et al. (2022), with 30% of the finest grounded FNS in their study, reached an 11% increase in compressive strength, the highest values in the articles analysed. By associating 30% of ferronickel slag and 30% of Crepidula fornicata, also a potential supplementary cementitious material due to its composition, Bouasria et al. (2021) attained a decrease of 69% of compressive strength, the lowest value in the studies reviewed.

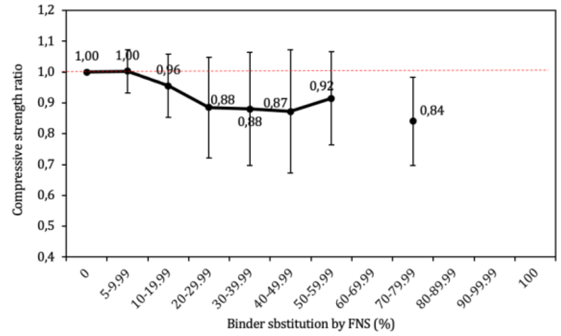
Three-quarters of the samples containing FNS as a partial binder had a greater modulus of elasticity (Fig. 11) than the reference. These variations ranged from a 12% increase achieved by the Qi et al. (2020) 20% FNS with C30 cement sample, to a 10% decrease found by Nuruzzaman, Kuri and Sarker (2022) replacing 30% of the binder with FNS.

With respect to split tensile strength (Fig. 12), 86% of the samples had greater values than the reference. It ranged from a 10% increase achieved by both Zhou and Shi (2021) and Qi et al. (2020), who replaced 30% and 50% of the binder with FNS respectively, to a 9% decrease attained by Nuruzzaman, Kuri and Sarker (2022) with a 30% FNS sample.

Finally, the flexural strength (Fig. 12) variation ranged from a maximum of a 5% increase achieved by a small replacement of 5% of the binder with FNS (by Kim, Lee and Ann, 2019) to a 51% decrease achieved by the mix of 30% FNS with 30% Crepidula Fornicata (by Bouasria et al., 2021). Overall, only three of the twelve samples (25%) achieved greater flexural strength than their respective references.



(a)



(b)

Fig. 9 – 28D compressive strength ratio of FNS as binder with different contents compared to the REF

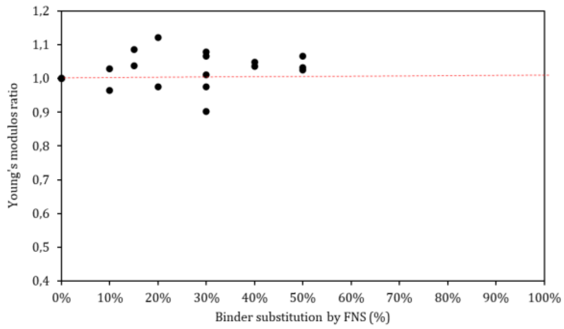


Fig. 10 - Modulus of elasticity (28 days) ratio of FNS as binder with different contents compared to the REF

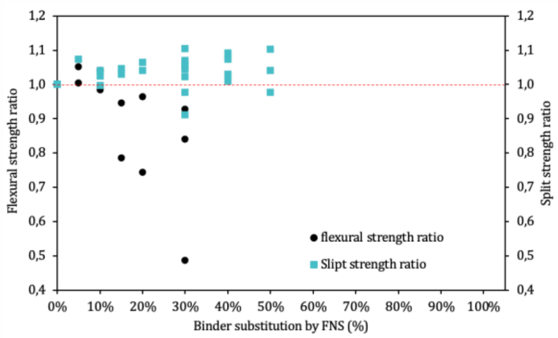


Fig. 11 – 28D flexural and split tensile strength ratio of FNS as binder with different contents compared to the REF

In terms of chloride ion penetration, Nuruzzaman et al. (2020), Bae, Lee and Choi (2021), Liu at al. (2020) and Zhou and Shi (2021) found that the addition of ferronickel slag, either as a partial or complete replacement for natural fine aggregate or as a supplementary cementitious material, proportionally decreased the penetration of chloride ions. As in, generally, the higher the amount of FNS, the less penetration resulted. Nuruzzaman et al. (2020) described the use of FNS fine aggregate as decreasing porosity. Liu et al. (2020) noted that FNS powder is beneficial to the durability of concrete, increasing its protection against external attack. Zhou and Shi (2021) further expanded on the notion that the pozzolanic reaction observed in the concrete containing FNS improved the microstructure of the interfacial transition zone, and the less amount of water needed in the mix reduced the connected pores, improving the chloride resistance.

Huang, Wang and Shi (2017) noted that the effect of the decrease of chloride ion penetration using FNS was obvious only with the blast furnace type (BFS), which presented either moderate or low permeability, while the electric furnace type (EFS) maintained the sample at the high permeability grade, although with nominally lower values than the reference. It was only at 90 days of curing that the positive effect of both types was made obvious, compared to the reference sample. Sun, Feng and Chen (2019) found that only blast furnace ferronickel slag (BS) improved the resistance of concrete to chloride ion penetration, as opposed to electric furnace ferronickel slag (ES) which had no positive impact. Chen et al. (2020) samples containing FNS all presented either low or very low permeability, although on a non-linear fashion, as opposed to the reference sample, which had moderate permeability. On the contrary, Wang, Huang and Wang (2017) found no improvement in this regard. Those results are presented in Table 5.

Table 5 - Chloride ion penetration

Authors	Year	Type of use	Matrix	FNS (%)	Charge passed at 28 days (Coulomb)	Variation to the reference (%)
Sun et al. (SUN; FENG; CHEN, 2019)	2019	Aggregate	Concrete	0%	2650	
			Concrete (BS)	25%	2250	85%
				50%	1550	58%
				75%	1200	45%
			Concrete (ES)	25%	2800	106%
				50%	2800	106%
				75%	3100	117%
				100%	3450	130%
Nuruzzaman et al. (NURUZZAMAN et al., 2020)	2020	Aggregate	Concrete	0%	360	
				20%	277	77%
				40%	248	69%
				60%	232	64%
Bae et al. (BAE; LEE; CHOI, 2021)	2021	Aggregate	Mortar	0%	9629	
				25%	9411	98%
				50%	9186	95%
Huang et al. (HUANG; WANG; SHI, 2017)	2017	Binder	Concrete	0%	5500	
			Concrete (EFS1)	30%	4200	76%
			Concrete (EFS2)	30%	4200	76%
			Concrete (EFS3)	30%	4100	75%
			Concrete (BFS1)	30%	1700	31%

			Concrete (BFS2)	30%	2900	53%
Wang et al. (WANG; HUANG; WANG, 2017)	2017	Binder	Concrete	0%	2400	
				50%	3100	129%
Chen et al. (CHEN et al., 2020)	2020	Binder	Concrete	0%	2500	
				10%	1550	62%
				30%	950	38%
				50%	1100	44%
				70%	1300	52%
Liu et al. (LIU et al., 2020)	2020	Binder	Concrete	0%	3800	
				15%	2700	71%
				30%	1750	46%
Zhou and Shi (ZHOU; SHI, 2021)	2021	Binder	Concrete	0%	2850	
			Concrete (4200cm²/g FNS)	30%	2300	81%
				40%	1800	63%
			Concrete (5500cm²/g FNS)	30%	1850	65%
				40%	1650	58%

Final considerations

This review study made it possible to draw the following conclusions about the use of ferronickel slag as either a fine aggregate or binder replacement:

• Mainly SiO2 and MgO, followed by, Fe2O3, CaO and Al2O3, compose most FNS samples. The high amount of MgO did not generally present a concern for harmful expansion;

• The use of FNS as fine aggregate generally reduced the workability of samples, due to the angularity of FNS fine aggregate. However, the use of FNS as a partial binder replacement could improve the rheological properties;

• Setting times were either delayed or not of much relevance when FNS was used as a partial binder;

• When used as a partial or total replacement for sand, FNS increased the compressive, split tensile and flexural strengths, as well as the modulus of elasticity, in most samples reviewed, with the compressive strength increasing 11% on average. This could be due to an improvement in particle size distribution;

• When grounded and used as a partial replacement for binder, FNS decreased the compressive and flexural strengths on most samples, while increasing the modulus of elasticity and split tensile strength in a clear majority of the mixtures studied. On average, the compressive strength was reduced by 10%, possibly due to delayed strength development;

• FNS generally improved the chloride ion resistance of mortars and concretes, when used as both fine aggregate or binder;

• Overall, FNS is suitable for use in cement-based materials as both binder and fine aggregate, with strengths and weaknesses that must be assessed by the mix designer. It might be an effective way of reducing waste and greenhouse gas emissions, by replacing CO2 emissions-heavy ordinary Portland cement.

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Additional informations

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