Sustainable Chemistry and Pharmacy 33 (2023) 101030

Contents lists available at ScienceDirect

Sustainable Chemistry and Pharmacy

journal homepage: www.elsevier.com/locate/scp

Use of blast furnace slag in cementitious materials for pavements - Systematic literature review and eco-efficiency

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ARTICLE INFO

Handling Editor: Klaus Kümmerer

Keywords:
Blast furnace slag
Concrete pavement
Portland cement
Pozzolanic additions
Supplementary cement

ABSTRACT

To reduce the environmental impact of Portland cement manufacturing and increase profits, the industry has been using some waste in cement composition; and blast furnace slag is one of the most used for this purpose. Thus, this work aims to carry out a systematic review of recent scientific literature focusing on applications of the use of this residue in pavements. The keywords: “Blast Furnace Slag” and "Cement replacement"; were used in the search using the Web of Science database. A total of 3731 articles published in the last five years were found, in which 33, with the word “pavement”, were selected. After applying the exclusion criteria, 20 articles were selected and analyzed for the present work. The main results published in the last five years that address the use of blast furnace slag in pavements, the effects on composites, the chemical composition and physical properties of the waste are summarized in this work. The highly cited articles, with more than 200 citations to date, dealing with the use of this residue in cementitious composites are also summarized. Additionally, based on the collected data, the life cycle assessment (LCA) was performed and showed that cement replacement by BFS reduces 48% CO_2 emissions, saves 37% of energy, and provides 16.28% of cost economy in process. Therefore, this work demonstrates the high potential of this residue in contributing to the reduction of environmental impacts by reducing the extraction of raw materials, as well as by reducing the emission of polluting gases.

1. Introduction

Concrete is the second most consumed material in the world after water, which is the first (Gagg 2014). In concrete, the cement is the most important constituent. Cement production requires extract non-renewable natural resources and use of high temperatures causing the emission of polluting gases that makes this industry responsible for 5–10% of global greenhouse emissions (Talaei et al., 2019; Vázquez-Rowe et al., 2019). In the cement production two main ores are used: limestone rich in CaO, and clay, rich in SiO_2, Al_2O_3, Fe_2O_3 and MgO. Limestone processing is the main part of the production and temperatures between 1450 and 1550 °C are used

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https://doi.org/10.1016/j.scp.2023.101030
Received 1 January 2023; Received in revised form 8 February 2023; Accepted 16 February 2023

(Heikal et al., 2020). In order to mitigate environmental impacts, the industry has been incorporating as cementitious materials wastes rich in silica and alumina and/or aluminosilicates, such as silica fume, blast furnace slag (BFS) and also in its granular form, ground granulated blast-furnace slag (GGBFS).

The European Committee for Standardization mentions that the BFS is the main constituents of cement type CEM III/C, reaching up to 95% of its composition (European Committee for Standardization 2011). In Brazil, the OPC type CP II-E presents between 6% and 34% of BFS in its composition, and the CP-III, is the type with the largest amount of this residue, between 35% and 70% (Ambrozewicz 2012). The American Society for Testing and Materials (ASTM) has established parameters for the use of BFS as a supplementary cementitious material (SCM) in concrete and mortars. That slag must not contain additions, and have to meet the requirements for chemical composition, fineness, air content, activity index, and compressive strength when used in mortars for construction (ASTM 2018).

Slags are residual materials from the iron and steel industry, resulting from the processing of silica, present as iron ore impurity, and limestone, at high temperatures, usually between 900 °C and 1200 °C. These by-products, resulting from the production of pig iron in blast furnaces and steel in the industry are, therefore, made up of calcium silicates, magnesium and impurities, with concentrations varying according to the type of product (Özbay et al., 2016).

Data from the World Steel Association of 2018 indicate that the world's largest pig iron producers are China, Russia and India. The amount and composition of the slag generated vary according to the fuel used, which can be charcoal or coke. In steel mills that use blast furnaces fed with coking coal, approximately 500 million tons of slag are generated worldwide per year (Gholampour and Ozbakkaloglu 2017).

The construction industry is highly dependent on conventional materials, but the innovation in road construction works is focused on the use of modified asphalt materials which has been growing and become a routine practice in numerous countries (Sojobi 2016; Mohanta et al., 2021). GGBFS is widely used in paving as partial cement replacement in different applications such replacing OPC or aggregate in reinforced cement concrete (RCC) (Bilir et al., 2015; Barišić et al., 2019), pervious concrete (El-Hassan and Kianmehr 2018; Ho et al., 2018) or self-consolidating concrete (SCC) (Shirzadi Javid and Arjmandi Nejad 2017; Sua-iam et al., 2019), and abrasion resistance increase (Bilir et al., 2015); or other uses such as soil stabilization (Phummiphan et al., 2018; Barišić et al., 2019; Eyo et al., 2020) or roller-compacted concrete (Moradi and Shahnoori 2021) in base layers.

The different applications of BFS and GGBFS is explained in the benefits of their use. Some of these advantages are the - Environmental Benefit: when BFS is used in the composition of binary and ternary cements, the clinkerization, grinding, mixing and transport processes have a reduction in energy expenditure and natural resource consumption when compared to the traditional process, in addition to reducing CO_2 emissions (Özbay et al., 2016). The use of this waste reduces their disposal in industrial landfills, bringing an environmental benefit (Paiva et al., 2021). – The Economic-Social: the use of wastes, such as BFS, is considered as a factor that significantly reduces the cost of cement production and, consequently, concrete and mortar (Özbay et al., 2016). In underdeveloped countries, with a high housing deficit, as can be seen in almost the entire southern hemisphere, civil construction materials can reach 2/3 of the total cost of construction and, therefore, the decrease in the final price of civil construction materials can be an important economic-social benefit (Adesanya and Raheem 2009). – The Improvement of the physical and mechanical characteristics: the GGBFS, when used as a substitute for aggregates in roller-compacted concrete pavements, improves the strength, reduces pore size and the chloride ion permeability (Moradi and Shahnoori 2021). The steel slag as a partial aggregate replacement improves durability and provides better freeze–thaw resistance of cement-bound layers (Barišić et al., 2019) and abrasion resistance of concrete (Bilir et al., 2015).

Due to the wide application and importance of the use of GGBFS and BFS in paving, this paper summarizes the recent research carried out in the last 5 years. A Systematic Literature Review, approaching the use of blast furnace slag in cementitious materials used in paving was performed, in which the physical-chemical properties and mechanical resistance were discussed. Subsequently, a simplified LCA study of the eco-efficiency of the GGBFS in concrete pavement based on the literature was developed. In contrast with the conventional literature review, in which the author selects the articles and discusses the topic, the systematic literature review guarantees the reproducibility of the selection of materials, since the search strategies, selection process, inclusion criteria and exclusion are informed (Xiao and Watson, 2019). The results obtained from the systematic review provide the production of a clear and replicable study, which can be easily audited and validated.

2. Methods

The bibliographic search for Systematic Literature Review was carried out in the Web of Science database over the last 5 years (2017–2022), using the keywords: “Blast Furnace Slag”; “Cement Replacement”.

Among a total of 3731 articles, 33 articles were selected after application along with the keyword “pavement”. Among these, after reading the abstracts, those reporting the physical and chemical properties of the residue and the mechanical properties of the composite were identified. Thus, 20 articles were selected and analyzed, extracting results about the effects of these residues on mechanical properties and the percentages of replacement. The main results obtained by the researchers are summarized in Fig. 1.

Due to the historic importance of this residue in civil construction, in another section (3.3), the highly cited articles, with more than 200 citations so far in the Web of Science (Clarivate Analytics) database are summarized, not restricted to the last 5 years and not applied only to pavements. In this search, the same keywords were used. In the Web of Science, it is possible to access the articles in descending order of the number of citations with the mentioned keywords. Those that contain more than 200 citations and that includes cement replacement were analyzed to compose this section.

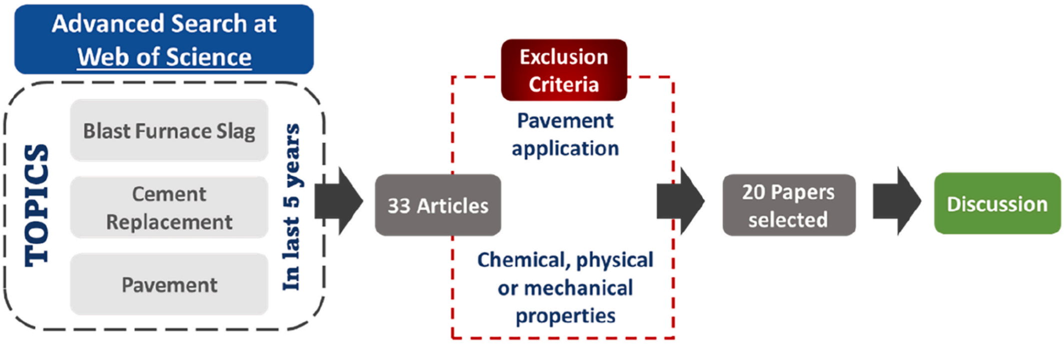

Fig. 1. Search process and results at each step of systematic literature review.

Based on the articles selected after the exclusion criteria, a mix constituent of concrete paving was used for the development of the simplified LCA. Because only one article among the selected ones evaluated the LCA of the GGBFS, other literature data were used to get quantitative data such as on embodied energy, CO_2 emission and cost of GGBFS and constituents of concrete.

3. Results

3.1. Physical and chemical characteristics of blast furnace slag

The blast furnace slag is classified by some countries, such as the United States and Canada, as a co-product of the iron and steel industry and, normally, silica, calcium, aluminum, magnesium and oxygen make up more than 95% of its composition (Özbay et al., 2016). The composition of the blast furnace slag changes depending on the ores, the type of fuel used and impurities in the coke, when it is used, among other factors (Oner and Akyuz 2007). Slag from industries that use charcoal-fueled blast furnaces generally produce acidic slag while slag from coke-fired furnaces generate basic slag. This classification is based on the ratio between CaO and SiO_2 values in which result less than 1 represent acidic slag and greater than 1 alkaline slag.

Table 1 shows the results of the physical properties, including the specific gravity (g/cm^3), specific surface area (m^2/kg) and loss on ignition (LOI %) of inorganics of the waste extracted in the articles selected in the bibliographic search.

Table 2 summarizes the chemical composition, in percentage by weight, of the studied materials according to previous research works. The CaO, followed by SiO_2 and Al_2O_3 are the main components. The SiO_2, Al_2O_3 and Fe_2O_3, in an amorphous state, are important compounds in the pozzolanic reaction when the wastes are used to replace the cement. These same compounds, and the CaO, are necessary for geopolymer materials.

Table 1
Physical properties of materials studied.

MATERIALS	SPECIFIC GRAVITY (g/cm^3)	SPECIFIC SURFACE AREA (m^2/kg)	LOSS ON IGNITION (%)	REFERENCES
OPC	3.00–3.20	305–390	0.60–2.99	(Bilir et al., 2015; El-Hassan and Kianmehr 2016; Nwaubani 2018; Ho et al., 2018; Saluja et al. 2019b, 2019c, 2019a; Chore and Joshi 2020; Eyo et al., 2020; Li et al., 2020; Xu et al., 2020; Chen et al., 2021; Moradi and Shahnoori 2021)
GGBFS	2.08–3.54	385–472	0.55–3.80	(Bilir et al., 2015; El-Hassan and Kianmehr 2016; Phummiphan et al., 2018; Nwaubani 2018; Sugapriya and Ramkrishnan 2018; Saluja et al. 2019a, 2019b, 2019c; Amulya and Ravi Shankar 2020; Pachideh et al., 2020; Chore and Joshi 2020; Eyo et al., 2020; Hossiney et al., 2020; Li et al., 2020; Xu et al., 2020; Chen et al., 2021; Moradi and Shahnoori 2021)
BFS	2.87–2.88	586	0.10	(Ho et al., 2018; Yildirim and Prezzi 2020)

Table 2
Chemical composition of materials studied, in percentage by weight.

MATERIALS	SiO_2	AlO_3	CaO	MgO	SO_3	Fe_2O_3	REFERENCES
OPC	19.08–22.45	4.30–5.26	61.96–64.86	0.80–4.60	0.85–3.80	2.10–3.35	(Bilir et al., 2015; El-Hassan and Kianmehr 2016; Nwaubani 2018; Ho et al., 2018; Saluja et al. 2019a, 2019c, 2019b; Eyo et al., 2020; Li et al., 2020; Pachideh et al., 2020; Xu et al., 2020; Chen et al., 2021)
GGBFS	23.0–37.0	2.84–21.7	30.38–64	1.4–10.93	0.16–5.13	0.3–18.65	(Bilir et al., 2015; El-Hassan and Kianmehr 2016; Nwaubani 2018; Phummiphan et al., 2018; Sugapriya and Ramkrishnan 2018; Saluja et al. 2019c, 2019a, 2019b; Perez-Garcia et al., 2019; Amulya and Ravi Shankar 2020; Pachideh et al., 2020; Chore and Joshi 2020; Eyo et al., 2020; Hossiney et al., 2020; Li et al., 2020; Xu et al., 2020; Bai Kamara et al., 2021; Moradi and Shahnoori 2021; Chen et al., 2021; Guo et al., 2021; Migunthanna et al., 2021)
BFS	33.68	14.37	40.24	7.83	0.66	0.29	(Ho et al., 2018)

3.2. Influence of BFS and GGBFS on pavements properties

The replacement of components by BFS in pavements should result in materials that meet several parameters such as mechanical strength, abrasion resistance, permeability, etc. In the scope of this application. Table 3 summarizes the properties regarding these aspects showing the performance of the use of GGBFS.

Abrasion resistance is an essential parameter for durability and acceptability of pavements. The addition of cementitious materials, and the type and size of aggregates exert great influence on abrasion resistance (Saluja et al., 2019a). For those reasons, some authors have done research about this parameter on pavements, like that described on Table 3.

Bilir's et al. (Bilir et al., 2015) replaced fine aggregate by GGBFS and demonstrated that even when the compressive strength decreased, the abrasion resistance does not change significantly due to the physical, chemical and mechanical properties of the residue. Xu et al. (2020) studied the effects of GGBFS on surface durability of Portland cement concrete pavement, replacing the cement with

Table 3

Attributes and feasibility of use of BFS and GGBFS on pavements.

AUTHORS	YEAR	REPLACEMENT METHOD	SUMMARY OF RESULTS
Moradi and Shahnoori (2021)	2021	Addition of 15% GGBFS	GGBFS reduced the permeability of roller-compacted concrete pavement (RCC), improved the chemical resistance and also the compressive strength, avoiding the reduction of mass after submission to cure in 5% sodium sulfate solution in the durability test.
Chen et al. (2020)	2021	Cement replacement by 0%–40% GGBFS	Mortars with 30% of cement replaced by GGBFS performed better than many conventional pavements repair materials. Furthermore, it presented superior durability under chemical environments.
Chore and Joshi (2021)	2020	Cement replacement by 3.34–15% GGBFS	All compositions fulfilled the requirements of the concrete that could be utilized to build robust pavement for both high- and low-traffic routes.
Yildirim and Prezzi (2020)	2020	Cement or lime replacement by 3–7% BFS or electric-arc-furnace steel slag (EAF-SS)	The findings demonstrated the effectiveness of the composition containing 7% EAF-SS plus 3% BFS in reducing the swelling of the in situ clayey soil and demonstrating adequate performance for usage as soil stabilization mixtures. After implementation project on field, stabilized subgrade sections have operated successfully for roughly ten years.
Barišić et al. (2019)	2017	Gravel replacement by 25%, 75% BFS	Compressive strength and the dynamic modulus of elasticity increased with the percentage of slag in the composition of cement-bound layers.
Amulya and Shankar (2020)	2020	The soil was stabilized with 25% GGBFS	The highest flexural strength under heavy compaction and fatigue life were achieved by the soil sample treated with 25% GGBFS and alkaline solutions.
Eyo et al. (2020)	2020	OPC was substituted by GGBFS 50, 60 and 70%	Searching for a soil stabilization, all replacement percentages studied in soil samples resulted in a compression index above the control, after 28 days of cure.
Pachideh et al. (2020)	2020	Cement replacement by 10 or 20% GGBFS	The addition of GGBFS decrease the water absorption and increased the tensile strength of concrete specimen's.
Saluja et al. (2019a)	2019	Cement replacement by 20%, 40% or 60% GGBFS	The mix with 40% GGBFS content exhibited the highest compressive strength over all other compositions. It was discovered that the RCC's compressive strength and abrasion resistance are exponentially related.
Saluja et al. (2019b)	2019	Cement replacement by 20%, 40 or 60% GGBFS	Addition of GGBFS into the RCC mix increased the water requirement. The results showed that the strength of RCC containing GGBFS increased up to 40% of substitution.
Saluja et al. (2019c)	2019	Cement replacement by 20%, 40 or 60% GGBFS	Due to the increased amount of paste and denser matrix produced by the GGBFS particles, RCC mixes with GGBFS display higher shrinkage strain than the control.
Phummiphan et al. (2018)	2018	GGBFS contents were varied to replace lateritic soil from 10% to 30%	The study's findings suggest that up to 10% GGBFS could be employed as a replacement material in geopolymer to stabilize lateritic soil for creating a low carbon stabilized pavement base.
Javid and Nejad (2017)	2017	50% cement replacement by GGBFS on SCC	In SCC the cement replaced by GGBFS leads to an increase in the workability. The use of GGBFS in the SCC causes a sharp reduction in mechanical strength.
Ho et al. (2018)	2018	Cement replacement by 50%, 60% or 70% BFS	For typical engineering applications, such as the construction of waterworks structures or pervious backfill materials that do not require compacting, the concrete demonstrated proper strength. BFS was used replacing cement to attribute greater resistance against chemical substances in pervious concrete.
Bai Kamara, Ganjian and Khorami (2021)	2021	Cement replacement by 0–60% GGBFS	The compressive strength of the chosen mixes has the potential to be used not only for highway pavement projects but also for more general civil engineering, architecture, and building construction applications. The purpose of compacting the pastes into cubes was to mimic real-world applications on construction sites.
Li et al. (2020)	2020	Cement replacement with 10%, 15% or 20% GGBFS	Mixtures with GGBFS served as a rigid skeleton to fill the micropores with the C–S–H gel, ensuring improved mechanical properties of concretes.
Nwaubani (2018)	2018	Cement replacement with 10%, 30% or 50% GGBFS.	Although lower than the control mixture, at young ages, the compressive strength of pastes incorporating 30% or 50% GGFBS demonstrated greater strength development rates at older ages. GGBFS generally reduced total porosity and produced a finer pore structure when used to partially replace regular Portland cement.
Xu et al. (2020)	2020	Cement substitution by 15, 25, 35 wt% GGBFS.	The use of slag in the concrete affected the initial compressive strength, but the strength values of these concretes became higher than the reference mixture after 28 days.
Perez-Garcia et al. (2019)	2019	30%, 40% and 50% of cement by GGBFS	The consistency, workability, and mechanical capabilities of grout for foundation by injection was tested. The final mix's fluidity was unaffected by the usage of the slags up to 50%. The compressive strength substitution of slag grew as the substitution percentage increased.
Sugapriya and Ramkrishnan (2018)	2018	Cement replacement by 10% GGBFS	Compressive strength and damping property were analyzed in concrete containing rubber in replacement of fine aggregates and ultra-fine GGBFS in replacement of cement. The usage of Ultra-Fine GGBFS improved the strength characteristics which can be attributed to the completion of the hydration process and formation of Calcium-Silicate-Hydrate (CSH) gel in the cement.

up to 35% GGBFS. The results showed concrete with slag exhibited better surface frost resistance when cured in saturated sodium chloride solution than the reference (Xu et al., 2020). Saluja, Goyal and Bhattacharjee substituted the cement with GGBFS up to 60%. They observed abrasion resistance is reached until the limit of 40% substitution of cement with GGBFS, which can be correlated with the chemical composition of cement and GGBFS (Saluja et al., 2019a).

The weather in cold regions reduces durability of concrete pavement. The GGBFS, when it is used as a supplementary cementitious material in mortar and concrete, contributes to increase mechanical and durability properties such as freeze-thaw resistance (Bilir et al., 2015). Barišić et al. (2019) investigated the durability of cement-bound layers with steel slag as a partial aggregate replacement and the main conclusion is that steel slag aggregate presented good potential for use in adverse climates. Bai Kamara et al. (2021) investigated the cement replacement up to 60% by GGBFS and observed that, even after ten freeze-thaw cycles the strength and density increases.

3.3. *Influence of BFS and GGBFS on cementitious materials – the most cited in literature*

To expand the scope of this work to other traditional applications of BFS and GGBFS in cementitious composites, in this section we have reported the most cited articles in the literature which deals with cement replacement, with more than 200 citations in Web of Science. The dosages for better mechanical performance, effects on the hydration of cement in short and long-term, different curing conditions, durability, and use of artificial neural networks to the predict the compressive strength of cementitious composites are described.

Zhao et al. (2015) studied the effects of replacement of cement (20%, 30% and 40%) by GGBFS and fly ash (FS) for production of the SCC. GGBFS did not influence on the workability of the SCC. At initial stages of hydration (3 days), SCC presented higher porosity and lower mechanical strength; however, these properties reached similar values of the control in later hydration (90 days). In the initial curing periods, GGBFS presented a low pozzolanic reaction activity, requiring more time to produce the secondary hydration, by the reaction of calcium hydroxide (CH) of primary cement hydration. Durability tests demonstrated that SCC with GGBFS was more effective on resistance the chloride ion migration and drying shrinkage, however presented a higher depth of carbonation than the control SCC. This is because the GGBFS reduced the CH content and increased the porosity of the hardened SCC, accelerating the early stage of carbonation depth. Akçaözoğlu et al. (2010) evaluated the use of waste Poly-ethylene Terephthalate (PET) as an aggregate and BFS in replacement of cement for lightweight concrete application. The BFS contributed to the reduction of unit weight and shrinkage of the concretes and increased of the compressive strength. Similar results are reported by Zhao et al. (2015), that also found increased carbonation depth.

Brooks et al. (2000) evaluated the effect of replacing cement with up to 60% of GGBFS on setting time of high-strength concretes. The results showed that the GGFBS contributed to the retarded of setting time due with the smaller amount of cement used. In addition, the superplasticizer acted on a smaller portion of cement, also leading to the reduction of setting time. However, 40% and 60% replacements show excessive delay in setting time, with 11 and 17 h, above regulatory limits.

Oner and Akyuz (2007) investigated the optimal dosage of GGBFS in replacement of cement in concretes using several replacement ratio of 0%, 15%, 30%, 50%, 70%, 90% and 110%. As the GGBFS content increased, the water required in the mix design also increased due to higher specific surface of the GGBFS particles. It was observed that at early ages, strength values of GGBFS concrete mixtures are lower than the control mixtures. As the curing period was extended, the strength values of the GGFBS concrete mixtures increased more than the control mixtures. The optimum level of GGBFS content for maximizing strength was about 55–59% of the total binder content.

Megat-Johari et al. (2011) investigated the influence of mineral additions on high strength concretes As the replacement level increased, there was a significant increase in workability, up to 40% of very fine GGBFS. The inclusion of GGBFS resulted in a reduction in the early strength of the concrete. The results showed that OPC content can be reduced by 60% using GGBFS and compressive strength at 28 days comparable to OPC concrete was still achievable. In addition, at 20% replacement level, the GGBFS concrete reached greater strength than that control specimen, after 7 days of curing. Other study evaluated the replacement of cement by GGBFS in amounts of 50% and 70% in concretes (Berndt 2009). Characteristics such as strength, permeability and durability in chloride and sulfates medium were evaluated. Inclusion of 50% BFS was beneficial, giving the highest strength at 28 and 84 days. Increasing the cement replacement level to 70% BFS resulted in slightly reduced strength compared with concrete containing 50% slag. The coefficients of permeability of the mixes with and without BFS were very similar. The incorporation of slag resulted in reduced chloride diffusion coefficients. Therefore, results indicated that concrete mixes containing 50% replacement of cement with BFS resulted in the best results in terms of mechanical properties and durability of high strength concretes.

Aldea et al. (2000) evaluated the effects of curing conditions in concrete using slag replacement. The authors observed that steam curing reduces the compressive strength, while the chloride permeability and penetrability decrease in autoclave curing. The steam curing induces rapid initial hydration, with less uniform distribution of the hydration products, reflecting in large capillary pore distribution. Overall, it was concluded that room temperature curing presented the best performance, because provides higher compressive strength. Pastes of blended cements, with 30% and 50% slag cured under different conditions (10 ˚C, 30 ˚C and 50 ˚C) was also analyzed by Escalante et al. (2001). The effect of hydration conditions and slag characteristics affect the reactivity of slags. It has been shown that the intensification of some factors such as the ratio of vitreous fraction, the specific surface area of BFS, the temperature of cure and the water/solids ratio of composite, affect, individually or in combination, for greater the slag reactivity.

The influence of BFS in thermal conductivity of mortar has been evaluated by (Demirboğ;a 2003; Demirboğa 2007). The authors observed reduction of the maximum thermal conductivity of mortars, when replacing 11%–15% of cement by BFS. The reduction in thermal conductivity is partly due to the lower density of concretes and the amorphous structure of BFS (Lo-shu et al., 1980). Poon et al. (2001) investigated the strength and durability of normal and high performance concrete incorporating BBGFS and others mineral additions were compared when subjected to high temperatures (Poon et al., 2001). GGBFS was used to replace cement at 30% and 40% by mass. GGFBS concrete subjected to temperatures between 20 °C and 200 °C showed an increase in strength. The strength gain was probably due to the formation of tobermorite, which was formed by the reaction between not hydrated GGBFS particles and lime at high temperatures. A severe loss in strength was observed in the 400–600 °C temperature range but the GGBFS concrete performed better and showed no spalling or cracking like the control concretes. GGBFS performed better when incorporated in Normal concrete and the optimum replacement level was 40%.

Bilim et al. (2009) studied an artificial neural network to predict the compressive strength of GGBFS concrete. A total of 45 concretes were produced for ANNs study. The concretes were produced with three different water-cement ratios (0.3, 0.4, and 0.5) and three different cement dosages (350, 400, and 450 kg/m^3), with partial replacement of cement by 0, 20%, 40%, 60%, and 80%. The authors concluded that at early ages of curing, higher percentages of slag have a negative effect on strength, but in long-term the strength is equal to or greater than control concrete. Similar results were obtained in the study of Khatib and Hibbert (2005). The increase of the water-cement ratio reduced strength of concrete with high percentages of slag. Among the learning algorithms, the Levenberg-Marquardt algorithm was the best for learning, predicting the compressive strength results obtained in this study in long and short-term. This was possible by adopting a constant workability for all samples.

3.4. Cost and eco-efficiency

The sustainability potential of the roller-compacted concrete for rigid pavement with the partial replacement of cement by GGBFS was evaluated through simplified LCA as shown in Table 4. For the calculations, the proportion of concrete mix components used in pavements was applied as a reference parameter (Saluja et al. 2019b, 2019a). Estimative of embodied energy (EE, the energy consumed), embodied carbon dioxide emission (ECO$_2$e, CO$_2$ released for extraction of raw material, its transportation, manufacture and all steps over duration of product) per cubic meter (m^3), based on studies of Mithun and Narasimhan (2016), Yang et al. (2015) for concrete constituents, and Alsalman et al. (2021), Rasoul Abdar Esfahani et al. (2021) for GGBFS were listed. Based on the results of the systematic review (Table 3) it was found that most articles point to a range of 50–70% as the satisfactory percentage to replace cement. Among these, 60% is the most frequent value. Therefore, the following calculations of costs and eco-efficiency were made considering this replacement in Table 4. The term "Control" means the reference concrete, without replacements, and GGBFS60 means concrete made with 60% of cement replaced by GGBFS.

Cement is the building material that generates the greatest damage to the environment. GGBFS concrete pavement presents a clear potential to improve the sustainability of cementitious materials, with an approximate 37% reduction in embodied energy and 48% of CO$_2$ emission in comparison to concrete pavement control (Table 4).

Cost calculation (Table 5) was based in quantity of concrete constituents and values (USD/kg) related by Majhi and Nayak (2020).

The cost of 1 m^3 of concrete pavement (Control) found was 40.98 USD and with 60% of cement replaced with GGBFS (GGBFS60), was 34.31 USD (Table 5). The GGBFS60 concrete pavement presents a cost reduction of 16.28%. It is evident that the GGBFS has demonstrated a remarkable potential to reduce environmental impacts (CO$_2$ emissions and energy demand) and reduce costs in cementitious materials.

In another study, El-Hassan and Kianmehr (2018) evaluated the embodied energy, carbon footprint, and cost of pervious concrete pavement with cement replaced for 50% of GGBFS. According to the authors, to produce OPC, GGBFS and aggregates it was necessary embodied energy of 5.5, 1.6 and 0.083 MJ kg^{-1}, respectively. OPC and GGBFS, respectively, discharged 0.913 and 0.067 tons of CO$_2$

Table 4
Embodied energy and CO$_2$ emission for concrete pavement constituents.

Materials	Quantity (kg/m^3)		Data for each material (per kg)		EE (MJ/m^3)		ECO$_2$e (kgCO$_2$e)	
	Control	GGBFS60	EE (MJ)	ECO$_2$e (kgCO$_2$e)	Control	GGBFS60	Control	GGBFS60
Cement	327.87	128.14	4.800	0.930	1573.77	615.07	304.92	119.17
GGBFS	0.00	192.22	1.600	0.083	0.00	307.55	0.00	15.95
Natural Sand	1127.06	1101.23	0.081	0.005	91.29	89.20	5.75	5.62
Coarse Aggregate	922.14	901.01	0.083	0.048	76.54	74.78	44.26	43.25
Water	118.03	137.70	0.0013	0.017	0.15	0.18	2.00	2.34
Total					1741.75	**1086.78**	357.08	**186.33**

Table 5
Cost estimative of 1 m^3 control and GGBFS 60% mortar composites.

Material	Quantity (kg/m^3)		Rate (USD/kg)	Total (USD/m^3)	
	Control	GGBFS60		Control	GGBFS60
Cement	327.87	128.14	0.080	26.22	10.25
GGBFS	0.00	192.22	0.050	0.00	9.61
Natural Sand	1127.06	1101.23	0.004	4.50	4.40
Coarse Aggregate	922.14	901.01	0.011	10.14	9.91
Water	118.03	137.70	0.001	0.12	0.14
Total Cost				40.98	**34.31**

per ton production. The results showed that the pervious concrete pavement control results in embodied energy of 2310.6 MJ/m^3 and with 50% of GGBFS it was approximately 1500 MJ/m^3; a reduction of 35%. The embodied CO_2 emission was 383.6 kg/m^3 and 184.4 kg/m^3 for pervious concrete pavement control and GGBFS, respectively; a reduction of 52%. Based on the United Arab Emirate market, the cost of 1 m^3 of pervious concrete pavement control was 26.32 USD and with 50% of GGBS, 23.57 USD, representing a reduction of 10.5%. In addition, it was observed that more permeable concrete pavement had a lower embodied CO_2 emission, cost and embodied energy (El-Hassan and Kianmehr 2018).

Therefore, the use of GGBFS contributes to reduction of raw material extraction and the disposal of residues at landfills are in compliance with the Sustainable Development Goals and the 2030 Agenda challenges: the economic, social and environmental applied to engineering and construction sectors.

4. Future directions

Xu et al. (2020) investigated the effects of incorporating fly ash and blast furnace slag on the mechanical properties and durability of Portland cement concrete pavements. The samples with blast furnace slag, when tested by flexural strength, showed better results than those with the addition of fly ash. Although the phenomenon has been attributed to high slag activity, authors indicated that future research should be conducted to understand the phenomenon then, this result is not common with those reported by literature.

Ho et al. (2018) studied the partial replacement of cement by fly ash and blast furnace slag in pervious concretes and tested the samples for compressive strength, durability, and permeability. The results showed that as the replacement of cement by residues increased, the filling of voids decreased, which should harm the resistance to chemical attacks. These data motivated the authors to indicate future research that investigates how it is possible to reduce the filling of voids (improving permeability) and still achieve attack-resistant and durable concrete. In addition, cycle tests as well as resilient modulus and permanent strain are important to comprise the material performance (Phummiphan et al., 2018).

5. Conclusion

It was concluded that cement can be replaced by blast furnace slag in the composition of cementitious composites for application in pavements. Chemical analysis shows that SiO_2 and Al_2O_3 are the main components of this residue. The results of the works analyzed reveal that this industrial by-product is highly beneficial for the replacement of up to 60% of cement, when applied in pavements, leading to an increase in resistance to abrasion and resistance to compression. When applied for soil stabilization, the percentage of 3% BFS causes stabilizing effect due to its large amount of silicon oxide.

Despite the historical importance of this by-product in civil construction and the significant research carried out in recent years, steel slag is still not fully recycled and advanced scientific researches are still produced every year as shown in the latest published works.

The LCA analysis demonstrated that the use of BFS and GGBFS in cementitious materials represents an energy save (37%) and less CO_2 emission (48%) thus, reducing the environmental impacts of concrete production. Moreover, the replacement of 60% of cement by slag brings a reduction of 16.28% in costs of concrete.

Ethics approval

Not applicable.

Funding

Lucas H. P. Silva, Fabio F. G. de Paiva, Jacqueline R. Tamashiro, thanks to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 for scholarship; Angela Kinoshita thanks the National Council for Scientific and Technological Development -CNPq [grant 309186/2020–0]

Author's contributions

Conceptualization: VN, FFGP, JRT, LHPS, AK; Methodology: VN, FFGP, JRT, LHPS, AK; Validation: FFGP, VN, JRT, LHPS, APG, ALU, AK; Formal Analysis: VR, FFGP, JRT, LHPS, APG, ALU, AK; Investigation: FFGP, JRT, LHPS, APG, ALU, AK; Resources: AK; Writing Original: VR, FFGP, JRT, APG, ALU, LHPS, AK; Writing Review & Editing: VN, LHPS, APG, AK; Supervision: APG, AK; Project administration: AK.

Availability of data and material

The data are kept by the authors and available on request.

Code availability

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001. Angela Kinoshita thanks the National Council for Scientific and Technological Development – CNPq [grant 309186/2020–0]. The authors are grateful to IFSP, and PPGMADRE of University of Western São Paulo.

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