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GEORIS Pavers – A Small Scale Demonstration Within the GEORIS Project

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Technology of alkali activation is an alternative sustainable approach to producing paving paver, where reactive aluminosilicate precursor undergoes a reaction with an alkaline solution to form binded product. The case study presents the functional usability of a technology as part of the Georis project. The construction pavers are composed of over 75% industrial residues, with the majority of the materials sourced from steel slag industry. Laboratory testing of pavers confirmed the promising mechanical properties, demonstrating high compressive and flexural strength, as well as resistance to frost and abrasion. The results support the feasibility of scaling up from lab-scale to pilot manufacturing. The innovative approach in this project was the pilot production process itself, where more than 20 m^2 of pavers were manufactured and cured in a mobile unit. To assess their real-world performance, a demonstration case was implemented at the SIJ Acroni courtyard, where the pavers were installed to observe their application in a practical setting and to monitor their long-term durability. The valorisation of residues within GEORIS pavers highlights lower CO_2 emissions compared to conventional cement-based pavers and the potential of technology for industrial symbiosis and circular economy initiatives, making it an attractive solution for environmentally conscious industries.

Keywords:
geopolymers,
metallurgical residues,
pavers,
properties,
steel slag

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1 Introduction

Due to the rapid growth in both construction and population in many places around the world, large amounts of greenhouse gases are being emitted into the atmosphere, with a huge, negative environmental impact. The construction sector and its highly energy-intensive industry of material production contribute up to 40% of the greenhouse emissions. Concrete, the most used manmade material, requires binding by cement, which is responsible for 7% of greenhouse emissions on its own (United Nations Environment Programme, 2023). As a consequence, there is growing attentiveness to the development of sustainable materials in the construction sector, and among the most promising binders to replace Portland cement (OPC) are alkali-activated binders (AAB).

The technology behind AAB is based on the chemical reaction between a solid amorphous material rich in silicon and aluminium and an alkaline solution. This reaction leads to the formation of a solid-bound matrix composed of aluminosilicate gels, which serve as the primary binding phase. Various precursor materials can be used for AAB, with industrial residues and waste materials proving to be viable options for producing high-strength concrete with favourable mechanical properties (Shi et al., 2019). This technology with achievable comparable properties not only provides an alternative to OPC but also promotes sustainable construction by repurposing waste streams.

Although there are several types of alkaline activators, with also research on environmentally friendly alternative alkaline solutions (Mendes et al., 2021), the most commonly used activators are based on alkali hydroxide and silicate solutions (Provis, 2018), with sodium-based solutions dominating, mainly due to their availability and cheaper production. The function of alkaline solutions is to initiate the dissolution reaction of Si and Al species in a high pH environment, where free and reactive silicates undergo nucleation to form a solid interlinked aluminosilicate network.

Among metallurgical slags, ground granulated blast furnace slag (GGBFS) is one of the most widely used source materials for geopolymerisation. The abundance of SiO_2 and Al_2O_3 in GGBFS, its substantial production as a direct by-product of the iron industry, together with suitable physical and latent hydraulic properties, are the main reasons for its extensive use in the development of AAB. The significant amount of CaO and MgO in GGBFS enhances the structural integrity of the AAB matrix while contributing to a reduction in the required curing temperature (Mishra et al., 2024), making it more sustainable. As a result of the high Ca content and the presence of Ca^{2+} ions in alkaline media due to GGBFS, it leads to the formation of mainly calcium aluminosilicate hydrate (C-A-S-H) gel, that form binding at ambient conditions (Rashid et al., 2024). The amount of C-A-S-H gel is directly related to the development of mechanical properties such as compressive strength. GGBFS-based geopolymers have a characteristic fast development of high strength (early age strength) and high durability performance even at low curing temperatures (Mishra et al., 2024). Excessively high Ca content in GGBFS, one of its main chemical constituents, can significantly affect the performance of the material. To control these issues, such as reduced setting time, higher shrinkage, microcrack development and occurrence of expansion (Lee et al., 2019), proper mix design is essential to ensure a balanced ratio of precursors, activators and additives. Compared to highly amorphous precursors such as GGBFS, fly ash and metakaolin, the main challenge in using steel slag is its high crystallinity, which limits its reactivity. While the amorphous phase of steel slag can participate in the binding reaction, the crystalline phase acts primarily as an inert filler, contributing minimally to alkali activation but potentially influencing the microstructure and mechanical properties of the final material.

The hydration sensitivity and even mechanical behaviour of the material with regard to activation depend on several factors, such as the phase compositions and fineness of the precursor, the curing conditions and alkaline conditions, including initial alkalinity, and the type and concentration of activator used (Liu et al., 2021). Sun et al. (2020) found that alkali activated steel slag has a faster reaction time, fewer hydration products, poorer crystallization of $Ca(OH)_2$, a lower Ca/Si ratio, and a similar Al/Si ratio of gels compared to Portland cement.

The activation behaviour and mechanical performance of AAB are influenced by multiple factors, including the chemical composition and granulation of the precursor, as well as external conditions such as curing temperature, initial alkalinity, the type and concentration of the alkaline activator used (Liu et al., 2021). Research by Sun et al. (2020) indicates that alkali-activated steel slag reacts more rapidly than Portland cement but produces fewer hydration products. Additionally, it exhibits poorer crystallization of portlandite (CH), a lower Ca/Si ratio, and a comparable Al/Si ratio in the resulting gel structure. However, Adesanya et al. (2017) showed that ladle slag has the potential to serve as a sole precursor for AAB. After alkali activation, the major product was a silicate hydrate, achieving high compressive strength, 65 MPa, at 28 days. When steel slag is combined with GGBFS, the resulting blended AAB material exhibits significant cementitious properties when activated with an alkaline solution. As shown by You et al. (2019), the inclusion of steel slag influences several key characteristics of the material, including reduced hydration heat, mitigated autogenous and drying shrinkage, prolonged setting time and enhanced workability.

The aim of this study was to develop a low-carbon AAB from metallurgical residues while maximizing the use of metallurgical residues as aggregates. The developed GEORIS pavers were tested in the laboratory, used in the pilot-scale optimized production of pavers and implemented in a test demonstration site. The performance of the pilot pavers was tested to the standard for concrete pavers (EN 1338), as no specific standards exist for AAB pavers.

2 Experimental

2.1 Materials

In this study, two distinct types of industrial residues were utilized: carbon slag (EAF C slag) and the mineral product of processed stainless slag and ladle slag (Ekominit S1, SIJ Acroni). To formulate the mixtures of blended precursors, Ekominit S1 was mixed with finely ground secondary copper slag (SCS) and ground granulated blast furnace slag (GGBFS), leveraging their combined reactivity to enhance the cementitious potential of the system. In contrast, EAF C slag was incorporated as an aggregate, contributing to the overall structural stability of the material and maximizing the valorisation of poorly reactive slags as aggregates. This approach aimed to explore the synergetic effects of these industrial by-products in AAB systems, assessing their suitability for sustainable pavers.

The chemical compositions of these materials are given in Table 1. Ekominit S1 was found to be highly crystalline, consisting mainly of γ-C2S, β-C2S, merwinite and periclase. Whereas SCS and GGBFS showed a predominantly amorphous structure (>90%), indicating high reactivity.

Table 1: The chemical compositions of the metallurgical residues presented in wt%.

Parameters	Ekominit S1	EAF C slag	GGBFS	SCS
LOI (950 °C)	4	0.1	-	-
SiO_2	17	8	30	25
Al_2O_3	9	5	12	8
CaO	36	30	43	3
MgO	13	10	7	1
K_2O	-	<1	1	-
Fe_2O_3	10	32	-	56
MnO	2	5	-	-
TiO_2	<1	<1	-	-
Na_2O	-	<1	-	-
SnO_3	-	-	2	-
ZnO	<1	-	-	6
Cr_2O_3	3	2	-	-

2.2. Development of recipe and pilot production of GEORIS pavers

The mix design for GEORIS pavers was first developed on a small scale in the laboratory (Kriskova et al., 2025). Different parameters were evaluated, including the OPC or GGBFS and different type of activating solutions (hydroxide-based NaOH, KOH, Na_2SiO_3), and tested. After the optimum laboratory mix design for the GEORIS pavers was defined, the scalability, pot life, and castability for pilot production were considered. Additionally, maximizing the valorisation of metallurgical residues was set as the primary goal. Consequently, the mix design was adjusted to meet these criteria.

For the pilot production of GEORIS pavers (dimensions: 40x40x4 cm3), the Na-based activator was used instead of the K-based alkaline solution, which required further modification of the l/s ratio. The shrinkage-reducing agent was also added to reduce the drying shrinkage of the pilot pavers. The mix design of the pilot pavers, incorporating 75 % metallurgical residues, of which 63% were SIJ Acroni metallurgical residues, is shown in Table 3.

Table 2: Mix-design of the large format tiles, in wt%.

Phase (wt.%)							
Ekominit S1	**SCS**	**GGBFS**	**M800-fine quartz sand**	**EAF slag**	**1.65 NS 65**	**Shrinkage reducing agent**	**Binder/liquid**
11.5	11.5	4.1	8.0	51.6	13.0	0.4	2.08

More than 20 m^2 of GEORIS pavers (dimensions: 40x40x4 cm3) were produced in one of KU Leuven's mobile units (Figure 1). The production of GEORIS pavers is a very simple process, and not a lot of equipment is needed. The most demanding step with regard to utilizing metallurgical residues with geopolymerization technology is to obtain the proper mix design.

The GEORIS pavers demonstration site is located in the courtyard of SIJ Acroni in Slovenia, where the installed pavers will be continuously monitored under real-world conditions (Figure 2). A sufficiently large area exceeding 20 m^2 has been paved, ensuring exposure to regular foot traffic and operational loads, allowing for a comprehensive assessment of their long-term durability and performance in practical applications.

Figure 1: KU Leuven mobile unit for the production of GEORIS pavers

Figure 2: The area paved with GEORIS pavers at SIJ Acroni, Slovenia.

2.3. Methods

Based on current technical standards relevant for the GEORIS project and intended use of the GEORIS pavers, the properties listed in Table 3 have been tested.

Table 3: Test protocols

Testing method:	Standard:	Method type
Work dimensions (mm)	EN 1344	Non-destructive method
Flexural strength (MPa)	SIST ISO 10545 - 4	Destructive method
Freeze-thaw resistance in the presence of de-icing salts (g/m^2)	SIST 1026	Destructive method
Freeze-thaw resistance (visual)	ASTM 666	Destructive method
Hg porosity	-	Destructive method
Leaching (mg/kg)	EN 12457-2	Destructive method
Abrasion resistance (mm)	EN 1338	Destructive method

The environmental impact of the newly developed GEORIS pavers was compared to that of an alternative scenario, by using the standardized Life Cycle Assessment (LCA) method, conducted to evaluate the environmental impact of GEORIS pavers. The LCA analysis was performed using SimaPro 11.0 (v. 9.5) in combination with the Ecoinvent 3 LCI database, ensuring a realistic and consistent representation of the pavers' environmental performance. The focus of LCA was on assessing the environmental impact arising from the production of GEORIS pavers, rather than the development of the End-of-Life (EoL) scenarios, in order to have an idea of what causes this impact and how best to reduce it. This study was conducted for one functional units: the production of GEORIS pavers to cover an area of 1 m^2, which equals 97 kg of GEORIS pavers. The system boundaries of the GEORIS product that will be examined are as described in the EN 15804:2012+ A2:20199 standard.

3 Results and discussion

The GEORIS pavers produced in this study were tested according to standard procedures for concrete pavers. In order to compare the GEORIS pavers, they were compared with tests of commercially available concrete pavers tested in a previous study (Frankovič et al., 2020).

Table 4: Properties of GEORIS pavers from pilot production compared to the reference commercial product.

Testing parameter/samples	Freeze-thaw resistance in the presence of de-icing salts	Freeze-thaw resistance	Bending strength (MPa)	Skid resistance	Abrasion resistance
GEORIS pavers	0.01 - 0.03 mg/ mm^2	No visual change after 150 cycles	5.4	64	15.6 mm
Reference concrete product (Frankovič et al.)	Non-resistant	Non-resistant	4	69	22.1 mm

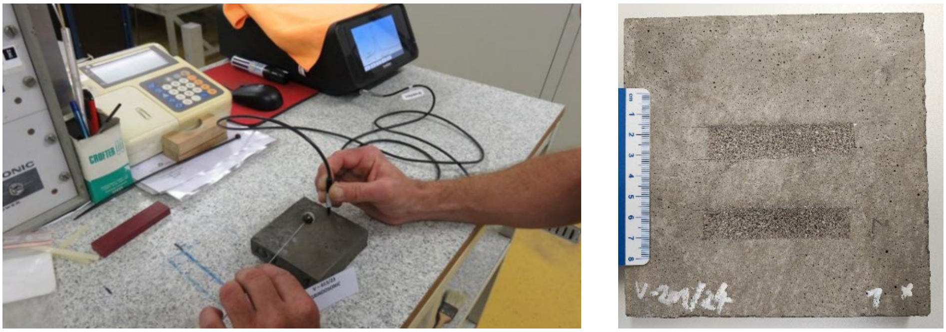

Figure 3: Evaluating freeze-thaw resistance through resonant frequency measurements with a GrindoSonic after n-cycles (left); samples after abrasion resistance testing (right).

The frost resistance evaluation revealed no visible changes or surface damage after 30, 90, and 150 freeze-thaw cycles, demonstrating the pavers' durability and resistance to freeze-thaw conditions, maintaining their structural integrity and surface quality throughout the testing period. The optimized GEORIS paver mixture exhibited satisfactory frost durability when exposed to a de-icing salt solution (3% NaCl), with surface scaling remaining well below the permitted values (0.038 mg/mm² after 20 cycles). These results confirm the material's suitability for applications in environments where de-icing salts are used, ensuring a non-slip surface in cold conditions while maintaining structural integrity.

The average skid resistance measured under wet conditions across all three directions was 64 (Pendulum Test Value), indicating a surface texture that meets safety standards for walkable applications, such as pavers. If required, the surface skid resistance can be further reduced through additional mechanical or chemical surface treatments.

Table 5: Values of leaching parameters of GEORIS pavers, compared to the permissible values in Slovenian waste regulations.

Parameter	Permissible levels of pollutants in leachate	GEORIS pavers
Cd	0.025	<0.0025
Cu	0.5	<0.05
Ni	0.4	<0.08
Pb	0.5	<0.035
Zn	2	<0.35
Cr	0.5	0.5
Hg	0.005	<0.001
Co	0.03	<0.003
Mo	0.5	0.9
Sb	0.3	<0.03
Se	0.06	<0.06
Ba	20	<0.5
As	0.1	0.02
F^-	10	<5
Cl^-	800	<50
SO_4^{2-}	2500	220

Long-term loss of mass due to wear and tear (traffic, walking, etc.) is an important parameter in assessing how the material will perform in the future. The GEORIS paver was subjected to a wear machine to test the wear resistance of the surface layer. The high abrasion resistance (15 mm) can be attributed to the compressive strength of the surface (Gencel et al., 2011). In addition to the geopolymerisation of the amorphous precursors, the remaining crystalline slag filler can increase the abrasion resistance, as reported for steel slag aggregates in road construction tests (Díaz-Piloneta et al., 2021).

While incorporating steel slag into AAB offers benefits like waste valorisation and enhanced material properties, it is also crucial to address the potential leaching of heavy metals. The leaching results for elements from crushed GEORIS pavers, tested in accordance with SIST EN 1744-3, revealed slightly elevated molybdenum levels (0.9 mg/kg), exceeding the threshold limit of 0.5 mg/kg. Additionally, chromium concentrations reached the threshold limit of 0.5 mg/kg as specified by the Slovenian directive on permissible pollutant content in products.

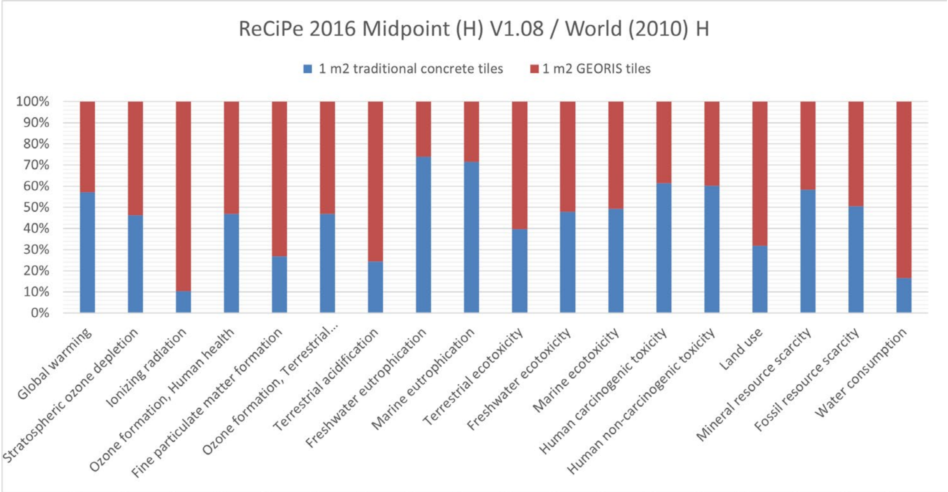

Figure 4: Comparison of impact factors of 1 m² GEORIS paving block vs 1 m² traditional paving block in the scenario of a larger-scale industrial production process.

Several strategies can be employed to mitigate leaching in AAB, focusing on both material design and process optimization. Binder composition can be optimized with secondary precursors, and another strategy is to optimize type and concentration of activator used (Łach et al., 2020). Matrix densification with micro- and nano-silica has been shown to limit the transport pathways available for leachable elements in cement-based materials (Kong et al., 2012; Fu et al., 2022), and this can also be achieved with post-treatment methods like carbonation curing (Greve-Dierfeld et al., 2008).

The LCA results for the manufacturing of GEORIS pavers are promising, beside the waste valorisation the impact on the environment was reduced compared to concrete pavers. The pavers demonstrated a significantly lower CO_2 footprint compared to conventional concrete tiles, achieving an approximately 26% reduction in carbon emissions per m^2. Additionally, the LCA results indicate a notable decrease in eutrophication potential, with GEORIS pavers showing a 60% lower impact than traditional concrete tiles. This reduction contributes to minimizing water pollution and mitigating ecosystem degradation, making them a more environmentally friendly alternative.

4 Conclusion

It has been shown that metallurgical residues can be used to a significant extent as reactive precursors or aggregate fillers for the production of pavers using AAB technology. By adjusting the mix through the process of laboratory testing and up-scaling to pilot production, the final product has comparable properties to OPC-based concrete pavers. The GEORIS pavers have high compressive strength and optimum durability prospects. They are resistant to frost (no visible damage after 150 cycles) and maintain their frost resistance even in the presence of de-icing salts following optimization. Additionally, they demonstrate exceptional abrasion resistance. From an environmental standpoint, the leaching parameters of GEORIS pavers generally meet regulatory standards, with the exception of molybdenum (Mo) and, in certain conditions, chromium (Cr). To ensure compliance before scaling up to industrial production, adjustments to the material composition may be necessary. Alternatively, mitigation strategies, such as the application of protective coatings, could be explored to minimize leaching and enhance environmental performance. In terms of environmental footprint, it has been confirmed that metallurgical residues (Ekominit S1, EAF C, SCS, GGBS) can be used instead of raw material, helping to reduce the carbon footprint and save natural resources. The GEORIS pavers demonstrated a lower CO_2 equivalent compared to conventional concrete pavers, highlighting their potential as a more sustainable alternative in the construction sector. As global policies continue to shift towards net-zero targets and stricter carbon emission regulations, the demand for low-carbon construction materials is expected to rise. In this context, the GEORIS technology may become even more economically viable, as industries seek cost-effective solutions that align with climate action goals.

By advancing to a higher Technology Readiness Level (TRL) through pilot production, key technological parameters of steel slag residues AAB have been identified, providing a solid foundation for further upscaling. These findings will facilitate the transition from pilot-scale to industrial production, ensuring optimized processing conditions and improved material performance, ultimately contributing to the market adoption of sustainable construction products.

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References

Adesanya, E., Ohenoja, K., Kinnunen, P., Illikainenm, M. (2017). Alkali Activation of Ladle Slag from Steel-Making Process. *J. Sustain. Metall., 3,* 300–310. doi.org/10.1007/s40831-016-0089-x

Díaz-Piloneta, M., Terrados-Cristos, M., Álvarez-Cabal, J.V., Vergara-González, V. (2021). Comprehensive Analysis of Steel Slag as Aggregate for Road Construction: Experimental Testing and Environmental Impact Assessment. *Materials, 14(13),* doi.org/10.3390/ma14133587

Frankovič, A., Ducman, A., Kriskova, L., Tatsis, E., Petrica, P., Pontikes, Y. (2020). The development and assessment of alkali activated paving blocks. Proceedings in 3rd International Conference on Technologies & Business Models for Circular Economy, Portorož, Slovenia.

Gaitero, J.J., Campillo, I., A. Guerrero, A. (2008) Reduction of the calcium leaching rate of cement paste by addition of silica nanoparticles. (2008). *Cem. Concr. Res, 38,* 1112-1118. doi.org/10.1016/j.cemconres.2008.03.021

Gencel, O., Sabri Gok, M., Brostow, W. (2011). Effect of metallic aggregate and cement content on abrasion resistance behaviour of concrete. *Mater. Res. Innov.*, *15(2),* 116–123. doi.org/10.1179/143307511X12998222918877

Kong, D., Du, X., Wei, S., Zhang, H., Yang, Y., P. Shah, S. (2012). Influence of nano-silica agglomeration on microstructure and properties of the hardened cement-based materials. *Constr. Build. Mater.,37,* 707-715. doi.org/10.1016/j.conbuildmat.2012.08.006

Kriskova, L., Ducman, V., Loncnar, M., Tesovnik, A., Žibret, G., Skentzou, D., Georgopoulos, C. Alkali-activated mineral residues in construction : case studies on bauxite residue and steel slag pavement tiles. Materials. 2025, 18,(2), 257, pp. 1-18, doi.org/10.3390/ma18020257.

Łach, M., Korniejenko, K., Walter, J., Stefańska, A., Mikuła, J. (2020) Decreasing of Leaching and Improvement of Geopolymer Properties by Addition of Aluminum Calcium Cements and Titanium Oxide. *Materials, 13(3),* doi.org/10.3390/ma13030495

Lee. W-H., Wang, J.H., Ding, Y.-C., Cheng, T.-W. (2019). A study on the characteristics and microstructures of GGBS/FA based geopolymer paste and concrete. *Constr. Build. Mater, 211,* 807-813. doi.org/10.1016/j.conbuildmat.2019.03.291

Mendes, B. C., Pedroti, L. G., Vieira, C. M. F., Marvila, M., Azevedo, A. R. G., De Carvalho, J. M. F., Ribeiro, J. C. L. (2021). Application of eco-friendly alternative activators in alkali-activated materials: A review. *Journal of Building Engineering*, 35, 102010, doi.org/10.1016/j.jobe.2020.102010

Mishra, J., Nanda, B., Kumar Patro, S., Krishna, R.S. (2024). A comprehensive review on compressive strength and microstructure properties of GGBS-based geopolymer binder systems. *Constr. Build. Mater, 417,* doi.org/10.1016/j.conbuildmat.2024.135242

Qiang Fu, O., Zhao, X., Zhang, Z., Xu, W., Niu, D. (2022). Effects of nanosilica on microstructure and durability of cement-based materials. *Powder Technol., 404,* doi.org/10.1016/j.powtec.2022.117447

Provis, J.L. (2018). Alkali-activated materials. *Cem. Concr. Res., 114,* 40–48. doi. org/10.1016/j.cemconres.2017.02.009

Rashid, K., Naeem Raoof, M., Maheen Daud, A., Wang, Y., Ju, M. (2024). One-part alkali activated binder activated by sodium metasilicate and ternary-factored sustainability of structural block. *Structures, 68,* doi.org/10.1016/j.istruc.2024.107108

Shi, C., Qu, B. and Provis, J.L. (2019). Recent progress in low-carbon binders. *Cem. Concr. Res., 122,* 227-250. doi.org/10.1016/j.cemconres.2019.05.009

Sun, J., Zhang, Z., Zhuang, S., He, W. (2020). Hydration properties and microstructure characteristics of alkali activated steel slag, *Constr. Build. Mater, 241,* doi.org/10.1016/j.conbuildmat.2020.118141

United Nations Environment Programme (2023). Building Materials and the Climate: Constructing a New Future. Nairob

You, N., Li, B., Cao, R., Shi, J., Chen, C., Zhang, Y. (2019). The influence of steel slag and ferronickel slag on the properties of alkali-activated slag mortar, *Constr. Build. Mater., 227,* doi.org/10.1016/j.conbuildmat.2019.07.340