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EVALUATION OF THE ENVIRONMENTAL PERFORMANCE OF RICE HUSK ASH AND TIRE RUBBER RESIDUES INCORPORATED IN CONCRETE SLABS

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ABSTRACT

This study analyses the potential environmental impacts of the use of tire rubber residue (TRR) and rice husk ash (RHA) for the production of concrete slabs in Brazil, to support decision-making regarding management alternatives for TRR and RHA. Three scenarios were assessed: (1) slab production without inclusion of TRR or RHA (discarded in landfills); (2) slab production with incorporation of TRR alone; and (3) slab production with incorporation of TRR and RHA. The impact assessment based on the ReCiPe 2016 method showed that Scenario 3 had the lowest environmental impacts and Scenario 1 had the highest impacts.

Keywords: Life cycle assessment (LCA); waste valorisation; agro-industrial wastes; landfilling; construction materials.

1 INTRODUCTION

Concrete and cement are widely used in the construction sector due to their mechanical properties, adaptability and affordability (Meyer, 2009). In 2016, the world concrete and cement industry produced about 33 billion tonnes, with an expected growth rate of 2.5% per year (ISO, 2016), representing yearly increase of over 800 million tonnes (GCCA, 2018).The construction sector was responsible for 36% of global energy consumption in 2018, contributing to approximately 39% of energy and process-related carbon dioxide (CO_2) emissions (IEA, 2019). Therefore, efforts are under way in this sector to develop new and more sustainable construction materials, in particular through the incorporation and consequent valorisation of waste (e.g. tire rubber residue –TRR and rice husk ash – RHA) (Batayneh et al., 2008; Thomas et al., 2016), with reduced need for virgin materials (e.g., limestone, sand, gravel) to produce concrete and cement (Albano et al., 2009; Nakic, 2018; Liu et al., 2022).

According to the Global Cement and Concrete Association, which represents around 80% of the world's concrete industry, reducing the quantities of raw materials through improved design processes and use of reprocessed and recycled materials are priorities of their roadmap to achieve net zero CO_2 emissions from products across the whole life cycle. This goal includes carbon capture from industrial plants, but excludes offsetting measures such as planting trees (GCCA, 2020).

The valorisation of TRR and RHA by their incorporation in construction materials such as concrete to replace natural aggregates reduces costs and environmental burdens related to their disposal in landfills while reducing consumption of virgin materials and energy during concrete production (Raheem and Ikotun, 2020; Roychand et al., 2020). The global tire market is estimated to produce over 2.2 billion tires each year, and about 1.5 billion old tires are discarded worldwide (Mashiri et al., 2015; Smithers, 2017). In 2018, 74.1 million tires were produced in Brazil (ANIP, 2020). Also, the global production of paddy rice in 2018 was 762 million tonnes, of which about 1.5% was produced in Brazil (FAOSTAT, 2020; IBGE, 2020). Rice husk represents 20% of paddy rice weight, and it is commonly burnt to generate energy, producing RHA (António et al., 2018; Gursel et al., 2016).

Over 50% of tires are discarded in landfills without treatment (Roychand et al., 2020). The disposal of these tires is problematic since landfill space is being depleted. Besides this, their disposal is dangerous to the environment and human health since they are not biodegradable and can serve as breeding grounds for mosquitoes and other pests (Rashad, 2016). The use of TRR in concrete is associated with a lack of mechanical strength due to interface (tire rubber and cement matrix) which can cause localized problems such as water accumulation and reduced bond strength, among others. However, improved mechanical properties of concrete can be attained when rubber is used as a replacement material for aggregates, especially when the particle size is small (Ince et al., 2022).

Regarding RHA, its landfill disposal can be problematic because of the mentioned space limitations, and its disposal in water bodies also has potentially negative environmental impacts (Ahsan and Hossain, 2018; Sensale, 2006). The processing and use of RHA as a supplementary cementitious material for concrete, partially substituting Portland cement, has been rising as an interesting RHA valorisation option, since RHA can increase the mechanical properties of concrete due to the chemical reaction between RHA and the calcium hydroxide released during Portland cement hydration (pozzolanic reaction), forming additional C-S-H gels (Ambedkar et al., 2017; Tashima et al., 2012).

Concrete slabs are used as structural elements of buildings in various construction systems, such as conventional reinforced concrete structures, flat plate slab systems (a structure without beams), precast concrete structures, and structural masonry systems (Evangelista et al., 2018; Oliveira et al., 2018; Mansour et al., 2015). The slabs provide a flat surface for occupants, transfer loads to the beams, and are responsible for building stability, acting with the columns to achieve the rigid diaphragm effect (Alves and Feitosa, 2020).

The environmental performance of conventional slabs has been evaluated through life cycle assessment (LCA) (Ahmed and Tsavdaridis, 2018; Paik and Na, 2020; Wang et al., 2018). LCA is a standardised and comprehensive method that evaluates environmental aspects and potential impacts of a product or service over its life cycle (ISO, 2006a). Existing LCA studies of slabs have focused on evaluating different concrete slab systems but not the slabs' concrete composition. Wang et al. (2018) studied the life cycle impacts of three slab systems (cast-in-situ slabs, precast slabs, and composite slabs) based on the carrying capacity and floor depth. Paik and Na (2020) compared the environmental impacts of the construction stage of a solid slab, a flat plate slab, and a voided slab. Ahmed and Tsavdaridis (2018) performed a combined LCA and life cycle costing study of three floor slabs: a prefabricated system, a hollow-core precast slab, and a proposed alternative using lightweight prefabricated concrete.

To date, only a few LCA studies have evaluated the potential environmental impacts of concrete composites with TRR (Fiksel et al., 2011; Rashid et al., 2019, Hossein et al., 2022) and RHA (Gursel et al., 2016; Moraes et al., 2010). However, so far, no LCA studies have evaluated and compared the environmental impacts and benefits between TRR and RHA use for slab production, avoiding the disposal of these wastes in landfills. Therefore, this study analysed the potential environmental impacts of the use of TRR and RHA in lattice girder slabs produced in Brazil to support decision-making regarding management alternatives for TRR and RHA.

2 MATERIALS AND METHODS

This study presents a process-based attributional LCA that follows the requirements of ISO 14040 and 14044 standards (ISO, 2006a, 2006b).

2.1 Functional unit, multifunctionality, and system boundaries

Three different scenarios were evaluated based on the experiments developed by Fazzan (2011) and Sousa (2014), who empirically studied the effect of TRR and RHA in the mechanical properties of concrete slabs. The lattice girder slabs (hereafter referred to as “slabs”) analysed in this study are lab-scale floor slabs of 1.806 m^2 (210 cm X 86 cm). Fig. S1 of the Supplementary Material (SM) shows the slab model cross-section. It comprises lattice joists with a precast concrete base and a partially embedded lattice reinforcement. Between the lattice joists, filling elements (hollow clay bricks) are placed to reduce the element's weight and complete the lower part of the slab. Finally, on top, a layer of concrete is poured to complete the slab (Sartorti et al., 2013). The properties of the slabs analysed in each scenario are presented in Table 1.

In Scenario 1, the slab was produced with conventional concrete without TRR and RHA, which were discarded in a landfill. In Scenario 2, the slab was produced from concrete with the addition of TRR in partial replacement of sand and disposal of RHA in the landfill. The amount of TRR incorporated in the slab was equivalent to 3.6% (by mass) of the amount of sand in Scenario 1. In Scenario 3, the slab was produced from concrete with the addition of both TRR and RHA, in partial replacement of sand and cement, respectively. The amounts of TRR and RHA incorporated in the slab was equivalent to 3.7% (by mass) of the amount of sand and 4.8% (by mass) of the amount of cement in Scenario 1, respectively.

To deal with the multifunctionality of the valorisation scenarios, the system expansion by adding the final disposal of TRR and RHA in a sanitary landfill was considered (JRC-IES, 2010). Therefore, the functional unit (FU) was defined as the production of 1 lab-scale floor slab that supports a 720 kg load and the management of 2.81 kg of TRR and 1.38 kg of RHA. The 720 kg load was defined based on a regular residential building slab with floor tile and cement mortar bed, including its weight and the load due to use and occupancy of the building (ISO, 1986, 1987). This load imposes a bending moment of 240 kN.cm, which all slabs studied can support, according to Table 1 (Fig. S2 of the SM shows further details of the calculations). Therefore, the slabs were assumed to fulfil the same function.

The slabs considered in all scenarios were produced to meet the Ultimate and Serviceability Limit States requirements (ISO, 2014). In addition, the studied floor slabs were considered to have distributed loads without walls or concentrated loads at a lab scale. Therefore, the flexural strength was more carefully evaluated. The flexural strength of the slabs was analysed by simulating the pure bending situation in the middle thirds of the models. The slabs' ends were simply supported. The forces were applied by two hydraulic actuators, with a 10 tonne force (tnf) load cell coupled to each actuator, to measure the intensity of the forces. For the distribution of forces in the span of the slabs, two steel profiles were used (Fig. S3 of the SM shows the experimental arrangement) (Fazzan, 2011; Sousa, 2014).

Table 1. Mechanical properties of the proposed slabs. Source: adapted from Fazzan (2011) and Sousa (2014).

Mechanical Property	Unit	Scenario 1	Scenario 2	Scenario 3
Compressive strength	MPa	26.3	28.5	26.5
Tensile strength	MPa	4.9	4.2	5.0
Modulus of elasticity	GPa	33.2	30.9	33.3
Density	kg/m³	2459.8	2262.1	2305.8
Air content	%	2.2	4.7	4.2
Water absorption	%	5.6	2.4	4.1
Flexural strength	kN.cm	462.9	498.1	489.3

The system boundaries (Fig. 1) included raw materials production, the transportation of these raw materials to the slab production plant, and the slab assembly process, which comprises the concrete production and pouring in the mould alongside the steel bars and hollow clay bricks. It also includes the transportation of wastes (to the slab production plant or the sanitary landfill) and management of these wastes. The transport of workers and production of capital goods were excluded. The use and end-of-life stages of the slabs were not included in the system boundaries since they were considered similar in all scenarios.

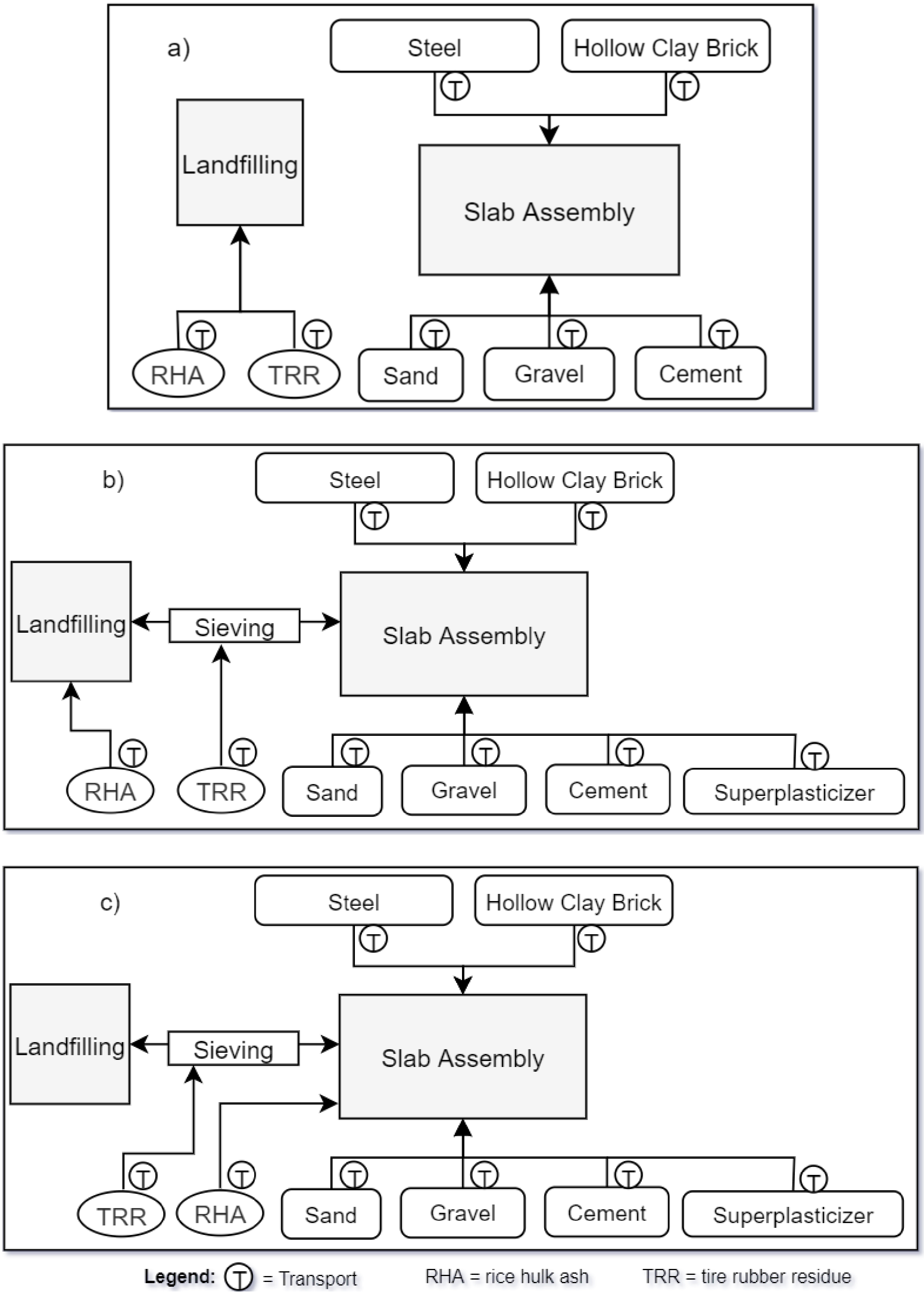


Fig. 1. System boundaries for: a) Scenario 1; b) Scenario 2; c) Scenario 3.

2.2 System description and inventory data

The life cycle inventory data to assemble one lab-scale slab, including the sieving of TRR, for the scenarios under study are presented in Table 2, considering that the production occurs in the Brazilian city of Ilha Solteira, in São Paulo state. Table S1 of the SM shows the Ecoinvent processes utilized and Table S2 shows the composition of the mixes in kg/m³.

Table 2. Inventory data for the sieving and slab assembly processes per FU for the scenarios under study. Adapted from: Fazzan (2011) and Sousa (2014).

Inputs:	**Unit**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Portland cement	kg	28.84	26.96	26.25
Sand	kg	74.62	57.87	59.13
Gravel	kg	84.65	89.66	91.26
RHA	kg	-	-	1.38
TRR	kg	-	2.81[1]	2.81[2]
Superplasticizer	kg	-	0.216	0.210
Tap water	m³	0.016	0.011	0.011
Hollow clay bricks	kg	73.50	73.50	73.50
Steel bars	kg	2.70	2.70	2.70
Electricity (kWh)	kWh	0.32	0.43	0.44
Outputs:				
Slab	un	1	1	1
Wastewater	m³	0.0029	0.0029	0.0029
TRR	kg	-	0.11	0.05
RHA	kg	-	-	-

[1] 2.70 kg is incorporated in the slab and 0.11 kg is residue from the sieving process.
[2] 2.76 kg is incorporated in the slab and 0.05 kg is residue from the sieving process.

In Scenario 1, the slab was produced with conventional concrete, and the wastes (TRR and RHA) were disposed of in a landfill, considering an average distance of 50 km by lorry. In Scenario 2, the slab was produced from concrete with TRR (substituting sand), and the RHA was disposed of in the landfill, considering an average distance of 50 km by lorry. Lastly, in Scenario 3 the concrete to produce the slab contained TRR (substituting sand) and RHA (substituting cement). In this scenario, TRR and RHA were transported to the slab production plant considering an average distance of 50 km by lorry. Background data on transport were obtained from the Ecoinvent database (Wernet et al., 2016).

In Scenarios 2 and 3, TRR was used to partially replace sand. However, a previous sieving process in a vibratory sieve was needed to reduce the TRR particle size, by discarding the ticker residues (1.7% of the TRR by total weight). Besides this, as a consequence of the TRR addition, the workability needed to be adjusted with a superplasticizer at a dose of 0.8% of the binder mass (aqueous solution of sulphonated salts and carbohydrates, with density of 1.20 ± 0.02 kg/L). Using a superplasticizer can also increase the compressive and flexural strength of the mixtures (Dash et al., 2022), which compensates for the reduction caused by the incorporation of TRR. The concrete in Scenarios 2 and 3, as shown in Table 1, had lower density (kg/m^3) than in that in Scenario 1.

Data on raw materials and wastewater quantities to produce all the slabs were collected from Fazzan (2011) and Sousa (2014), and data on energy consumed were obtained from Van den Heede and de Belie (2014). Data on emissions from wastewater treatment and the Brazilian electricity mix were obtained from the Ecoinvent database (Wernet et al., 2016). Sand, gravel, hollow clay bricks, and steel bars are transported over 50 km by lorry to the slab production plant. The Portland cement was transported over 300 km (Celik et al., 2015) and the superplasticizer was hauled over 500 km (Souza et al., 2016) by lorry from regional producers. Data on the environmental impacts of transport by lorry were obtained from the Ecoinvent database.

2.2.1 Disposal of TRR and RHA in the landfill

The TRR and RHA landfilling were modelled based on the Ecoinvent model for waste disposal at a sanitary landfill (Doka, 2003), considering the TRR and RHA compositions (shown in Tables S3 and S4 of the SM). The inventory data for TRR and RHA landfilling and downstream activities are shown in Table 3 (Table S5 of the SM shows the processes used). Background data related to the production of the inputs shown in Table 3 were obtained from the Ecoinvent database (Wernet et al., 2016). It was assumed that, at the sanitary landfill, the TRR and RHA are distributed and compacted by special loaders (Doka, 2003). Other energy requirements are associated with the heat and electricity demands of the administrative facilities (Doka, 2003).

The sanitary landfill produces landfill gas and leachate. In addition, the decomposition of organic materials under the anaerobic conditions prevailing in the landfill mainly produces carbon dioxide (CO_2) and methane (CH_4) (Doka, 2003). Nonetheless, RHA does not generate landfill gas since it does not have carbon in its composition (Sousa, 2014). Even though the model evaluates the long-term emissions (more than 100 years after TRR and RHA deposition), it is challenging to predict emissions over long timespans (da Costa et al., 2019). Therefore, this study did not consider these emissions.

Leachate is formed when water infiltrates and permeates through the waste. The short-term emissions (less than 100 years after waste deposition) are calculated from TRR and RHA decomposition rates and chemical compositions. Following Doka (2003), stable decomposition rates of 1% for TRR and 5% for RHA were assumed during the first century after deposition. All pollutants are released from the waste to the leachate at the same rate for each waste type. The landfill leachate generated in the first 100 years is assumed to be collected and treated in a municipal wastewater treatment plant (with a total treatment capacity of over 4.7 million per-capita equivalents per year) with a three-stage treatment (mechanical, biological, and chemical) (da Costa et al., 2020). The wastewater treatment plant needs electricity for lighting and to drive pumps to aerate the activated sludge bed. Other energy requirements are associated with the heat and electricity demands of the administrative facilities. The sludge generated in this step is transported 10 km by lorry to a waste incinerator plant. The solid residues generated in the incineration process are disposed in slag compartments and residual material landfills (Doka, 2003).

The slag compartment is a landfill sector (physically separated from the sanitary landfill) destined for slags that do not have more than 3% total organic carbon (TOC) in their composition. Residual material landfills are used for wastes with less than 5% TOC and that are not reactive in water. In residual material landfills, the ashes buried must be solidified with cement to comply with technical regulations. Loaders are used to distribute the slag and ashes in these landfill sectors (Doka, 2003).

Table 3. Inventory data for the landfilling of 1 kg of TRR and RHA.

	Unit	**TRR**	**RHA**
Inputs:			
Sanitary landfill			
Electricity	kWh	1.37E-03	1.37E-03
Light fuel oil	kg	3.77E-05	3.77E-05
Diesel	kg	1.09E-03	1.09E-03
Wastewater treatment			
Electricity	kWh	2.20E-04	5.50E-04
Light fuel oil	kg	8.58E-07	2.60E-05
Natural gas	MJ	4.92E-05	1.49E-03
Iron chloride	kg	5.49E-07	-
Hydrochloric acid	kg	1.81E-09	2.84E-12
Municipal waste incineration			
Electricity	kWh	2.18E-05	4.37E-04
Natural gas	MJ	7.45E-06	1.50E-04
Ammonia	g	7.64E-05	1.53E-03
Chromium	g	4.47E-08	8.97E-07
Titanium dioxide	g	2.18E-06	4.38E-05

Water	L	1.51E-04	3.04E-03
Slag compartment			
Electricity	kWh	3.81E-12	2.06E-08
Light fuel oil	kg	9.65E-12	5.23E-08
Diesel	kg	2.40E-10	1.30E-06
Residual material landfill			
Electricity	kWh	3.75E-10	1.04E-08
Light fuel oil	kg	9.50E-10	2.63E-08
Diesel	kg	4.20E-09	1.16E-07
Cement	kg	6.67E-06	1.85E-04
Outputs:			
Water emissions (after leachate treatment)			
Sulphate	g	4.21E-02	-
Cl	g	0.50	-
Cd	mg	7.15E-03	-
Hg	mg	2.17E-07	-
Pb	mg	4.53E-04	-
Zn	mg	2.34	-
Si	g	-	6.54E-02
Fe	mg	-	0.22
Ca	g	-	6.51E-02
Al	mg	-	2.00
K	g	-	0.60
Mg	g	-	0.10
Na	g	-	0.49
Air emissions (landfill gas)			
CO_2	g	21.40	-
CO	mg	1.21	-
CH_4	g	3.28	-
NMVOC	mg	2.29E-02	-
Cd	mg	9.38E-05	-
Hg	mg	2.74E-07	-
Pb	mg	1.37E-06	-
Zn	mg	1.68E-03	-
$PM_{2,5}$	mg	0.41	-
SO_2	mg	4.83	-
HCl	mg	7.26	-
Air emissions (sludge incineration)			
CO_2	g	0.71	-
CO	mg	0.46	0.68
CH_4	g	1.40E-03	1.94E-05
NMVOC	mg	6.35E-03	-
Cd	mg	3.85E-07	-
Hg	mg	1.16E-12	-
Pb	mg	1.36E-07	-
Zn	mg	8.56E-05	-

Si	mg	-	2.38
Fe	mg	-	7.11E-06
Ca	mg	-	1.18E-02
Al	mg	-	4.90E-02
Mg	mg	-	1.53E-02

2.3 Impact assessment

The life cycle impact assessment phase was based on the ReCiPe 2016 midpoint method (Huijbregts et al., 2016). The assessment was performed for 8 environmental impact categories – climate change (CC); fine particulate matter formation (PMF); ozone formation, terrestrial ecosystems (OF); terrestrial acidification (TA); freshwater eutrophication (FE); freshwater ecotoxicity (FET); fossil resources scarcity (FRS); and mineral resources scarcity (MRS). The LCA software SimaPro v.8.5.0.0 was used to perform the impact calculations (Pré Consultants, 2019).

2.4 Sensitivity Analyses

Two sensitivity analyses were performed to assess the influence of alternative ratios of TRR and RHA substitution and distances travelled. The transport distances for TRR and RHA to the slab production plant were estimated considering the proximity of suppliers, as these distances can have significant variability. Therefore, changing the transportation distances from 50 to 1000 km was evaluated.

The effect of changing ratios of TRR and RHA substitution was evaluated because it is possible to consider a maximum ratio of substitution of sand and concrete of 10.0% (by volume), without significantly affecting the slab mechanical properties (Rashid et al., 2019; Roychand et al., 2020; Youssf et al., 2020; Ambedkar et al., 2017; Givi et al., 2010; Sensale, 2006). For the materials used in the current study, this substitution ratio is approximately 4.0% by mass of sand by

TRR and up to 10.0% by mass of cement by RHA. Therefore, two hypothetical cases to assess the sensitivity of results were used, based on Scenarios 2 and 3, varying the substitution ratios of wastes.

In Case A, the slab would be produced from concrete with the addition of TRR (substituting sand in an amount equivalent to 2.0% by mass of the sand consumed in Scenario 1, i.e., approximately half of the amount considered in Scenario 2) and landfill disposal of RHA. The mechanical strenght would decrease less by reducing sand and replacing it with TRR. Thus, less additional dry cement per m³ would be needed in the concrete mixture to meet the slab structural requirements in comparison with Scenario 2.

In Case B, the slab would be produced from concrete with the addition of TRR (substituting sand in an amount equivalent to approximately 3.7% by mass of the sand consumed in Scenario 1) and RHA (substituting cement in an amount equivalent to 10.0% by mass, i.e., approximately twice the amount considered in Scenario 3). By increasing the RHA incorporation, less cement per m³ would be required in the mix and less waste would be landfilled compared to Scenario 3.

3 RESULTS AND DISCUSSION

Fig. 2 presents the environmental impacts of each scenario, demonstrating that slab material production represents most of the total environmental impacts in all environmental impact categories (84 to 99% of the total impacts). Transport impacts were greatest in the OF and FRS impact categories, representing 11 and 13% of the total impacts, respectively. Waste landfilling had a low contribution to environmental impacts (representing up to 3% of the impacts), which is attributed to the small amount of landfilled wastes. The slab assembly process, including the sieving of TRR, had the lowest influence in all impact categories, representing less than 0.5% of the impacts.

The results showed that Scenario 1 was as the alternative with the greatest impact in all categories. Scenarios 2 and 3 presented reductions compared to Scenario 1 in all environmental impact categories. Scenario 3 was the best alternative for all impact categories, with impacts 0.6 to 6.4% lower than in Scenario 1. Scenario 2 was the intermediate option, decreasing the impacts of Scenario 1 by 0.2 to 4.5%. The impact categories with the most significant reductions compared to Scenario 1 were CC and OF, for which Scenario 2 presented reductions of 5% and 4%, respectively, while Scenario 3 showed reductions of 6% for both. For the absolute contributions of each scenario to the selected impact categories, please refer to Tables S6 and S7 of the SM.

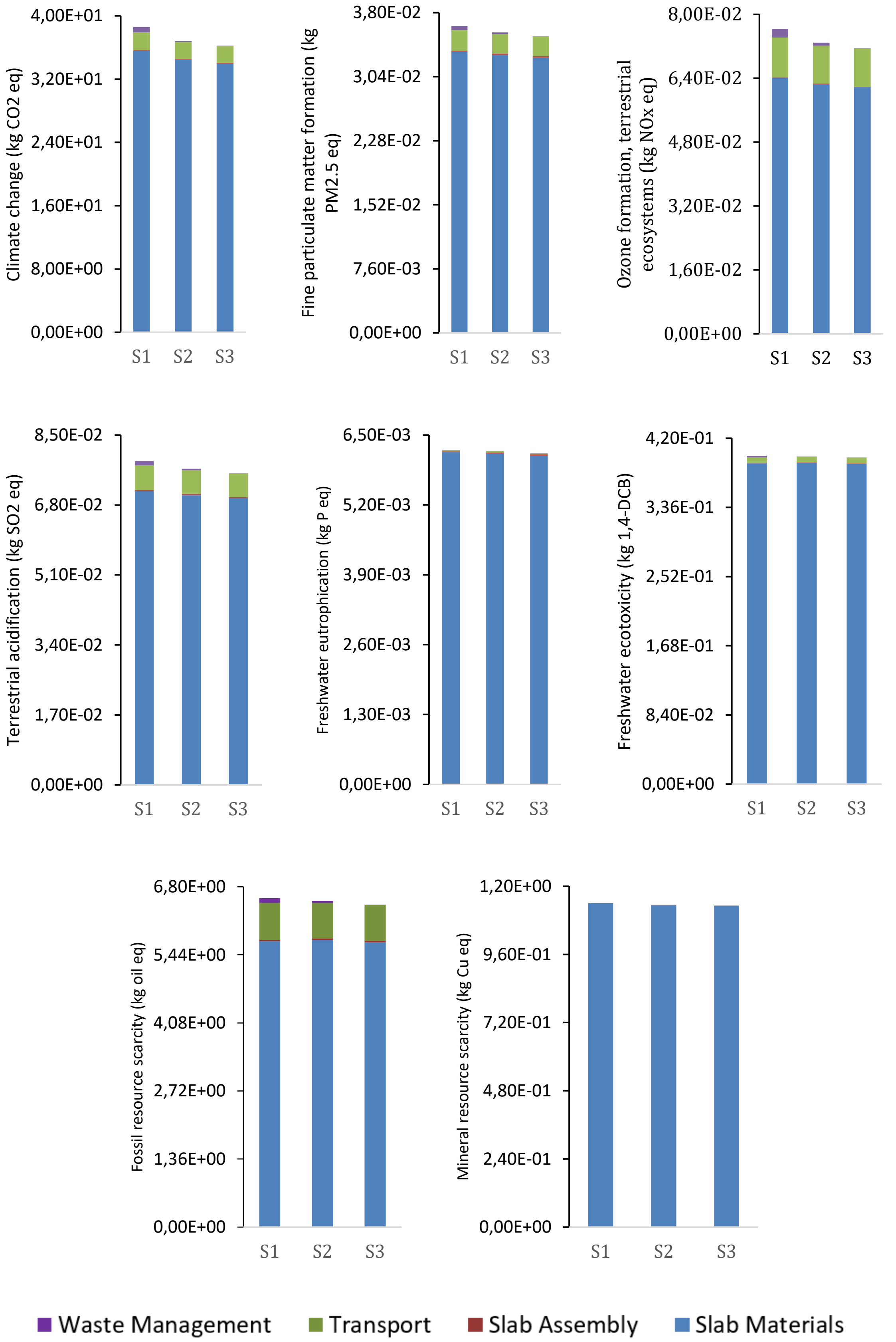
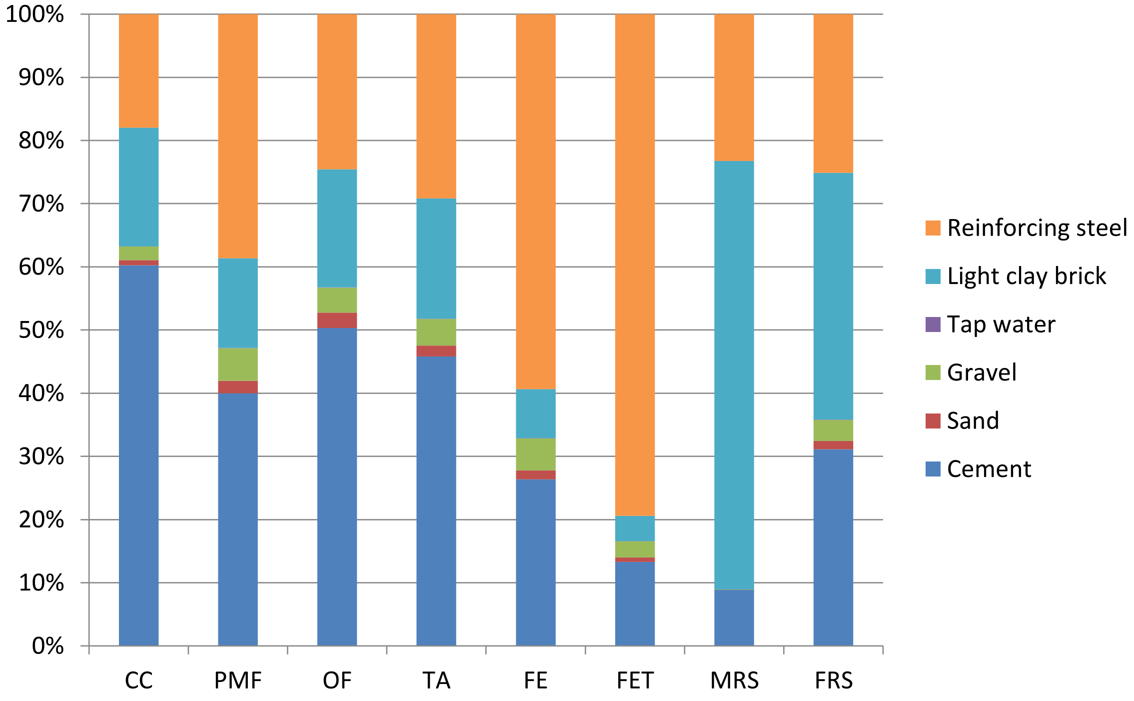
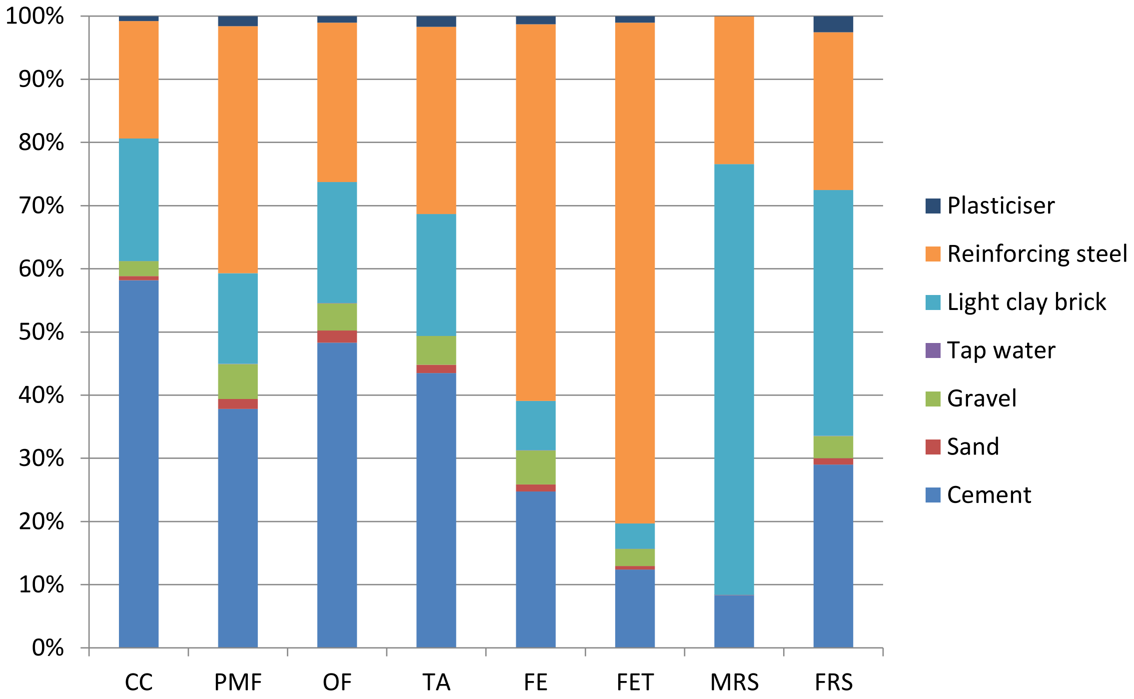


Fig. 2. Comparative environmental profiles of the proposed scenarios for slab production per FU.

Fig. 3 depicts the contribution of each material to the slab materials impacts. In the CC, OF, and TA categories, cement production was the primary hotspot, representing 57-60%, 47-50%, and 42-45% of the total impact, respectively, mainly due to clinker production. In the PMF impact categories, reinforcing steel and cement production had the greatest contributions, 38-39% and 37-39%, respectively. As in the previous environmental impact categories, clinker production was the main factorresponsible for these results. For the FE and FET impact categories, steel bars had the greatest contribution to the impact categories, representing 58-59% and 78-79% of the total impacts. These impacts were mainly caused by wastes from hard coal and lignite mining and sulfidic tailings. Lastly, in the FRS and MRS impact categories, light clay brick production contributed the most to total impacts, representing 39 and 68%, respectively. The dominant processes causing these impacts were natural gas and clay extraction, respectively.



(a)



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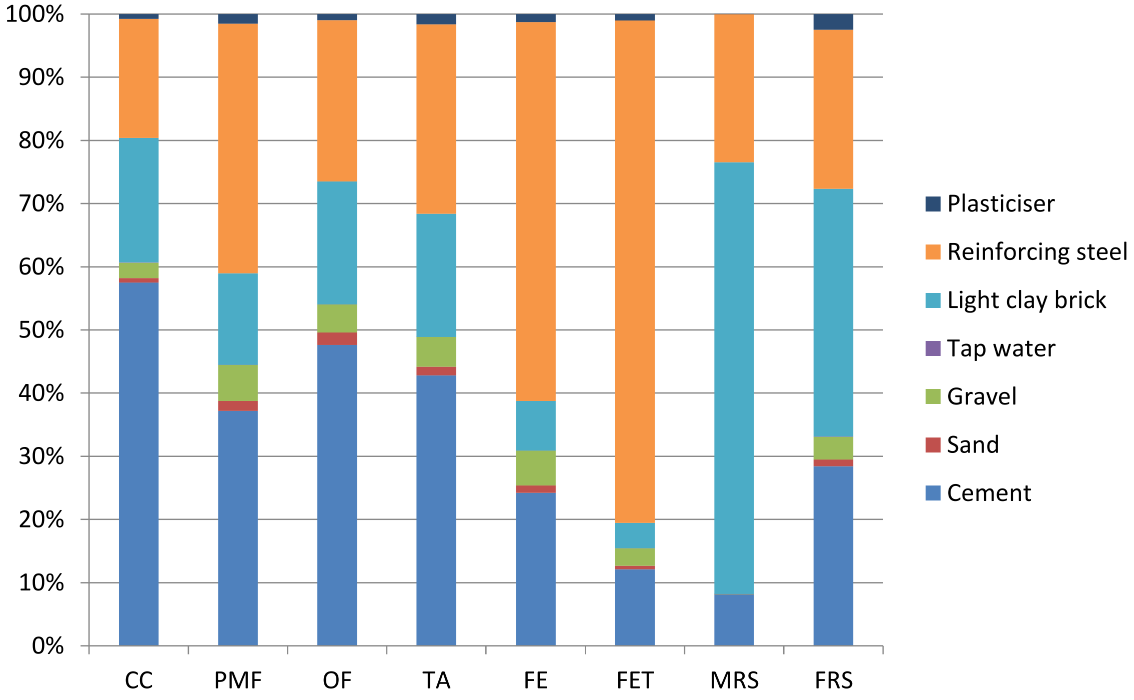

(c)

Fig. 3. Contribution of each material for the impacts of slab materials production in Scenarios 1 (a), 2 (b), and 3 (c). Acronyms: CC = climate change; PMF = fine particulate matter formation; OF = ozone formation, terrestrial ecosystems; TA = terrestrial acidification; FE = freshwater eutrophication; FET = freshwater ecotoxicity; FRS = fossil resource scarcity; MRS = mineral resource scarcity.

According to the results cement production is the primary driver of environmental impacts from slab production due to the large quantities of virgin materials and the intensive use of fossil fuels to supply the furnaces that produce the cement clinker (Stafford et al., 2016). The impacts of this step are caused by chemical reactions and the combustion of fossil fuels, which can be reduced by an improvement in the rotary kilns' efficiency and the broader utilization of cleaner energy sources (Mokhtar and Nasooti, 2020).

The use of TRR instead of sand in concrete mixes avoids extracting this raw material and disposal of waste in landfills. However, for the conditions of this study, the sand-TRR tradeoff did not generate a substantial environmental impact improvement, since sand has low impacts in the categories analysed. Other studies have reported similar findings related to substituting sand with TRR. For example, Fiksel et al. (2011) compared the impacts of using scrap tires in different LCA applications. Employing finely shredded tires to replace sand in lightweight backfill caused small reductions of impacts in all categories analysed. However, it was negligible compared to other uses, such as incineration in cement plants. Rashid et al. (2019) observed that the substitution of 10% of fine aggregate with rubber in concrete mixtures led to slight increases of compressive strength and CO_2 footprint because the scope of the study included the energy required for shredding the rubber, which was higher than sieving the natural aggregate. Gravina and Xie (2022) used a large database to model the mechanical properties of crumb rubber concrete and assessed the environmental performance of its production. The authors found that high crumb rubber incorporation in the concrete (over 25% replacement ratio substituting natural aggregates) was associated with the worst environmental performance in comparison with conventional concrete, due to the energy consumption involved in the crumb rubber collection and retreading process. Finally, Ince et al. (2022) investigated the effects of pretreated and natural rubber in concrete. Although the compressive strength decreased slightly, the authors found that the rubber enhanced the concrete flexural strength, similar to the present study (Table 1), leading to a more ductile failure mode.

Contrarily, the substitution of cement for RHA was more effective, reducing the potential impacts in all impact categories analysed, although the RHA mass represented less than 1% of the mixture. These findings agree with previous studies, such as Moraes et al. (2010), who substituted cement by RHA in mortar coatings. Besides enhancing mechanical properties, incorporating RHA, an available regional waste in Brazil, reduced the number of significant environmental impacts in the studied mortars. Gursel et al. (2016) analysed “green” concrete mixtures using fly ash, RHA, and limestone flour. The conventional concrete (only Portland cement) showed higher compressive strength (9-20%) but had the worst environmental performance. Impacts related to air emissions (CO_2, NO_x, PM, CO, SO_2), the focus of the study, decreased with the increase of supplementary cementitious materials (up to 50%). However, the regional availability of these materials determines the feasibility of the application since these wastes have low economic value, and long transport distances can significantly impact sourcing cost.

A concern related to RHA was discussed by Ahsan and Hossain (2018), for whom to achieve good mechanical performance with RHA, it is necessary to control the quality of the grinding and burning processes, since coarse particles and incomplete combustion can lead to a considerable decrease in the mechanical properties of those materials. Amin et al. (2022) studied binary concrete mixtures containing RHA to replace cement. The authors found that cement production was by far the major factor responsible for the CO_2 emissions of the mixtures, followed by the transportation of material, which is in line with the results of the present study.

Portland cement production is the largest source of CO_2 emissions from carbonate decomposition and combustion of fossil fuels. Cement production has constantly increased, inscreasing 30-fold since 1950 and more than 3-fold since 1990. The current global production level is equivalent to more than half a ton of cement per person annually. This demand will continue growing for some time, since several countries like China, Brazil and India, are developing quickly, requiring risign amouts of cement and aggregates to build infrastructure (Andrew, 2019). As a widely used material with increasing demand, it is possible to obtain significant emission and waste generation reductions if there is an improvement in its production or application efficiency. With solutions like the one proposed in this study, a small reduction in the impacts of this material applied comprehensively can achieve significant results, helping countries to reach the reduction targets proposed in international agreements such as the Paris Agreement or the recent Leaders Summit on Climate.

The results of the mechanical tests (Table 1) indicated that the slabs with residues had slightly higher flexural strength. This can be directly influenced by using a superplasticizer (in Scenarios 2 and 3), increasing the modulus of elasticity and reducing the air content. However, simply supported lab-scale slabs with a span of 2 meters were analysed. If the study had been carried out with commercial slabs, larger than those considered, the slabs with incorporation of residues would not have met the mechanical strength requirements, changing the material requirements.

In addition, reductions in density were observed in the alternative slabs in relation to Scenario 1, indicating the possibility of reducing the structural weight, and thus reducing the amount of materials used in pillars and foundations, for example. In this study, all slabs were assumed to have the same durability. However, the alternative slabs of Scenarios 2 and 3, with less water absorption, could have a longer service life or need less maintenance. In this case, potential environmental gains over time could be achieved.

3.1 Sensitivity analysis

Emissions from diesel combustion due to transport by road are relevant for the OF and FRS impact categories. Fig. 4 presents the sensitivity analysis results for OF and FRS by varying the transport distances from TRR and RHA origin to the slab production plant (the remaining categories are shown in Fig. S4 of the SM). For OF, the alternative ranking was the same, with Scenario 3 being the best option for this impact category, even for long distances. This outcome was the same for the remaining categories, except for FRS.

Points A and B in Fig. 4 show the distances for which there is a change in the environmental impact ranking among the proposed alternatives for the FRS impact category. Up to 520 km (point A), the classification of scenarios remained the same. From distances between 520 km (point A) and 733 km (point B), Scenario 2 surpassed Scenario 1, the most alternative with the greatest impact, while Scenario 3 remained the best option for this impact category. For distances greater than 733 km (point B), Scenario 1 showed the lowest environmental impact for the FRS category, followed by Scenario 3 and Scenario 2, respectively. The sensitivity analysis showed that since the wastes have a small weight compared to the slab, the environmental performance rank related to the impact categories remained the same even for longer distances, only changing for transport distances greater than 520 km.

This observation is valid for the transport of TRR and RHA considered in this study. Other studies evaluating the Brazilian context have demonstrated that transporting raw materials to produce concrete inputs can significantly impact the cost and thus the attractiveness of the final product (Souza et al., 2015; Stafford et al., 2016). This is caused by the heavy weight of these materials and the predominance of road transportation in Brazil.

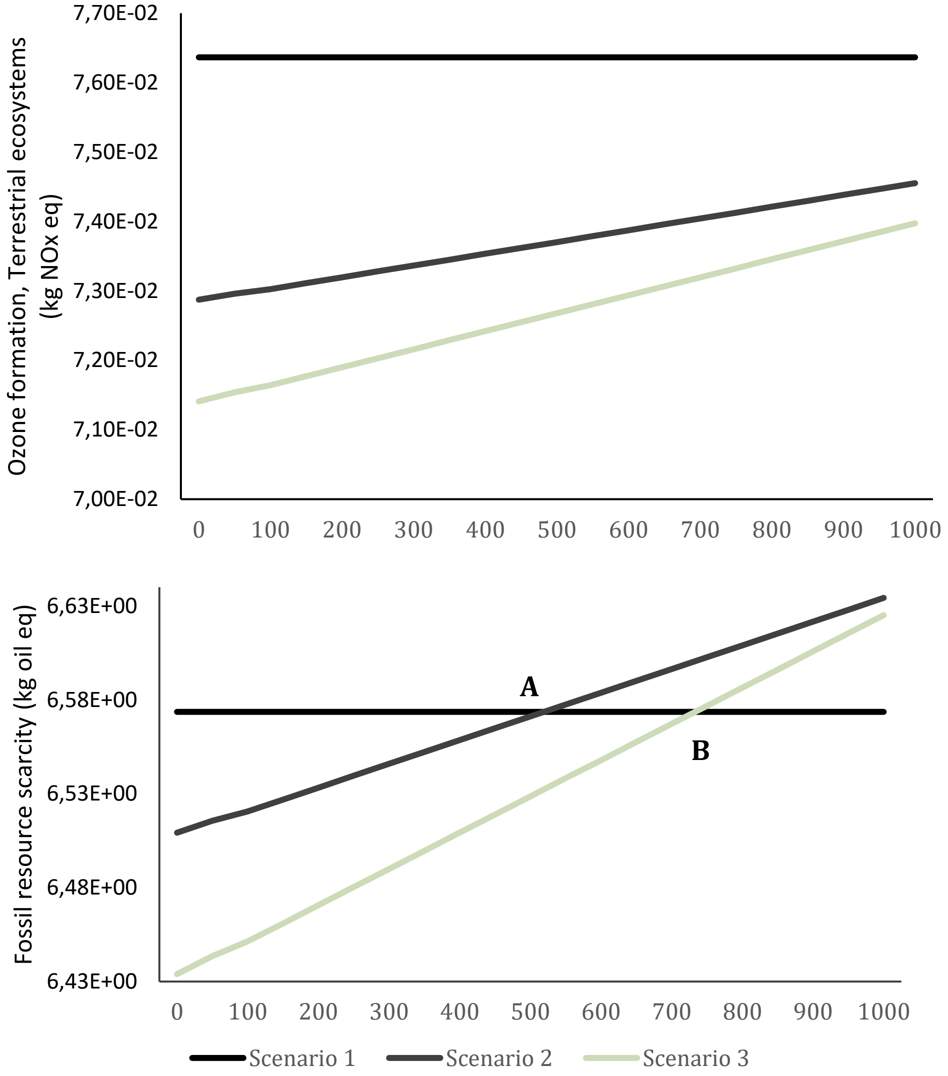

Fig. 4. Sensitivity analysis considering changes in TRR and RHA transportation distances.

Fig. 5 presents the sensitivity analysis results for the alternative cases proposed, changing TRR and RHA substitution rates in the concrete used to produce the slabs. In the CC, OF, TA and MRS impact categories, Scenario 1 presented the worst environmental performance. In the PMF, FE, FET and FRS categories, sensitivity analysis Case A (SA-CA) was the option with the greatest negative impact. However, Scenario 1 and SA-CA had similar results, with variations lower than 2% for all analysed impact categories. This confirms that cement is the predominant factor in the impact of the product studied.

The SA-CA results were not significant because the reduction of TRR would cause an increase in the concrete density, since it would have less air incorporated. Consequently, this alternative would need more materials per cubic meter of concrete. Besides this, the substitution of sand by TRR did not provoke significant results, because sand represented less than 2% of the total impacts. On the other hand, sensitivity analysis Case B (SA-CB) had better outcomes since 10.0% of the cement mass would be sreplaced by RHA, along the sand-TRR tradeoff. This situation would combine the benefits of both wastes, as the concrete would have the lowest density (due to TRR addition) and the lowest cement consumption (because of the RHA). With 2% of the total concrete mass substituted by wastes, SA-CB had the best environmental profile in all scenarios studied, with impacts between 1.2% (MRS) and 8.9% (CC), lower than the most impacting alternative.

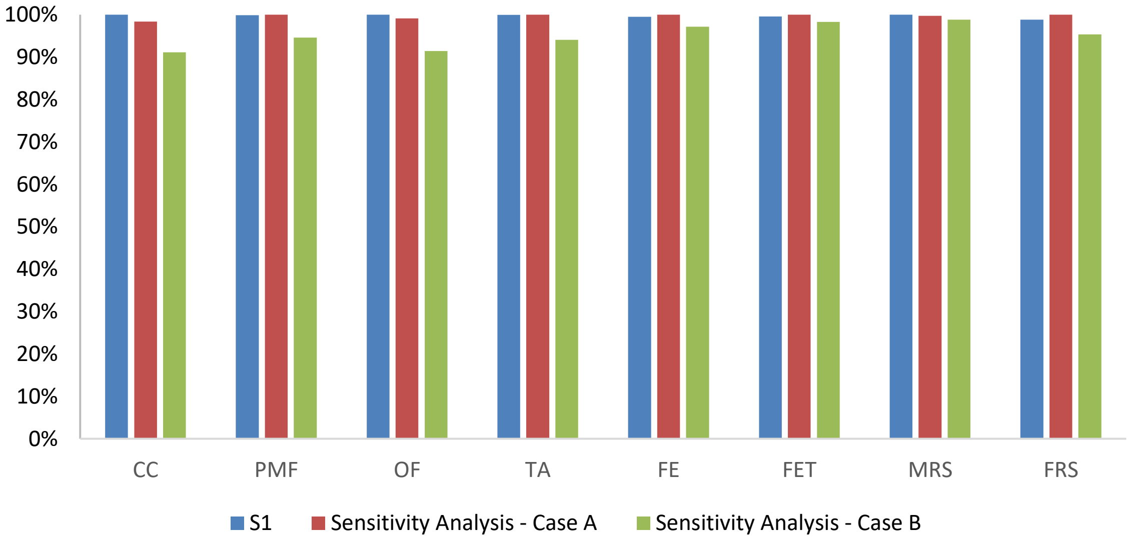

Fig. 5. Sensitivity analysis considering changes in TRR and RHA substitution. Acronyms: CC = climate change; PMF = fine particulate matter formation; OF = ozone formation, terrestrial ecosystems; TA = terrestrial acidification; FE = freshwater eutrophication; FET = freshwater ecotoxicity; FRS = fossil resource scarcity; and MRS = mineral resource scarcity.

4 CONCLUSIONS

This study evaluates the environmental impacts of different valorisation scenarios for TRR and RHA by incorporating these wastes in concrete slabs, and thus avoiding their disposalint landfills. The following conclusions can be drawn:

- The production of concrete slab materials had the gratest impact in all impact categories analysed, mostly due to production of cement and steel bars. Therefore, Scenario 3, where both residues are incorporated in the slabs, thus lowering the amount of cement consumed, ranked as the best option for all impact categories. The reduction in the impacts in relation to Scenario 1, where the wastes are totally discarded in landfills, ranged between 0.6 and 6.4%.
- The sensitivity analysis of different substitution rates of TRR and RHA showed that the SA-CB scenario, consisting of the replacement of sand by TRR (3.7% by mass) and cement by RHA (10.0% by mass), had the best results. It would decrease the concrete density and cement consumption of the slabs, reducing the environmental impacts by up to 8.9% by replacing only 2% of the total concrete mass by wastes.
- The sensitivity analysis also showed that changes in the transportation distances of wastes resulted in minor modifications of the impacts, due to the low weight of the wastes.
- Future research on incorporating wastes in concrete elements should focus on reducing the total amount of cement and steel bars, which are the primary adverse materials. The effect on the durability of these new materials should also be further studied, to ensure obtaining more durable and sustainable construction materials.

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