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CARBON FOOTPRINT OF BAMBOO PARTICLES, RICE HUSK AND WOOD SHAVINGS-CEMENT COMPOSITES

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Abstract

The growing concentration of greenhouse gases (GHGs) increases more and more the heat trapping in the atmosphere, leading to a rise in global temperatures, also known as global warming. For these reasons, in the last decade, in order to counteract this phenomenon, a special effort has been made also in the construction sector by developing new sustainable building materials and, moreover, one of the most promising solution is the possible employment of forest waste as a raw material for the production of cement based construction systems. In this context, the present study aims at evaluating the carbon footprint production of bio-based cementitious composites (BBCCs) produced with three types of bio-aggregates: bamboo particles, rice husk and wood shavings. The carbon footprint of the BBCCs was calculated using a life cycle perspective following the guidelines of ISO 14067:2014. The biogenic carbon was quantified based on the carbon content of the bio-based materials, considering the landfill process in the end-of-life stage. System boundaries were established according to a cradle-to-gate approach, based on data collection (in literature and laboratory) regarding the raw material production, transportation and processing. The results were presented in three ways: (1) the amount of CO_{2e} emissions to produce 1m³ of composite (kgCO_{2e}/m³), (2) the amount of CO_{2e} emissions considering the 1MPa strength of the composite (kgCO_{2e}/m³.MPa), (3) the amount of CO_{2e} emissions to produce 1m³ with 1MPa strength considering the dry density of the composite (MPa.CO_{2e} index./Dry density). The wood shavings composite was the most carbon efficient, while the rice husk showed to be the lowest efficient. Finally, the main criteria for a low carbon footprint bio-based material were described in order to help designers.

Keywords:
Carbon footprint; Bamboo particles; Rice husk; Wood shavings.

1 INTRODUCTION

Bio-based materials have been used for thermal insulation purposes for years in building envelopes. Nevertheless, with the development of society and higher performance requirements of buildings, the bio-based materials were replaced by new synthetic materials, generally polymeric, such as polyvinylchloride (PVC), polystyrene (EPS) and inorganic synthetic materials such as rock and glass wool [Korjernic et al. 2016].

On the other hand, environmental aspects like global warming, energy savings and life cycle issues are the main factors that justify the fast growing interest of research and development of plant-based materials for buildings. In fact, these materials can be qualified as environmental-friendly and efficient in terms of thermal, structural and sound performance [Amziane and Sonebi 2016].

In the literature, cement based composites including bio-based aggregates are called "Agro-concretes". They can be defined as: "*a mix between granulates from lignocellular plant matter coming directly or indirectly from agriculture or forestry, which form the bulk of the volume, and a mineral binder*" [Amziane and Arnald 2013]. Moreover, it is noteworthy that, especially in the tropical countries, the development of bio-based construction materials have a considerable potential due to local availability of several types of vegetable sources: hemp, flax, coconut, corn, cob, wood shaves, bamboo, rice husk, cork, sunflower and others [Amziane and Sonebi 2016].

From both the practical and environmental point of view, one the main issue related to the used of bio-based cementitious composites is the mixture and production process that, generally, requires huge amount of energy due to the intrinsic characteristics of vegetal bio-based aggregates. For example, several studies demonstrated that, for the production of cement-wood panels (up to now developed at laboratory scale) the pressed process is the most used, while, the molded process is the most widespread in industrial and commercial applications. In this sense, one important objective of the research analyzed herein was the development of bio-based cementitious composites capable of being molded characterized by an adequate workability at the fresh state. As a matter of the fact, an experimental research is being carried out at *Núcleo de Ensino e Pesquisa em Materiais e Tecnologias de Baixo Impacto Ambiental na Construção Sustentável Laboratory* (NUMATS) located in the *Universidade Federal do Rio de Janeiro* (UFRJ), Brazil, comparing workable bio-based cement composites for building application made with bamboo particles, rice husk and wood shavings.

In fact, according to Mokhothu and John [2015], vegetal materials are characteristically hydrophilic because of the existence of a large number of hydroxyl groups (single bond OH) present in cellulose and hemicellulose. Cellulose, which forms the major part of the natural fibre, is hydrophilic in nature and it can absorb water molecules. Therefore, vegetal bio-based materials are considered hygroscopic. The same authors define hygroscopy as the capability of a material to easily absorb moisture from the surrounding environment and change volume. In this sense, in a cement bio-based composite, the water sequestered from the mixture by bio-based materials, must be compensated, to guarantee sufficient water for both cement hydration reactions and workability.

Different international studies have been carried out on bio-based materials and composites, some of them concentrating on the evaluation of the thermal performance, presented by Alavez-Ramirez et al. [2012], Sassoni et al. [2014], Korjenic et al. [2016] and Rahim et al. [2016]. All authors concluded that the increase of density increases conductivity and loss of the thermal performance for insulation purpose. Other studies used the life cycle assessment (LCA) methodology to evaluate the environmental impacts of bio-based materials, according to Edwin et al. [2014], La Rosa et al. [2014a] and La Rosa et al. [2014b], Ferrari et al. [2015]. In these four studies, bio-based systems were compared with conventional systems and presented a better environmental performance. Silvestre et al. [2016] evaluated the environmental impacts of the production, use and end-of-life processing of insulating cork boards, serving as an important methodological reference for application of LCA in bio-based building material products.

However, in a research in the Brazilian literature, a deficit of studies was noticed concerning bio-based materials and their environmental assessments, such as carbon footprint. This gap was the initial motivation for this research.

Recently, embodied carbon has become especially important for estimating the life-cycle carbon of buildings. Embodied carbon refers to carbon dioxide emitted or sequestered during the manufacture, transport and construction of building materials [Kang et al. 2015]. Wiedmann and Minx [2007] suggest that such metric should include all CO_2 emissions – direct and indirect – expressed in mass unit. The ISO 14067:2014 defines the carbon footprint of a product as “the sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalents (CO_{2e}) and based on LCA using the single impact category of climate change. In this study, the LCA approach, based on ISO 14067:2014 was adopted.

In this context, the aim of the present study was to quantify the CO_{2e}, using the carbon footprint methodology, to compare workable bio-based cementitious composites for building application produced with bamboo particles, rice husk and wood shavings, with adequate mechanical performance.

2 METHODOLOGY

In accordance with the ISO 14067:2014 the analysis of the carbon footprint is, mainly, divided in four phases: goal and scope, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. Following this standard the analysis proposed in the present study was divided in four stages: (1) composites characterization; (2) goal and scope definition; (3) life cycle CO_{2e} inventory analysis and (4) life cycle impact assessment. The interpretation stage is covered in the “Results and Discussion” section.

2.1 Composites characterization

The composites produced herein were manufactured using different plant based raw materials (bamboo, rice husk and wood shavings). All these materials are considered wastes of an industrial process and subsequently treated at NUMATS/UFRJ, Rio de Janeiro, Brazil.
Both raw materials and cementitious composites produced with bamboo particles (BPCC), rice husk (RHCC) and wood shavings cement composites (WSCC) are presented in Fig. 1.

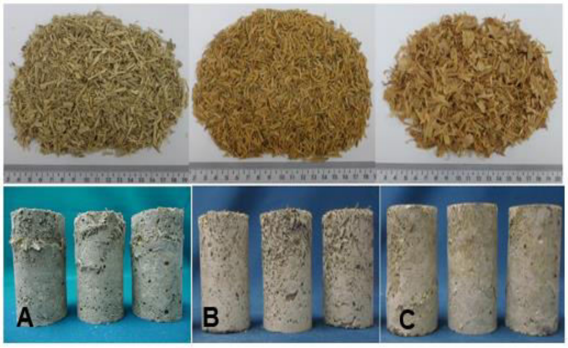

Fig. 1: Raw biomass and samples of the equivalent bio-based composites of (A) bamboo particles, (B) rice husk and (C) wood shavings

The bamboo composites were dosed based on a mass relation of 1:0.4 (cement: bio-based material) and a relation water/cement (w/c) of 0.45. The volumetric fraction of aggregates and the mass per meter cubic of cement obtained, were applied to the two other composites, in order to be independent of the densities of each biomass with the same volumetric proportions.

The consistence index, fixed at 250 and 280 mm as an indicative of good workability, according to the Brazilian standard ABNT NBR 13276 – 2016, was considered as a comparison unit between the three composites. Different from other composites, where the pressed process was used, these were developed to be molded.

Due to the characteristic of water absorption by the bio-based materials used in the mixture, additional water, varying from material to material, was poured into the amount of the mixture to produce a composite with good consistence. For example, the rice husk composite presented the highest value of additional water.

In this sense, there are two kinds of water used in the mixture, the hydration water, concerned with the required water for cement hydration and the additional water to compensate for the water loss by biomass materials absorption.

Additionally, to reach the required consistence, a viscosity modifying agent (VMA) was used in the three composites, while the calcium chloride $CaCl_2$ additive was incorporated only in the wood shaving composite as a setting accelerator.
The mass per cubic meter (m³) obtained in the mixture are summarized in Table 1.

Tab.1: Mixture composition (kg/m³).

Materials	BPCC	RHCC	WSCC
Cement CPV	712	712	712
VMA additive	0.9	1.8	1.4
$CaCl_2$ additive	-	-	21.4
Bamboo	285	-	-
Rice husk	-	150	-
Wood shavings	-	-	275
Hydration water	320	320	320
Compensating water	285	300	275

2.2 Goal and scope definition

The goal of this study is to present carbon footprints for bamboo, rice husk and wood shaving cement composites in the Brazilian context, considering the carbon emissions and removals.

The carbon footprint boundary was a cradle to gate assessment as its evaluation is limited to the manufacturing phase of composite. Concerning the accounting of the biogenic carbon emissions, the end-of-life stage is considered in the calculations.

According to Brandão et al. [2013] and Garcia and Freire [2014] there are a number of critical issues associated with the life cycle of forest-based materials, particularly regarding the carbon footprint, specifically the quantification and consideration of the biogenic carbon of the products. The storage and delayed carbon emissions in both use and end-of-life stages is of key importance. Moreover, long service life products, such as the composites evaluated in this study, which could be used for structural and walls application (with a minimum service life of 50 and 40 years, respectively, according to the Brazilian standard ABNT NBR 15575-1 – 2013).

The stored carbon uptake through photosynthesis may be re-emitted to the atmosphere in the end-of-life stage totally or partially. For example, if the bio-based material is incinerated or used as a fuel, all stored carbon will be released to atmosphere. On the other hand, in a landfill scenario, a great share of the biogenic carbon will be indefinitely stored. Pawelzik et al. [2013] recommended that in cases of landfilling scenarios, without degradation (or very low degradation), the biogenic carbon storage is the adequate approach for bio-based materials.

Garcia and Freire [2014] and Demertzi et al. [2017] considered that 98% of biogenic carbon permanently remains in their materials for landfill scenarios, since these materials have a very slow decomposition. The first study evaluated the carbon footprint of particleboard and the second the environmental impacts of cork slabs and granules. Both studies considered the accounting of biogenic carbon in the global warming potential category.

In the present study the landfill process was considered in the end-of-life stage, since this alternative is the most used in Brazil and intends to continue to be for many years for these kind of materials. The transportation to the landfill was not considered since it is practically negligible. The incineration, burning and energy recovery are not applied to building materials, such as concretes and composites.

In this sense, based on Garcia and Freire [2014] and Demertzi et al. [2017], it was assumed that 98% of biogenic carbon permanently remains in the composites. Even more knowing that the bio-based materials are mixed and agglutinated with cement, which may decrease the composite degradation process in landfills.

The functional unit (FU) is defined as 1 m³ of composite. Although the composites have the same amount of cement in the mixture, the densities of bio-based materials and compensation water were different, which leads to different values of compressive strength and dry densities of the composites. To overcome this, two indicators were used in this study to try to verify these differences: (1) the volume and compressive strength (m³.MPa) and (2) a proposed indicator that incorporated the relation between the differences in the dry density of bio-based composites and compressive strength, as presented in equation 1. A similar approach was used by Van Den Heede and De Belie [2012] and Celik et al. [2015].

$$Indicator = IxCO_{2e}index \qquad (1)$$

$I = \sigma_c/\gamma_{dry}$ (MPa/g.cm^{-3});

CO_{2e} index = mass of net GHG emissions per kg of composite (kgCO_{2e}/kg);

In this sense, the results were expressed in the following ways:

(1) The amount of GHG emissions (in CO_{2e}) to produce 1m³ of the composite (kgCO_{2e}/m³).
(2) The amount of GHG emissions (in CO_{2e}) to produce 1m³ with 1MPa strength of the composite (kgCO_{2e}/m³.MPa).
(3) The amount of GHG emissions (in CO_{2e}) to produce 1m³ with 1MPa strength considering the dry density of the composite (MPa.CO_{2e} index/Dry density).

The composite system boundaries in this carbon footprint study is shown in Fig. 2.

The production process, at the factory, of materials used in composites: cement, VMA additive, $CaCl_2$ additive (just for WSCC) were considered, including the internal transport distances between the raw materials extraction and the factories (It was used the values presented in Ecoinvent database and Votorantim EPD).

For the bio-based materials it was assumed the mass allocation process of production of bamboo, rice and wood materials. The forest management process such as fertilization, thinning and pruning were not considered.

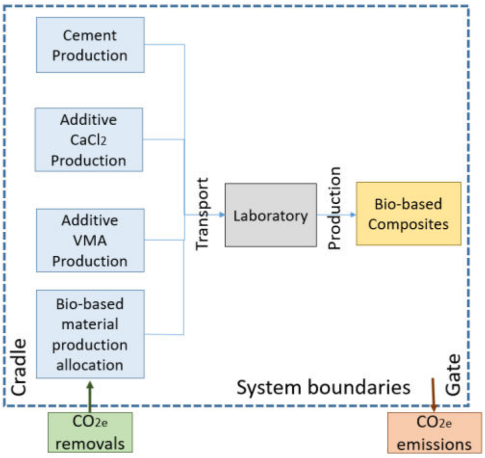

Fig. 2: System boundaries of composites production

The materials transport from their origin locals to laboratory was considered in terms of diesel consumption. Finally, the electricity consumption in the laboratory was quantified considering the mix and compaction processes for the composites production.

2.3 Life cycle CO_{2e} inventory analysis

The CO_{2e} (The 100-year GWPs were adopted according to the Fifth Assessment Report for the IPCC, 34 for CH_4 and 298 for N_2O [Myhre et al., 2013]) inventory of biomass and additives (VMA and $CaCl_2$) was carried out using the Ecoinvent database version 3.3 with modifications in energy grid mix for the Brazilian context (using SimaPro software) which is the same approach adopted by Saade et al. [2014]. For the cement, the data was collected in an environmental product declaration (EPD) of a Brazilian cement company [Votorantimn 2016].

For the biomass materials used, the cultivation process was not considered as they are waste products from other industrial processes. However, the CO_{2e} emissions from the allocation related to the industrial process and laboratory were considered.

The biogenic carbon (M_{CO2}) was accounted for according to equation 2 [BRE 2013]:

$$M_{CO2} = m_{dry} \times C \times \frac{mm_{CO2}}{mm_C} \quad (2)$$

M_{CO2} = mass of CO_2 sequestered (kg) – biogenic carbon;

M_{dry} = dry mass of the bio-based material (kg).

C = percentage of carbon in dry matter (%)

mm_{CO2} = molecular mass of CO_2 (44)

mm_C = molecular mass of carbon (C) (12)

For the percentage of carbon in dry matter values obtained in elemental analysis CHN (determination of carbon, hydrogen and nitrogen, contents of the material) at Xistoquímica Laboratory/UFRJ, Rio de Janeiro, Brazil (for bamboo and wood shavings) and from literature (for rice husk) were used.

The biogenic carbon can be defined as the fixation of atmospheric CO_2 in biomass during biomass growth. This flow is accounted as negative in the GWP model [ISO, 2014].

The electricity CO_{2e} factor was collected from data of the *Ministério da Ciência e Tecnologia* [MCTI 2016], a medium value 0.064 $kgCO_{2e}$/kWh from 2006 to 2015, was adopted in this study.

For transporting the material, diesel was used with a medium consumption of 0.019 L/t.km [Campos, 2011] and FCO_{2eq} of 2.64 $kgCO_{2e}$/L [IPCC, 2006; MME, 2015], resulting in FCO_{2e} of 0.050 $kgCO_{2e}$/t.km. The distances between the cities of origin of the materials and Rio de Janeiro, where composites are produced, were considered constant in the analysis, in a radius of 200 km, a common practice adopted in Brazil for building materials transportation.

The spillage (S), CO_{2e} emissions factors (FCO_{2e}) for raw materials production, bio-based materials production allocation and carbon content (C) are summarized in Table 2.

Tab.2: Summary of data used in Life cycle CO_{2e} inventory analysis.

Materials	S (%)	FCO_{2e} ($kgCO_{2e}$/kg)	C (%)
Cement CPV	5	0.76	0
VMA additive	0	1.27	0
$CaCl_2$ additive	0	0.66	0
Bamboo	5	0.04[1]	45.6[2]
Rice husk	5	0.06[1]	39.1[3]
Wood shavings	5	0.01[1]	53.6[2]

[1] As these materials are production wastes the allocation procedure by mass was carried out, considering 20% of the GHG emissions during the production of bamboo materials [van der Lugt et al. 2009] and production of husk rice and wood shavings (data was obtained in Ecoinvent v.3.3). Both of them were adapted to Brazilian electricity grid.

[2] Values obtained in CHN elementary analysis.

[3] Value found by Ramos e Paula et al. [2011].

2.4 Life cycle impact assessment

The CML 2 baseline 2000 v.3.03/EU method was applied for the life cycle impact assessment (LCIA) phase. The chosen method was based on the EN 15804:2012. According to ISO 14067:2014 in the LCIA phase of a carbon footprint study, the impact analyzed is the potential climate change or global warming potential for 100 years (GWP 100), expressed in units of $kgCO_{2e}$ per functional unit.

3 RESULTS AND DISCUSSION

3.1 Properties and relations

Some properties and relations between these properties are presented in Table 3.

The RHCC showed the lowest values for most of properties and relations, while the WSCC highest values. The CO_{2e}index values were higher for the RHCC and lower for the WSCC. The difference of dry density between bamboo and wood shavings composites compared with the rice husk were 3% and 28%, respectively. Lower densities are interesting from the point of view of the sustainability, resulting in less fuel consumption in the transportation phase, economy in structural design and the possibility of using the material in retrofit designs. These potential benefits will be evaluated in future studies. Therefore, the rice husk composite was the most advantageous in these terms. However, related to mechanical properties, cement consumption and CO_{2e} emission, the WSCC presented best results. The BPCC presented intermediate results.

Tab.3: Materials properties and relations.

Materials	BPCC	RHCC	WSCC
γ_{dry}(kg/m³)	710	689	818
σ_c (MPa)	3.25	2.25	4.14
Cement compressive strength index (MPa.ton cement^{-1})	4.57	3.16	5.82
$I = \sigma_c/\gamma_{dry}$ (MPa/g.cm^{-3})	4.58	3.27	5.06
CO_{2e}index (kgCO_{2e}/kg)	0.17	0.55	0.06

3.2 Carbon footprint

The carbon footprints considering the FU and the first indicator are presented in Fig. 4.

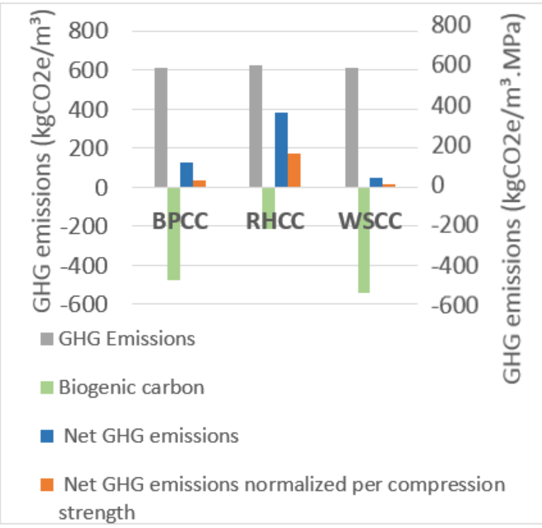

Fig. 4: Composite carbon footprints considering the functional unit and the first indicator.

When the FU is considered (kgCO_{2e}/m³), the WSCC presented the best results, 61.6 kgCO_{2e}/m³, followed by BPCC (133.2 kgCO_{2e}/m³) and the RHCC, which presented the biggest carbon footprint (386.2 kgCO_{2e}/m³).

When considering the first indicator (kgCO_{2e}/m³.MPa), the differences between the WSCC and the other two increased, due to the higher value of its compression strength. The WSCC presented 14.9 kgCO_{2e}/m³.MPa, the BPCC 41.0 kgCO_{2e}/m³.MPa and the RHCC 171.6 kgCO_{2e}/m³.MPa.

These results showed the importance of considering the performance criteria in the functional unit of building material carbon footprint studies, where units of volume or mass only may lead to false conclusions. These results showed that in order to produce 1m³ with 1MPa of wood shavings composite, less CO_{2e} are emitted. Comparing the cement compressive strength index (Table 3), the WSCC resulted in 5.82 MPa for each ton of cement, while the RHCC in 3.16 MPa/ton of cement. The use of $CaCl_2$ additive contributed to improve the mechanical performance of WSCC. This behavior should be verified in the other two composites in future studies.

The results using the second indicator are presented in Fig. 5.

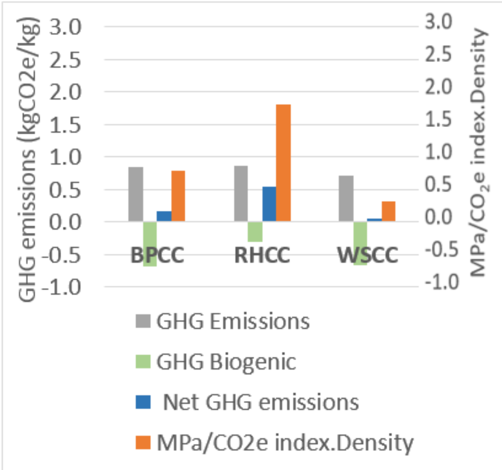

Fig. 5: Composite carbon footprints considering the second indicator.

When the dry density is considered, the differences between the three composites decrease, while a lower dry density is advantageous, principally, in terms of the building design and materials transport. The WSCC presented the biggest dry density while the RHCC and BPCC presented lower values, which have improved their carbon footprint. The WSCC presented 0.3, the BPCC 0.8 and RHCC 1.8.

The second indicator (MPa.CO_{2e} index/Density) incorporated more variables (mass, volume and compressive strength), which shows a more realistic, and consequently, a more correct way to compare these three composites.

An important objective of a product carbon footprint is to enable the producers to improve their development in order to reduce their emissions. For this, it is important to find where the critical stages and processes, in terms of carbon emissions, are localized, as presented in Fig. 6.

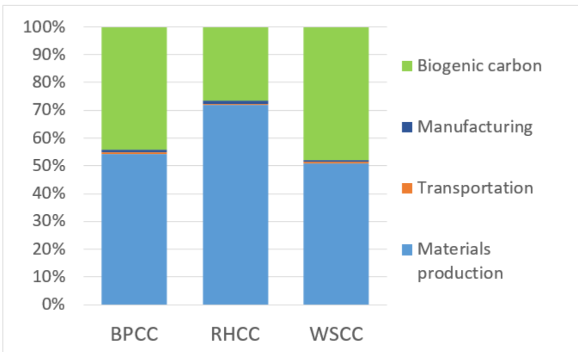

Fig. 6: CO_{2e} emissions participation in life cycle stages.

The transportation presented a minimum participation. The manufacturing of composites also presented a minimum participation as the process considered in the laboratory uses just electricity and the fact that the CO_{2e} emissions of the Brazilian electric matrix is low when compared with other countries. This is associated with a large share of renewable and cleaner sources, such as hydraulic energy in Brazil. Other important fact that contributed to low CO_{2e} emissions in this stage was the adequate workability at the fresh state of the produced bio-based cementitious composites. More studies will be made to evaluate the impact of the different production processes in CO_{2e} emissions and other enviromental impacts.

The materials production stage was the one that presented the highest participation in CO_{2e} emissions. Therefore, this stage is critical and deserves special attention to minimize CO_{2e} emissions.

Finally, the biogenic carbon is associated with the bio-based materials used, which is associated with the quantity and the amount of CO_2 sequestered during the photosynthesis (measured by carbon content). In this sense, the wood shavings composite presents an advantage, due to its high carbon content.

Knowing that the materials production stage was the most impactful stage, the CO_{2e} emissions participation for each composite was assessed as presented in Fig. 7.

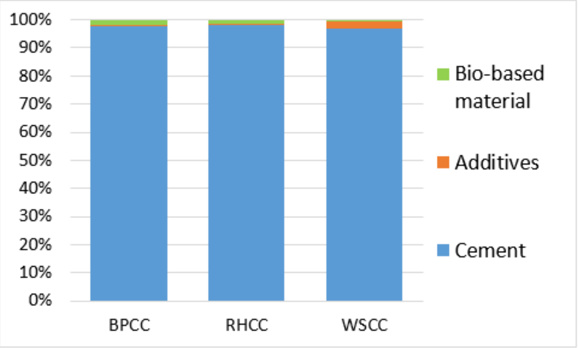

Fig. 7: CO_{2e} emissions participation in materials production stage.

As expected, the cement presented the biggest participation in CO_{2e} emissions. Therefore, its use should be minimized if low carbon footprints bio-based materials are desired, with the exception of evaluating the impact on the mechanical strength of the material. In this sense, different binders, such as lime and supplementary cementing materials (SCMs), such as fly ash and blast furnace slag, can be developed in substitution of cement, the material with the greatest carbon footprint. The carbon footprints of the composites studied in this paper served as an initial parameter to guide the specification of bio-based materials for composite façade systems with low carbon.

The allocated CO_{2e}, in the material production of the bio-based materials, before going to laboratory (bamboo, rice husk and wood shavings) presented some participation. Therefore, it is also desirable to use biomasses with a minimum treatment to decrease the CO_{2e} at this stage.

The used VMA additive showed a minimum participation because of its minute quantities in all mixtures (less than 0.3% in mass) and for wood shavings the $CaCl_2$ additive presented a higher participation (around 2.4%). However, the additives usage presented a small participation in total emissions. In this sense, if the mechanical performance improvement provided by the $CaCl_2$ additive is proven, a dosage which considers the increase of $CaCl_2$ and the decrease of the cement content should be evaluated, which may lead to a reduction in the carbon footprint of the composites.

3.3 Low carbon bio-based materials specification

Based on the results, the authors highlight the main criteria for a low carbon footprint bio-based material design:

(1) decrease of the amount of cement in mixture;
(2) high values of biomass proportion in the mixture;
(3) choice of a bio-based material with high values of carbon content if the landfill scenario is considered in the end-of-life stage;
(4) choice of a bio-based material with low CO_{2e} emissions production allocation;
(5) Choice of a bio-based material with adequate workability at the fresh state ;
(6) availability of bio-based material near the factory location.

4 CONCLUSIONS

This study compares the carbon footprint of three workable cement bio-based composites for building application. They are composed of bio-aggregates made of bamboo particles, rice husk and wood shavings, mixed with cement. The results were presented in three ways: (1) the amount of CO_{2e} emissions to produce 1m³ of composite ($kgCO_{2e}/m^3$), (2) the same amount considering the 1MPa strength of the composite ($kgCO_{2e}/m^3.MPa$), (3) relation between the compressive strength and dry density (MPa/CO_{2e} index. Dry density).

The wood shavings composite presented the highest dry density, followed by bamboo and rice husk composites.

The wood shavings composite was the most carbon efficient, followed by bamboo and rice husk. When the structural performance unit was considered, the differences between the rice husk and other composites increased. When the compressive strength and dry density is considered the differences between them decrease, due to lower dry densities of rice husk and bamboo composites. The second indicator (MPa/CO_{2e} index. Density) incorporated more variables (mass, volume and compressive strength), performing a more realistic and correct way to compare these three composites.

The materials production presented the most impactful stage related to CO_{2e} emissions, mainly related to the cement production.

In future studies this carbon footprint will be extended evaluating the impact of thermal performance of composites, the energy consumption, the CO_{2e} emissions during the usage stage and recycling end-of-life scenario.

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