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CO₂ EMISSION ASSESSMENT FOR RICE HUSK ASH IN CONCRETE ON ENVIRONMENTAL APPROACH

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Abstract

The construction industry causes significant negative environmental impact, partly due to the vast amounts of building materials used, and rice husk ash (RHA) is a solid waste produced in thermal power stations with potential applications as a partial replacement to Portland cement. Due to the increasing demand for research on environmental issues, the life-cycle approach emerges as an important tool in such investigations. This study evaluates the environmental performance of RHA as a replacement material for cement during the life-cycle of concrete. Environmental aspects and impacts associated with the combustion of rice husk biomass in a grate furnace and in a fluidized bed reactor, the transportation of the RHA produced, and its use in concrete production were evaluated. The most significant environmental impact caused by RHA production processes was global warming potential. The replacement of 20% Portland cement by RHA produced by combustion on fluidized bed reduced CO_{2eq} emissions by 24%. Even though this ash type had to be transported for 400 km to its destination, its use remained environmentally advantageous. But the replacement of 20% Portland cement by RHA produced by combustion on a grate furnace led to a reduction of only 7.7% in CO_{2eq} emissions.

Keywords: cement replacement, concrete, life-cycle assessment, rice husk ash.

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Introduction

One of the most relevant aspects concerning the environmental quality of concrete production is its share in climate change, especially the CO₂ emissions generated in the manufacturing of Portland cement (Teixeira *et al.*, 2016). For example, the cement industry alone produces between 5% and 7% of global CO₂ emissions (Damineli *et al.*, 2010; Le Quéré *et al.*, 2016). Estimated by Lima (2010) at 659 kg CO₂/t of cement, CO₂ emissions in Brazil were also assessed by a major cement production company operating in the country, which found a similar value (627 kg CO₂/t of cement). However, due to widespread use of supplementary cementitious materials such as fly ash and blast-furnace slag in the country, these values are significantly lower than mean global CO₂ emissions in the production of cement, which vary between 800 and 880 kg CO₂/t of cement (John, 2010). Such number should be interpreted in view of perhaps one of the main challenges faced by the industry: to decrease the amounts of construction materials currently used (John, 2010).

Rice husk, an agricultural waste with great potential for bioenergy production, is abundantly available at virtually zero costs in several developing countries (Ramchandra *et al.*, 2015; Ramchandra, 2016). In Brazil, based on current unmilled rice production (ABIARROZ, 2017) rice husk generation is approximately 3.3 million t/year, and 75% of production is concentrated in the country's south region. Although only a fraction of that amount is currently being used for energy production, potential rice husk ash generation in the region can reach up to 495,000 t/year, which is equivalent to more than 20% of local cement production in the Rio Grande do Sul state (SNIC, 2012), where the present study was conducted.

Therefore, in the effort to minimize environmental impacts associated with constructions, rice husk ash (RHA) becomes an important alternative in the replacement of part of the cement used in the production of concrete. This substitution is justified based on several advantages, like the potential of RHA to reduce pollution hazards and to decrease CO₂ emissions and energy demand associated with cement production. RHA is a renewable resource with low levels of toxic components, and may be used as a pozzolanic material in blended cement or incorporated directly in concrete mixtures. Another interesting prospect of using RHA in concrete production is the possibility to reduce the amounts of natural resources such as clay and limestone in formulations (Kishore *et al.*, 2011; Gursel *et al.*, 2016).

The composition of RHA includes important compounds and elements, mostly silicon dioxide (or silica, SiO₂) and smaller amounts of carbon (C), potassium oxide (K₂O), phosphoric oxide (P₂O₅) and calcium oxide (CaO), besides trace amounts of magnesium (Mg), iron (Fe), and sodium (Na) (Armesto *et al.*, 2002; Fernandes *et al.*, 2016). Production processes currently used to burn rice husk and obtain RHA include ordinary uncontrolled incineration methods as well as combustion on moving grates or in bubbling fluidized bed reactors under preset conditions. Importantly, since

these processes are conducted at variable temperatures and times, the ashes produced exhibit different structures, like amorphous or crystalline phases (Ferro *et al.*, 2007; Ferro, 2009). In this sense, these amorphous or crystalline phases of the silica present in RHA affect the material's pozzolanic activity. For example, the RHA produced by controlled combustion techniques is highly pozzolanic, reacting quickly with calcium hydroxide ($\text{Ca}(\text{OH})_2$) and forming a secondary type of calcium silicate hydrate (C-S-H), thus improving the microstructure of concrete (Sensale, 2010; Metha & Monteiro, 2014). Therefore, it can also be inferred that the behavior of cementitious products in concrete mixtures containing RHA will be influenced by the method it was produced (Sensale, 2010).

In this scenario, it becomes clear that effective strategies supporting appropriate decision-making in environmental issues surrounding the production processes of concrete with RHA should be further developed. Such strategies are often based on tools that help understand how to control and, most importantly, to reduce the environmental impacts associated with these processes, enabling the identification of critical nodes in the concrete production chain using robust scientific information (Yang *et al.*, 2017). One of such tools is the life-cycle assessment (LCA), which has been proven essential in the effort to understand the environmental hazards intrinsic to the various stages of a product's life-cycle (Song *et al.*, 2016).

This study evaluated the environmental performance of RHA as a replacement of Portland cement in concrete formulations during the product's life-cycle using a LCA tool standardized by the International Organization for Standardization (ISO) in ISO 14.040. The methodology to use LCA includes four main stages: definition of an objective, definition of the scope, inventory analysis, and impact assessment (ABNT, 2009).

Materials and methods

The method used to conduct the LCA of RHA was based on standards NBR ISO 14.040 and 14.044:2009, which give the guidelines to be observed in this kind of assessment.

Stages of the LCA carried out

Objective and scope. The LCA was conducted to compare the environmental performance of concretes produced with RHA as a replacement of Portland cement. The types of RHA used were generated by combustion of rice husk in a bubbling fluidized bed reactor (RHA-FB) and a moving grate furnace (RHA-GF).

Experimental functional unit. A 1-m³ concrete block of characteristic compressive strength (fck) equal to 35 MPa was used in the assessments.

Experimental system boundaries.

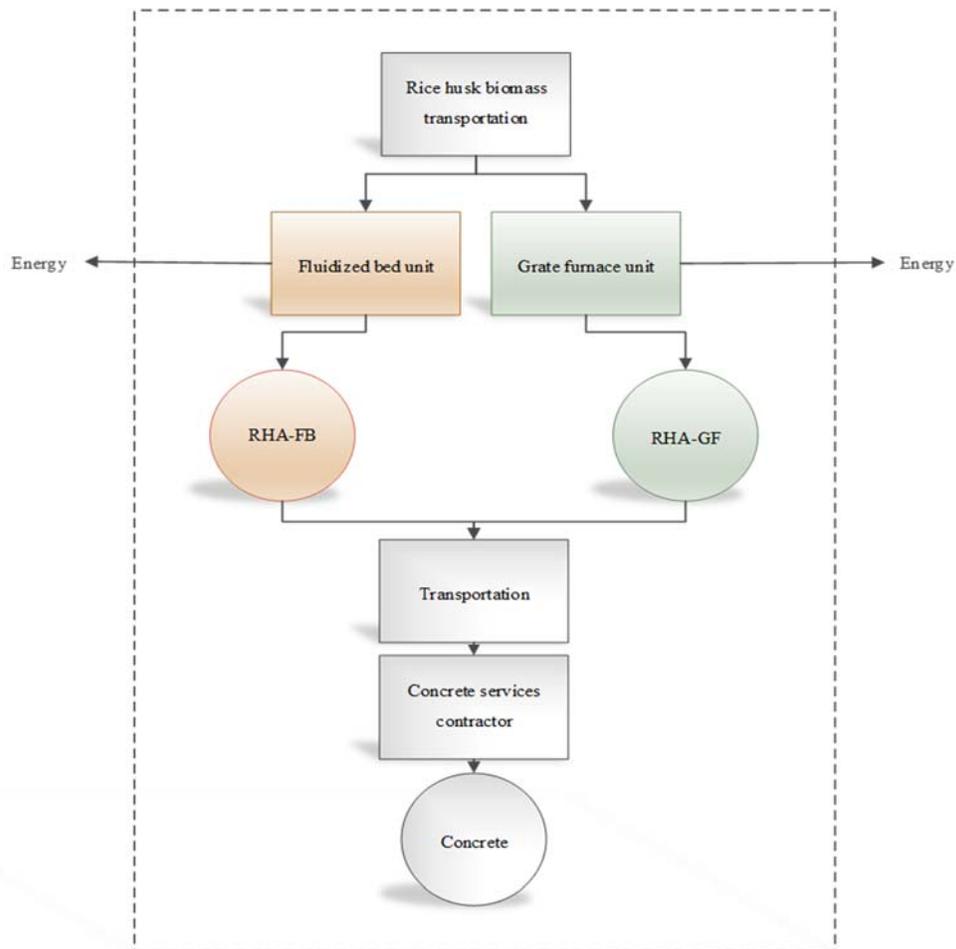


Figure 1. Experimental system boundaries for the production of RHA in bubbling fluidized bed reactor and grate furnace

Considering that RHA is a byproduct of combustion of rice husk as biomass in energy generation, it was decided to include only the steps of transportation of raw material (rice husk) and the generation of the product (energy) in rice production companies that use the combustion of biomass in fluidized bed reactors or moving grate furnaces to generate energy. The evaluation of the pozzolanic potential of RHA in concrete formulations included the transportation of RHA to concrete services contractors. Fig. 1 illustrate the boundaries of the experimental system. Steps associated with construction processes such as building operations as well as primary sector activities such as the extraction of raw materials used to manufacture equipment and build concrete structures were not included.

Visits to companies that burn rice husk for energy production

In the effort to obtain data about the combustion of RHA biomass as energy source, a questionnaire was answered by the companies that use RHA to produce energy. Scientific literature data and documental analysis were also used to collect information.

The RHA studied

The two RHA types used (RHA-FB and RHA-GF) were produced by two companies in the municipality of Alegrete, state of Rio Grande do Sul (RS), southern Brazil. RHA-FB is produced burning rice husk in a bubbling fluidized bed at temperatures below 800°C. Briefly, rice husk is loaded onto the fluidized bed chamber and instantly burned on a sand bed and an ascending air flow.

The company that produces RHA-FB is the only one in RS to use a fluidized bed system to burn rice husk for energy. Similarly, RHA-GF is produced burning rice husk on a moving grate furnace system that includes air feed and ash removal modules (Yin *et al.*, 2008).

The composition of RHA is a function of the production method employed to obtain it. Gross inspection affords to observe the difference in color between ash generated as RHA-FB and RHA-GF. Figs. 2 and 3 illustrate combustion technologies system and Figs. 4 and 5 presents the two types of ash obtained by the the processes.

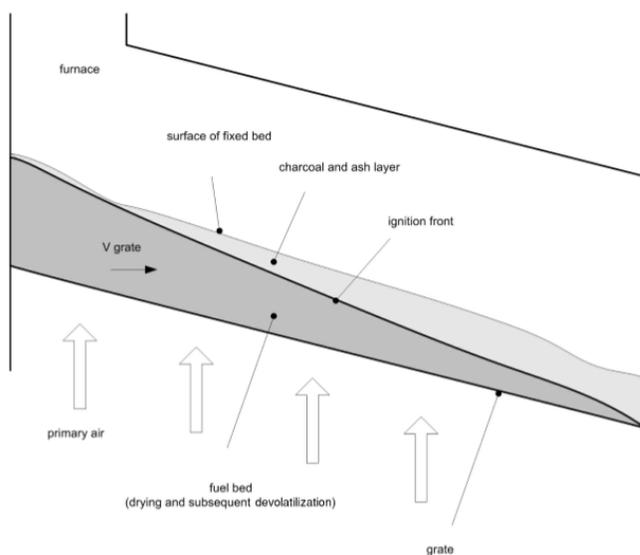


Figure 2. Moving grate furnace system
Source: Van Loo and Koppejan (2008)

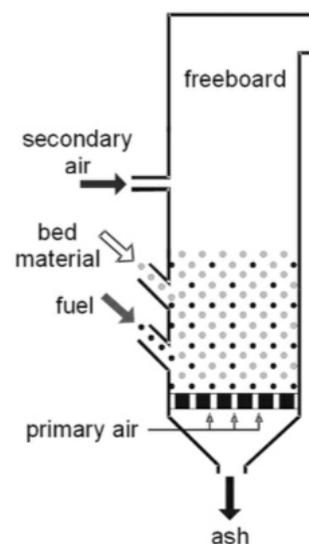


Figure 3. Bubbling fluidized bed reactor
Source: Van Loo and Koppejan (2008)



Figure 4. RHA obtained by combustion in a bubbling fluidized bed reactor



Figure 5. RHA obtained by combustion in a grated furnace

The RHA types studied were previously characterized in a study published by Fernandes (Fernandes *et al.*, 2015). As a preparation step to enable comparison between the two RHA types, RHA-GF was milled in an eccentric ball mill (CB2-T) for 2 h and 20 min before analyses. RHA-FB is milled by the company that obtains it as byproduct of energy generation, and has higher specific weight compared with RHA-GF (2.11 g/cm³ and 1.98 g/cm³, respectively).

The main difference between RHA-FB and RHA-GF is the content of SiO₂: while RHA-FB has 95.9% SiO₂, RHA-GF has 89.1% of the oxide. The pozzolanic character of SiO₂ is influenced by the morphology of SiO₂ after combustion (amorphous or crystalline). This is an essential characteristic in the use of RHA as mineral admixture in concrete formulations, so much so that a specific standard adopted in Brazil (NBR 12653:2012) determines that, to be considered a pozzolanic material, the total amount of the three oxides together (SiO₂ + Al₂O₃ + Fe₂O₃) must be at least 50% (by weight). This requirement was met by the two RHA types studied (96% and 89.2% for RHA-FB and RHA-GF, respectively). However, maximum loss on ignition is 6% according to the same standard. Loss on ignition obtained by Fernandes (2015) for RHA-FB was 2.96%, while the value for RHA-GF was 9.88%, which exceeds the maximum value established in that standard. Krug (2011) and Calheiro (2011) observed similar results for loss on ignition of RHA-GF. But it should be emphasized that loss on ignition is not the only parameter used to establish pozzolanic behavior. The pozzolanic nature of materials used as mineral admixture do concrete formulations can also be assessed according the method proposed by Luxan (1989), which is based on the

variation in electrical conductivity of 200 mL of a saturated $\text{Ca}(\text{OH})_2$ solution due to the addition of 5.0 g of the pozzolanic material tested, with constant shaking at 40°C. This test enables the classification of pozzolanic material in three categories: $\Delta\text{mS}/\text{cm} < 0.4$ indicates materials with no pozzolanic activity, while moderately pozzolanic materials have $\Delta\text{mS}/\text{cm}$ values between 0.4 and 1.2, and highly pozzolanic ones have $\Delta\text{mS}/\text{cm}$ values > 1.2 . Using the method developed by Luxan (1989), Calheiro (2011) observed moderate pozzolanic activity in the RHA samples that were generated by combustion on a grate furnace.

Evaluation of environmental aspects and impacts

Despite the widely acknowledged importance in environmental research, particularly in the building industry LCA is rarely carried out from a more holistic approach that considers local data, variations in raw materials, and up-to-date information. This apparent deficiency makes it more difficult to understand the implications of industrial processes for the environment and human health (Gursel *et al.*, 2014).

As a means to collect information about the classes of environmental impact to investigate in the present study, we carried out a qualitative analysis of the environmental aspects and the impacts generated by the combustion methods used to produce RHA-GF and RHA-FB. The data collected were expressed as a spreadsheet and evaluated by a multidisciplinary team according to a methodology used to assess Environmental Aspects and Impacts adapted from the approach adopted by the Environmental Management System of Unisinos University Gomes (2013). The characterization of environmental aspects and impacts took into consideration the range, severity, and frequency of events.

Range indicates the area affected by a given environmental impact, showing its spatial size in the area affected (Table 1). Severity indicates the intensity of changes and the reversible character of impacts, or how far it can be remediated. Scores are assigned as illustrated in Table 2. Frequency is the interval at which environmental aspects and impacts occur under normal circumstances, according to the scoring system shown in Table 3.

The scores obtained for range, severity, and frequency are added, and the overall scores obtained are shown in Table 4.

Aspects interpreted as “critical” by the evaluation team were considered “significant”. Based on the identification of significant environmental impacts in each stage of RHA production, the life-cycle inventory data were collected, providing the information necessary to carry out a quantitative analysis of environmental impacts. Table 5 illustrates the spreadsheet used to evaluate environmental aspects and impacts developed for this study.

Table 1. Range criteria

Classification	Example	Score
May cause local impact around the event site.	Smell of household sewage and all aspects associated with impact. Health hazards.	1
May cause environmental impact beyond the event site, though it is restricted to the industrial facility.	Fires caused by flammable products and leaking or spillage of chemical products.	2
May cause regional impact, beyond the boundaries of industrial installations, within a 100-km radius of facilities.	Consumption of gases, use of materials (pens, stamps, cartridges, etc.), waste generation, use of flammable chemicals.	3
May cause regional impact beyond 100 km of facilities.	Water and energy consumption, waste generation, fluorescent or mercury bulbs.	4

Source: adapted from *Environmental Management System of Unisinos* [25]

Table 2. Severity criteria

Classification	Score
No damage.	1
Mild damage characterized by parameters above maximum permissible levels defined by regulations or standards, though the impact ceases to be when operation processes are adapted. For example, the recovery or mitigation based on adaptations in the firm's internal structure.	2
Values above maximum acceptable levels defined in regulations or standards may induce severe damage; however, despite the fact that the impact is mitigated with the adoption of operational control measures, the damage caused to the environment are irreversible and/or require an outsourced structure to address the applicable mitigation and recovery efforts.	4

Source: adapted from *Environmental Management System of Unisinos* [25]

Table 3. Frequency criteria

Classification	Score
One event every six months or longer period	1
One event every month	2
One event every week	3
One event every day	4

Source: adapted from *Environmental Management System of Unisinos* [25]

Table 4. Overall score of environmental aspects and impacts

Score	Result
3 to 6	Negligible
7 to 9	Moderate
10 to 18	Critical

Source: adapted from *Environmental Management System of Unisinos* [25]

Table 5. Spreadsheet used to evaluate environmental aspects and impacts

Identification			Evaluation of environmental aspects and impacts			Significance evaluation	
N°	Aspects	Impacts	Range	Severity	Frequency	Significance	Notes

Life-cycle inventory analysis

This analysis included the data survey to quantify all streams within the experimental system's boundaries, as described above.

Global warming potential. The global warming potential of a gas is measured based on the total energy it absorbs in each period, usually 100 years, compared with that absorbed by carbon dioxide (CO₂) (USEPA, 2014). The global warming potential of processes in the production chain of RHA was analyzed according to the guidelines established by the US Environmental Protection Agency (USEPA).

Transportation. The inventory of data about transportation was based on the First National Automobile Atmospheric Emission Inventory [30]. The publication categorizes vehicles considering fuel type, age or technological generation, specific uses, and size. Using data collected from a questionnaire answered by concrete services contractors, the transportation category selected for LCA in this study was that of heavy-haul trucks over 15 t in total weight. Concerning the emission factors of diesel engines, we used the seventh phase of the Brazilian Automobile Atmospheric Emission Control Program, which stipulates a significant decrease in allowed emissions for heavy vehicles produced from 1st January 1992 onwards. Based on a preliminary study of the locations of RHA producers and concrete services contractors in the state, the

distances used to evaluate the environmental impact of the transportation of RHA-FB and RHA-GF in this study were set at 100 km and 400 km, respectively.

Unit weight. The unit weight of ash is particularly important in transportation, since the mass amount to be transported (by the trucks in volume) is directly determined by this parameter. Unit weight of RHA and rice husk was determined according to a specific Brazilian standard, NBR NM 45 [31].

Concrete. The concretes evaluated presented fck of 35 MPa, and the formulations prepared were obtained from previous studies carried out by our research group using the same type of cement and aggregates, but with either RHA-FB or RHA-GF (as described in the works published by Fedumentti (2013) and Krug (2011), respectively) as supplementary cementitious material. The study by Fedumentti (2013) demonstrated the advantages of admixing RHA-FB to concrete mixtures, when the best result was observed with the replacement of 20% of Portland cement by RHA-FB. The cement used in the experiments in both studies was type CP II F - 32, a Portland Cement with 10% limestone filler. The materials used to prepare the concretes evaluated in those works are shown in Table 6, and amounts were calculated according to Cremonini et al. (2001). Importantly, 20% RHA in this case means that RHA takes 20% of the total volume of binder employed in the concrete formulations.

Table 6. List of materials and respective amounts used to produce concrete of fck of 35

Material kg/m ³	RHA-FB		RHA-GF	
	0% RHA	20% RHA	0% RHA	20% RHA
Water	188	189	192	191
Cement	381	285	415	381
RHA	0	49	0	61
Fine aggregate	820	851	741	706
Coarse aggregate	983	969	1025	1018

Source: adapted from Krug [21] and Fedumentti [29]

The levels of atmospheric emissions in the production of Portland cement considered in the manufacture of the concretes studied were adapted from Carvalho (2002), which used a LCA tool to compare the environmental impact of Portland cement in Brazil. The author adopted the value of 320 as global warming potential for NO_x, but the present study uses 280, as recommended by USEPA. Also, considering that the exact type of cement used by Krug (2011) and Fedumentti (2013) was not investigated by Carvalho (2002), we chose to use the emissions associated with ordinary Portland cement (with no mineral admixtures) and reduce the emission factor by 10% (in order to account for the 10% limestone filler, which decreases the amount of clinker in the cement).

For the CO₂ emissions generated during the production of aggregates, the values used were calculated from data published by Marcos (2009), which were also used by Lima (2010) and represent the actual scenario of RHA recycling into concrete formulations. The CO₂ emissions released in the production of chemical admixtures were not included. According to Flower & Sanjayan (2007) such contribution to the greenhouse effect per cubic meter of concrete is negligible.

Results and discussion

The environment impact assessed and classified as significant in both RHA production processes was global warming potential, which originates from the aspect emissions of gases produced during the combustion of rice husk into the atmosphere.

The unit weight of rice husk was 125 kg/m³, while the values obtained for RHA-FB and RHA-GF were 488.9 kg/m³ and 578.9 kg/m³, respectively. It was possible to observe that the unit weight of RHA-GF is higher than the value calculated for RHA-FB. However, the unit weight of unburnt rice husk is four times lower than the values observed for both ash types.

The concrete formulations based on the distances was considered for the transportation of RHA-FB and RHA-GF to the concrete services providers. The CO₂ emissions generated in the production of 1 m³ of concrete of fck of 35 MPa and a 20% replacement of Portland cement by either RHA-FB or RHA-GF was not relevant. CO₂ emissions by concrete formulations produced with RHA-FB due to the transportation of studied ashes for 100 km and 400 km presented 381.83 and 381.93 Kg CO_{2eq}/m³ of concrete, respectively. For RHA-GF due to the transportation for 100 km and 400 km presented 503.43 and 503.52 Kg CO_{2eq}/m³ of concrete, respectively.

The 35-MPa concrete formulated with a 20% replacement of Portland cement by RHA-FB presented better environmental performance, compared with the formulation containing 20% RHA-GF as partial replacement of cement. The results obtained show the difference of approximately 121 kg CO_{2eq}/m³ of concrete between the concretes produced with RHA-FB and RHA-GF.

Fig. 6 shows the CO₂ emissions associated with the transportation of RHA-FB to concrete service providers for two distances. The comparison of results shows that CO₂ emissions associated with the concrete formulated with 20% RHA-FB were approximately 24% lower than the reference value, by nearly 120 CO_{2eq}/m³. However, distance was not a relevant factor in the CO₂ emissions associated with the concrete, which are largely determined by the emissions coming from cement use (see table 7).

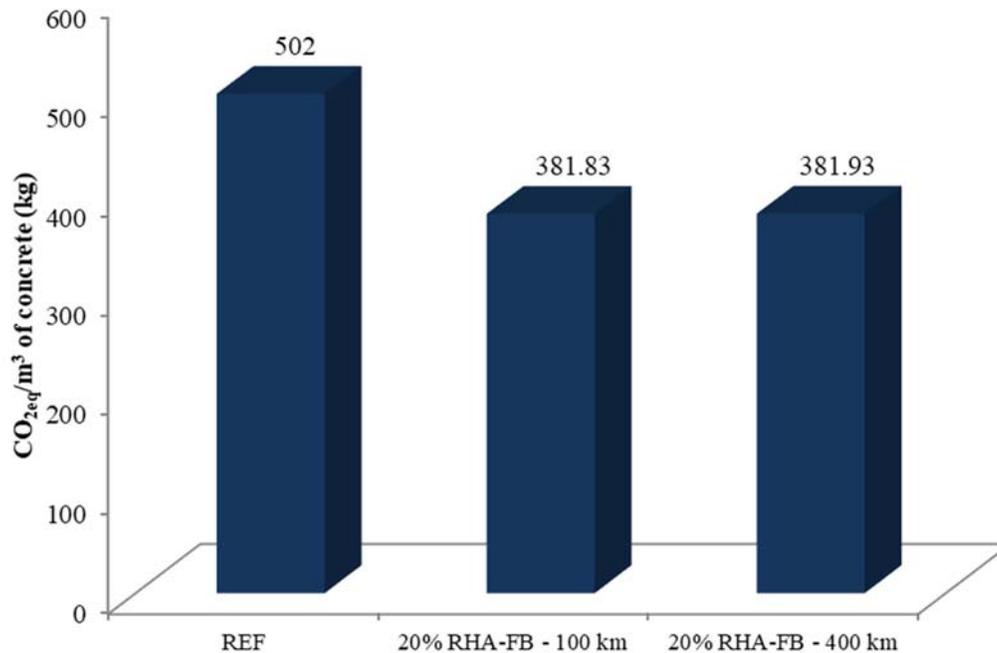


Figure 6. CO₂ emissions (CO₂eq/m³ of concrete) for a concrete produced with RHA-FB as partial concrete replacement due to the transportation for 100 km and 400 km

Fig. 7 presents CO₂ emissions in the transportation of RHA-GF to concrete service providers, also for two distances. As with RHA-FB, CO₂ emissions were lower than the reference value, but by 42 kg CO₂eq/m³ of concrete, meaning a decrease of only 7.7%.

Turk et al. (2015) compared a series of concrete formulations using a LCA. The author investigated several alternative materials, concluding that fly ash originates from the coal combustion processes was the best choice in the effort to reduce greenhouse gas emissions. In their study, the use of fly ash afforded to reduce greenhouse gas emissions by about 64 kg/m³, compared with conventional concrete of equivalent composition. The concrete samples analyzed had fck of 42 MPa.

For Flower and Sanjayan (2007), even a small decrease in greenhouse gas emissions per ton of concrete may have a significant impact globally, since concrete is the most used construction material worldwide. The authors investigated the use of cementitious materials to reduce greenhouse gas emissions from concrete manufacturing processes, and observed that the addition of fly ash to formulations decreased these emissions by approximately 15%, while blast furnace slag led to emissions reduction of 22%.

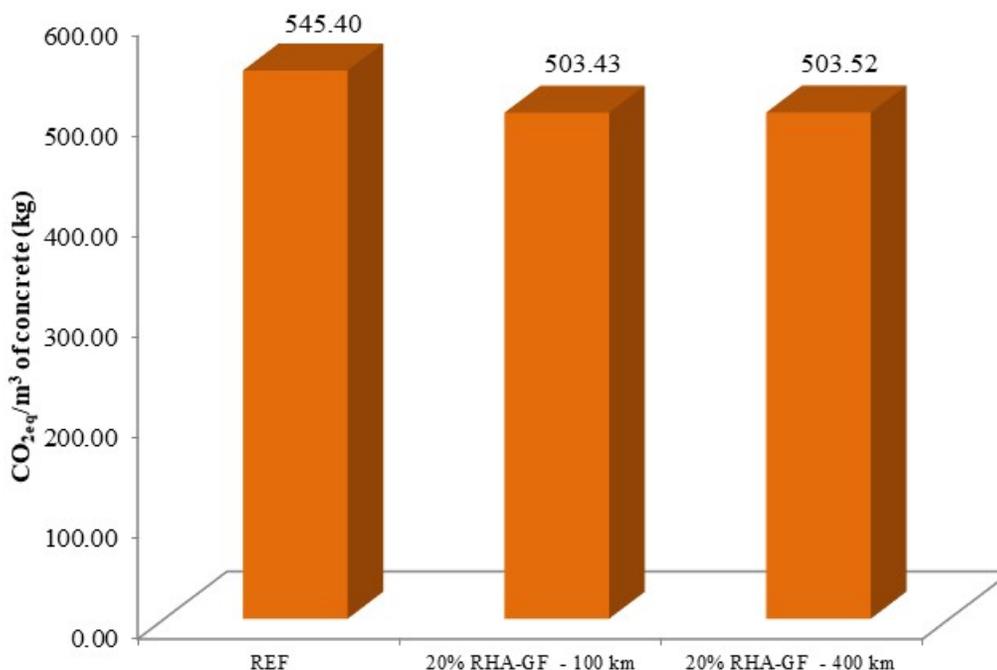


Figure 7. CO₂ emissions (CO_{2eq}/m³ of concrete) for a concrete produced with RHA-FB as partial concrete replacement due to the transportation for 100 km and 400 km

The results obtained by Gursel *et al.*, (2016) were likewise positive for the reduction of the global warming potential of concrete admixtures. The concrete produced with 100% Portland cement emitted 544 kg CO_{2eq}/m³, while the concrete containing RHA (15%) and fly ash from coal combustion (40%) emitted 284 CO_{2eq}/m³. The authors also observed that the lower the amount of Portland cement used and the larger the amount of admixtures required, the lower the global warming potential of concrete. Nevertheless, it should be highlighted that the authors used one kind of RHA only.

Similarly, Moraes *et al.*, (2010) also reported that the higher the amount of RHA used as partial replacement to Portland cement in cement mortar formulations, the greater the possibility to mitigate the more aggressive environmental impacts. Teixeira *et al.*, (2016) also analyzed several concrete mixtures and observed that coal or biomass ash may be used as cement replacement, whether alone or in combination, to reduce the environmental impact of concrete production. The concrete formulation with the best environmental performance included a 60% replacement of cement by coal ash fly.

The production of concrete in Brazilian batching plants was estimated at 72 million cubic meters for 2017 [39]. For the sake of comparison, if all this concrete were to be produced in a manner similar to presented in this study (for example, with a reduction of 24% in CO₂ emissions), the reduction in greenhouse gas emissions would be approximately 8.7 billion kg CO_{2eq}/year.

In addition, even if RHA-FB is transported to a concrete services contractor 400 km away from the source, the environmental impact produced by partly replacing cement with 20% RHA-FB would still be smaller than the one caused by the production of concrete with no potentially interesting mineral admixtures, such as RHA. In the sensitivity analysis carried out during an LCA, Turk *et al.*, (2015) observed that the inclusion of fly ash in concrete formulations is viable, even when the distance between the source and the concrete services provider is significantly longer than 250 km, confirming the results obtained in the present study.

Since concrete strength was kept constant in the present study, due to the considerably different pozzolanic activity presented by RHA depending on its generation (in FB or GF), different proportions of materials were used in concrete formulations. In this sense, the formulation designed including RHA-FB included less Portland cement than RHA-GF, for the 35 MPa fck value to be obtained. Moreover, the amount of binder used, which was comparatively low in the concrete produced with RHA-FB, was higher in the concrete made with RHA-GF, even in comparison with the reference formulation with no RHA.

Based on the input data and conditions and on the results obtained, CO_{2eq} emissions associated with the ingredients of concrete formulations were calculated and are shown in Table 7. In the present study, Portland cement accounted for approximately 96% of total CO_{2eq} emitted by the reference concrete formulation. In turn, the contributions of Portland cement to the total CO_{2eq} emitted by the formulations containing 20% RHA-FB and RHA-GF were 94.5% and 95.8%, in that order. Therefore, even though the concrete produced with RHA-GF has higher environmental impact concerning CO_{2eq} emissions compared with the one produced with RHA-FB, the reduction in the use of raw materials from nonrenewable sources should be considered an advantage, especially concerning clay and limestone, which are used in clinker production, the main constituent of cement.

Table 7. Contribution (%) of the materials used in concrete formulations to CO_{2eq} emissions

Materials	Concrete + 0%	Concrete + 20%	Concrete + 0%	Concrete + 20%
	RHA-FB	RHA-FB	RHA-GF	RHA-GF
Cement	96.0	94.5	96.3	95.8
RHA 100 km	0.0	0.3	0.0	0.3
Fine aggregate	0.9	1.3	0.8	0.8
Coarse aggregate	3.0	3.9	2.9	3.1

As mentioned above, Flower and Sanjayan (2007) observed that between 74% and 81% of the total CO_{2eq} emissions from concrete are associated with Portland cement. Similar value was obtained by Turner and Collins (2013) (76.4%), while Lima (2010) found a higher value (90%). According to Briem et al., 2009, fly ash content alone is not a good indicator of embodied emissions in concrete; increasing fly ash content only reduces embodied emissions when there is a corresponding reduction in the mass of Portland cement used.

Cement is the material that offers the highest contribution to CO_{2eq} emissions from concrete. Therefore, the partial replacement of Portland cement by 20% RHA demonstrates that it was possible to reduce the amount of cement by 96 kg and 34 kg per m³ of concrete produced with RHA-FB and RHA-GF, respectively (considering the production of a 35-MPa concrete). This allows concluding that the partial replacement of Portland cement by RHA-FB represents an important alternative in the effort to reduce environmental impacts associated with the production of concrete with no mineral admixture.

The ash obtained as a byproduct of biomass combustion for energy generation has various applications. In addition to generation of energy, the combustion of rice husk in fluidized bed is carried out so that the ash may be used as mineral admixture (in fact, the RHA-FB used in this study is currently being commercialized locally as a high-quality mineral admixture for concrete, as an alternative to silica fume and metakaolin). However, the combustion of rice husk in a moving grate furnace is used to generate energy only, and the ash produced is seen only as a consequence of the process. Therefore, the kinds of ash generated have different characteristics, which influences the amounts of materials needed for concretes to reach the same resistance (35 MPa).

These differences between RHA-FB and RHA-GF are due to the specifics of combustion in fluidized and grate furnace: while the former affords the uniform burning of biomass, in the latter the combustion process occurs under a temperature gradient. In a study about ash types produced by different energy generation processes, Fernandes *et al.*, (2016) discovered that the main characteristics affected by the various techniques currently used to burn rice husk are specific surface area, SiO₂ levels, and total carbon content, in addition to the structure of the SiO₂ produced. In other words, the environmental benefits to be gained using RHA as mineral admixture to concrete formulations also the technical benefits can vary according to the combustion method used to obtain the material. Prassara-A and Grant (2011) carried out an LCA considering the various applications of RHA, and stipulated the most environmentally appropriate use of the material based on the environmental impact categories included in their study.

The use of raw materials available on regional scale as supplementary cementitious materials, like RHA, is one of the many possible efforts to be made to mitigate the environmental problems

associated with the use of Portland cement, thus reducing the environmental impacts of concrete production processes.

Conclusion

The results of the present study show that global warming is the most significant environmental impact of the processes used to produce concrete of fck of 35 MPa with a 20% replacement of Portland cement with RHA-FB and RHA-GF used as mineral admixtures. The differences between the characteristics of the two ash types vary with the combustion processes used to burn rice husk. While fluidized bed methods afford the uniform burning of biomass, grate furnace combustion processes occur along a temperature gradient. This means that the characteristics of the two ash types affected the amounts of materials needed to prepare concrete formulations of fck of 35 MPa.

Therefore, the environmental gains are more expressive when 20% RHA-FB is used to partly replace Portland cement in concrete formulations, compared with the 20% RHA-GF: the use of RHA-FB allowed reducing the CO_{2eq} emissions by 24% in the concrete production chain. Despite the distance between the source of RHA-FB and the concrete services contractor that used the ash in formulations (400 km), the environmental advantages of using this ash type were preserved. Also, the use of 20% RHA-GF to partly replace cement Portland in concrete formulations afforded to reduce CO_{2eq} by 7.7%.

It was also observed that transportation did not affect environmental impacts in the concrete production chain, highlighting the need to accurately determine the best composition of concrete mixtures based on the sustainability of ingredients, like the RHA types analyzed.

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