DYNAMIC LIFE CYLE CARBON ASSESSMENT OF THREE BAMBOO BIO-CONCRETES IN BRAZIL

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Abstract

Brazil has a vast use of concrete in the construction sector. Having the ability to store carbon for long periods, the development of concretes mixed with bio-based materials can be a promising alternative to ordinary concrete products in the Brazilian building sector, as a measure to reduce the GHG emissions. A bio-concrete with bamboo waste (BB) as main material, mixed with ordinary Portland cement (OPC) and supplementary cementitious materials (SCM), metakaolin (MK) and fly ash (FA), has been developed in laboratory for use as building panels for walls, roofs and floors. This article aims to investigate the effect of storing carbon in three different mixes of bamboo bio-concrete, considering the mass relation of OPC/MK/FA mixed with bamboo waste, additives and water. A cradle to grave life cycle carbon assessment (LCCA) was carried out, considering the production, transportation and end-of-life stages in a Brazilian context, based on data collected in laboratory, literature and the Ecoinvent database. A dynamic LCCA method was applied in order to investigate overall GHG-emissions from compared system and the impact of biogenic carbon emissions and removals over the investigated time-frame. The influence from different transport distances were evaluated through a sensitivity analysis. The bio-concrete with the highest replacement of OPC with MK and FA presented 77% reduction in terms of the sum of instantaneous global warming impact (GWI_{cum}), when compared to no substitution of OPC. When the strength of the bio-concretes (in kg $CO_{2\text{-}eq}$ /m²·MPa) was considered, it presented a reduction of 88%. The use of SCMs, especially FA in the cementitious materials relation, also results in great benefits between the three bio-concretes. The use of DLCCA allowed a more consistent and informed assessment of life cycle GHG emissions flows and global warming impact of the bamboo bio-concretes.

Keywords:

Bamboo bio-concrete; Bio-based building material; LCCA; Dynamic LCA; Brazil

1 INTRODUCTION

In Brazil, the use of concrete in the construction sector is very common for different applications, such as: structures, floors and walls. However, concrete is commonly pointed out as a non-climate friendly material, due to the use of cement and extraction of large amount of raw materials.

In Europe, the incentive for a bio-based circular economy has gained strength since 2012 [BMBF 2015]. Brazil has suitable conditions for the development of a bio-based economy, because of its available lands and adequate climate conditions in most part of the country. In addition, since 2015, Brazil is compromised to certain goas for reduction of greenhouse gas (GHG) emissions by its Intended National Determined Contributions – iNDC. Use of bio-based materials could be an important part in achieving these goals, especially in the construction sector, that normally produces materials and buildings with long service life.

Besides the use of wood, there are some initiatives of special interest in the development of a bamboo industrial chain [Drumond 2017]. Brazil has very good conditions for the development of bamboo forests, plantations and industrialization of the process, since it has a cleaner electric energy matrix, with a big share of renewable sources.

In the bamboo industrialized chain, the amount of waste generated throughout the process, from cutting the culms, processing and production of laminates, can be vast. According to Escamilla [2014], almost 50% of bamboo that enters for lamination process becomes waste, normally generated as bamboo particles. The larger share of this waste is incinerated, sometimes with energy recovering [Restrepó 2016], while a remaining part stays as a waste material, going to landfills and sometimes for inadequate places.

In this context, Andreola [2017] developed a bamboo bio-concrete that uses, for the first time, ordinary

Portland cement (OPC) mixed with bamboo waste, viscosity modifier additive (VMA) and water. After the development of the first mixtures, it was observed that the consumption of cement was high, which resulted in high amount of GHG emissions, as verified by Caldas [2017], even when the CO_2 stored by bamboo waste is quantified in the carbon footprint. A new formulation of bamboo bio-concrete was developed, replacing part of OPC for metakaolin (MK) and fly ash (FA), reducing the water content using superplasticizer additive and improving the mechanical performance using calcium chloride ($CaCl_2$) as accelerator setting additive.

Considering that the OPC partly was replaced by supplementary cementitious materials (SCM), it was expected that the carbon footprint of the bamboo bio-concrete would have an expressive decrease. In this context, the new SCM bamboo bio-concretes must be evaluated in order to see how the carbon footprint changed with these modifications, considering not just the GHG emissions but also the differences in terms of mechanical performances of the different bamboo bio-concretes.

In the scientific literature there is no consensus in regard to the most adequate approach for evaluations of the carbon footprint from bio-materials [Brandão 2013; Tellnes 2017]. There are different standards and guidelines such as ISO 14067:2014, PAS 2050, ILCD Handbook, Dynamic Life Cycle Assessment (DLCA), etc.

Several studies of bio-based materials have been carried out using the DLCA to consider the contribution of the carbon storage in construction products and the biogenic emission during production and end of life. Collinge [2013] applied the DLCA in a simplified case study of a building and verified that the use of dynamic modelling in LCA increases the relevance of the results and gives more support for decision making. Fouquet [2015] compared three buildings, one out of wood and two out of concrete. The wood building, considering a landfill scenario presented the best results. Peñaloza. [2016] analysed three constructive alternatives, one of alternative timber design with increased bio-based content. They found that the increase of bio-based material content in a building have a great potential to reduce the impact on global warming potential (GWP). The end-of-life option, the timing of forest cycles ant the time horizon had an import influence in the final results. Pittau [2018] compared the potential of carbon storage for different constructive technologies. They verified that fast-growing bio-based materials, such as hemp and straw, could be very good alternatives to decrease the climate change impact of buildings.

All these studies indicated benefits and advantages when using DLCA. Most of them pointed out more accurate and sensitive assessments, especially when bio-based building materials were estimated. The bio-based materials evaluated showed great potential to store CO_2 and reduce the climate change impacts. This article aims to investigate the effect of storing carbon in three different mixes of bamboo bio-concrete, considering the mass relation of OPC/MK/FA mixed with bamboo waste, additives and water. The three following mixes were compared: (1) a mixture with 100% in mass of OPC (BB-100/0/0), (2) with replacement, in mass, of 60% of the OPC by MK (30%) and FA (30%) (BB-40/30/30) and (3) replacement of 70% of the OPC by MK (30%) and FA (40%) (BB-30/30/40). A cradle to grave life cycle carbon assessment (LCCA) was performed, considering the production, transportation, repair and end-of-life stages. Two different methods were used, the Dynamic Life Cycle Carbon Assessment (DLCCA) and the Global Warming Potential at 100 years (GWP100) developed by IPCC.

2 METHOD

2.1 Bamboo bio-concretes characterization

The bamboo bio-concretes (BB) produced were manufactured using bamboo particles and different cementitious materials, such as ordinary Portland cement (OPC), metakaolin (MK) and fly ash (FA), mixed with additives and water.

The bamboo particles were considered waste materials, normally obtained from bamboo lamination process. The material was treated at NUMATS/UFRJ, Rio de Janeiro, Brazil. A sample of the bamboo bio-concrete is presented in Fig. 1.

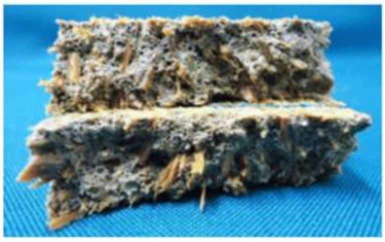

Fig. 1: A sample of the bamboo bio-concrete.

To reach the required consistence for the BB-100/0/0, a viscosity modifying agent (VMA) was used. While, for the BB-40/30/30 and BB-30/30/40 the VMA was not necessary due to SCM properties, however the superplasticizer was used for rheology and calcium chloride $CaCl_2$ additive was incorporated as a setting accelerator.

The mass per cubic meter and its compressive strength obtained in the three BB are summarized in Tab.1.

Tab. 1: Mixture composition (kg/m³) and compressive strengths (MPa).

Materials	BB-100/0/0	BB-40/30/30	BB-30/30/40
Cement CPV	744.21	320.41	238.65
Metakaolin	-	240.31	238.65
Fly ash	-	240.31	318.20
Bamboo waste (particles)	267.84	236.10	236.10
VMA additive	0.93	-	-
Superplasticizer	-	8.01	7.95
$CaCl_2$ additive	-	9.61	7.16
Water	320.02	256.32	238.65
Compressive strength (MPa)	3.25	10.63	8.86

2.2 Dynamic Life Cycle Carbon Assessment (DLCCA)

Normally, in a conventional LCA, the impact of GWP of biogenic CO_2 is not considered. The absence of timing during the biogenic CO_2 flow can lead to significant differences in GWP calculation [Fouquet 2015; Pittau 2018]. Levasseur [2010] proposed the Dynamic Life Cycle Assessment, with focus on GWP, which, in this paper, will be named the Dynamic Life Cycle Carbon Assessment (DLCCA). In the last years, different authors adopted the DLCCA for calculation of global warming impact (GWI), for example: Levasseur [2013], Fouquet [2015] and Pittau [2018].

The method proposed by Levasseur [2010] uses time-dependent characterization factors (DCF) for the calculation of the climate change category, in order to measure the cumulative radiative forcing generated by release of GHGs to the atmosphere. The instantaneous GWI (GWI_{inst}) at the end are summed up in the defined time horizon for cumulative GWI (GWI_{cum}). The GWI_{inst} and GWI_{cum} can be calculated using Equations 1-3, proposed by Levasseur [2010].

$$DCF_{inst;GHG}(t) = \int_{t-1}^{1} a_{GHG} C(t)_{GHG}{}^{dt} \quad (1)$$

$$GWI_{inst}(t) = \sum GHG \sum_{i=0}^{t} g_{GHG}(t_i) . DCF_{inst,GHG}(t - t_i) \quad (2)$$

$$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(t_i) \quad (3)$$

$DCF_{inst;GHG}(t)$ – is the dynamic characterization factor of a specific GHG emission that occur at time t.
$C(t)_{GHG}$– is the atmospheric load of the given GHG t years after the emission.
a_{GHG}– is the instantaneous radiative forcing per unit mass increase in the atmospheric for the specific GHG.
$GWI_{inst}(t)$– is the instantaneous global warming impact as a given time t.
$g_{GHG}(t_i)$ – is the result of the dynamic inventory for the given GHG for year i.
$GWI_{cum}(t)$ – is the sum of all $GWI_{inst}(t)$ from zero to time t.

Goal, scope and functional unit definition

The standard EN 15804:2012 was used to the LCCA model, considering the following modules: raw materials supply – A1; raw materials transport – A2; bio-concrete manufacturing – A3; transport of bamboo bio-concrete for its use – A4; use of bio-concrete – B6 (considering the bamboo regrow in the forest/plantation); repair – B3; demolition – C1; waste transportation – C2; and disposal in landfill – C4. The system boundaries considered in DLCCA is presented in Fig. 2.

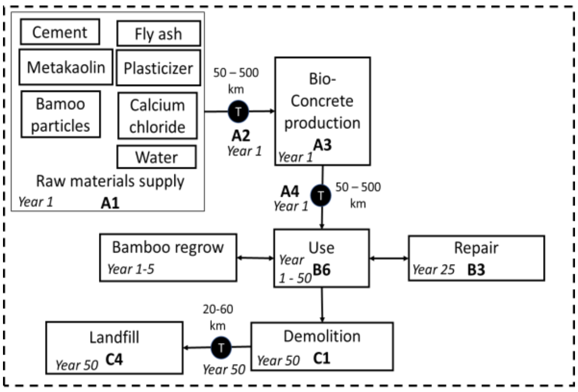

Fig. 2: System boundaries of DLCCA model.

The functional unit chosen in this study is the surface area of a wall (in m²) made of bio-concrete, with 10 cm thickness (following the Brazilian common practice for concrete walls technology) considering the wall has 50 years of service life, according to Brazilian performance standard ABNT NBR 15575 [ABNT 2013]. Although the bamboo bio-concretes have a different mechanical performance, they all have minimum compressive strength values for use as walls in Brazil. In order to reflect this difference in the DLCCA, a mechanical performance indicator, in terms of compressive strength, was used in the functional unit (FU) established in the study.

Life cycle inventory

The life cycle inventory was performed based on data collected in laboratory, literature and Ecoinvent v. 3.3 database. The electricity consumption of original Ecoinvent data was adapted to Brazilian energy mix for year of 2014. GHG emissions and removals, of CO_2, CH_4, N_2O and CO were accounted over all stages.

A high initial resistance cement, CPV, with 90% of clinker, 5% of crushed limestone and 5% of gypsum, was considered, as CPV normally is used in Brazil. The average thermal energy consumption and electricity used in Brazilian cement plants for clinker and cement production was used, according to WBCSD [2016] and MME [2018].

A kaolin extraction and calcination process using charcoal as energy source, based on Borges [2014], was considered for metakaolin in the study. For FA it was considered just the treatment normally performed to use as a SCM and data from Chen [2011] was adopted considering the Brazilian electric energy mix for year of 2014.

As bamboo particles are generated as waste in commercial production of bamboo products, without any economic value, it was considered they do not have any environmental impacts in their acquisition, besides the treatments performed in laboratory, such as sifting and washing in 80º C. 0.8 kWh of electrical energy and 10 L of water per kg of bamboo particles were accounted in the laboratory.

Brazil is a county with continental dimensions which impacts in the transportation distances of building materials. Thus, different distances for transportation of raw materials (A2) as well as bio-concrete presumed to be transported from factory to site (A4) were assumed. Based on map research we considered 50 km as minimum distance, 200 km as average and 500 km as maximum, similarly to Lecompte [2017]. The road modal with EURO 3 and 16-32 tones, was adopted for transportation from Ecoinvent database, considering that Brazilian trucks normally have these characteristics for building materials transportation.

Since these bio-concretes are new materials, with no data available about service life, for the repair stage (B3) we considered that 10% in mass of the old bio-concrete is demolished and send to an inert landfill and a new bio-concrete, with the same amount, characteristics and properties of the old one, was produced and transported to the site.

As no data is available for bio-concrete demolition (C1) and landfilling (C4) activities, we considered the same process used for reinforced concrete demolition and inert materials disposal in landfill. The distance of 20, 40 and 60 km between the site and the nearest inert landfill was adopted for the waste transportation (C2). For the landfilling decomposition process it was assumed that no GHG emission occurs, since the cement and SCM mineralizes the bamboo waste, the same approach performed by Pittau [2018]. All the processes were modeled in SimaPro v.8.5.2.

Carbon sequestration from biomass regrowth in bamboo plantation

To calculate the amount of atmospheric CO_2 captured by bamboo plantation in the photosynthesis process, the approach suggested by Fouquet [2015] and Pittau [2018] was adopted. We considered the bamboo carbon content in the bio-concretes, using 45.6% of carbon in bamboo dry matter. This value was obtained in CHN elementary analysis, and used also by Caldas [2017].

We defined that the bamboo regrow started to occur after the bio-concrete manufacturing, considering a sustainable forest management. Bamboo is considered a fast-growing bio-based material, with a rotation period ranging from 3 to 8 years [Greco 2011]. Then, we assumed that the bamboo is fully regenerated within 5 years of collecting, considering just the equivalent amount of culm (other waste such as leaves, branches and roots were not accounted). Based on data of bamboo growth by Cruz Rios [2009] and Mognon [2015] and the model presented by Pittau [2018], a model was developed (Fig. 3): (A) bamboo biomass kept at steady state, (B) the aboveground bamboo is collected and the carbon is stored in the bio-concrete. At the same time the same biomass starts to grow in the bamboo-plantation, capturing and storing CO_2 and (C) the same quantity of the carbon that was collected is regenerated once again in the end of the bamboo plantation rotation.

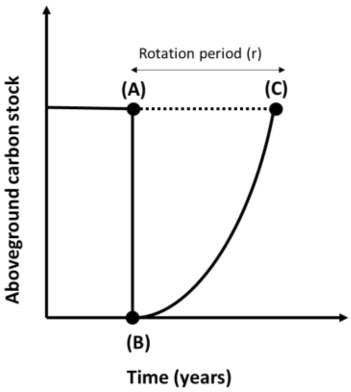

Fig.3: Simplified scheme of neutral carbon flux for the bamboo plantation model. Adapted from Pittau [2018].

Life cycle impact assessment

The results, initially expressed in instantaneous and cumulative radiative forcing, were converted to $kgCO_{2\text{-}eq}$, using the IPCC [Stoker et al. 2013] method.

2.3 Mechanical performance indicator

A mechanical performance indicator was used in this study to verify the differences between the compressive strength of the three bamboo bio-concretes related to GWP, a similar approach was used by Van Den Heede [2012] and Celik [2015]. In the end, the GWP (in $kgCO_{2eq}$) to produce 1m² with 1MPa strength of the bio-concrete ($kgCO_{2\text{-}eq}$/m².MPa) was calculated, according to the experimental data of compressive strength values presented in Tab. 1.

3 RESULTS AND DISCUSSION

3.1 Greenhouse gases inventory analysis

Figs. 4-7 show the results of GHG inventory of the three bio-concretes.

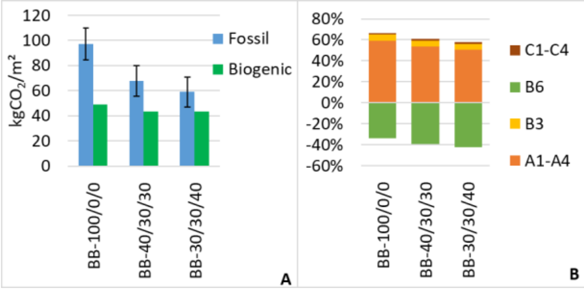

Fig. 4: Bio-concretes CO_2 inventory. (A) Average values and standard deviation of transportation. Biogenic carbon refers to carbon emitted for production and end-of-life and the amount stored in the bamboo waste. (B)Share of life cycle stages.

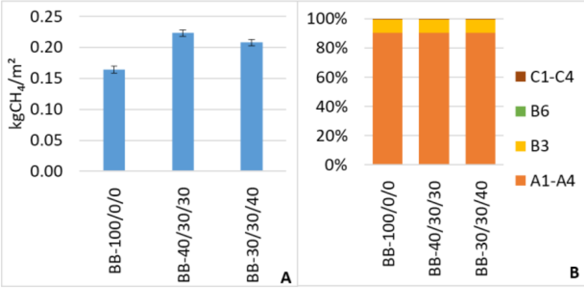

Fig. 5: Bio-concretes CH_4 inventory. (A) Average values and standard deviation of transportation. (B)Share of life cycle stages.

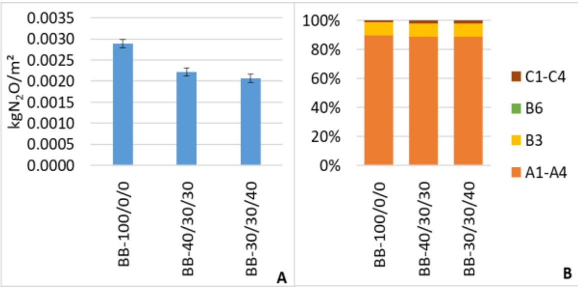

Fig. 6: Bio-concretes N_2O inventory. (A) Average values and standard deviation of transportation. (B)Share of life cycle stages.

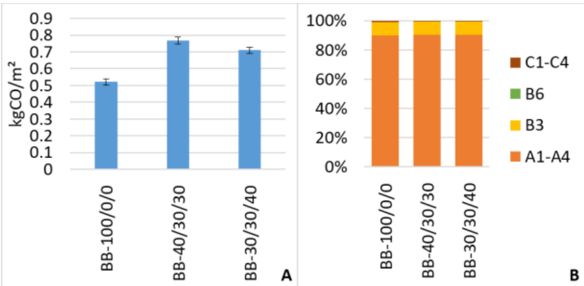

Fig. 7: Bio-concretes CO inventory. (A) Average values and standard deviation of transportation. (B)Share of life cycle stages.

The BB-100/0/0 presented higher GHG emissions for CO_2 and N_2O, while the BB-40/30/30 presented higher emissions for CH_4 and CO. These results are directly related to the cement content and MK of bio-concretes. Portland cement production emits a large amount of CO_2 and N_2O, mainly during clinker production. In the case of MK, since we considered charcoal as fuel, it has higher amount of CH_4 and CO emissions. The FA has the smallest amount of all GHG, which results in lower

GHG emissions for the BB-30/30/40, that has a higher content of FA.

The biogenic CO_2 (in green colour on Fig.4) refers to the biogenic carbon emitted for production and end-of-life and the amount stored in the bamboo waste. The production and repair stages were the most impactful, while the end-of-life stage is less relevant. The range of transportation showed expressive impact only for CO_2 emissions, due to diesel consumption.

3.2 Dynamic life cycle carbon assessment results analysis

Fig. 8-10 present the instantaneous, cumulative global warming impacts and the GWP in year 100, calculated using the DLCCA, of the three bio-concretes, respectively.

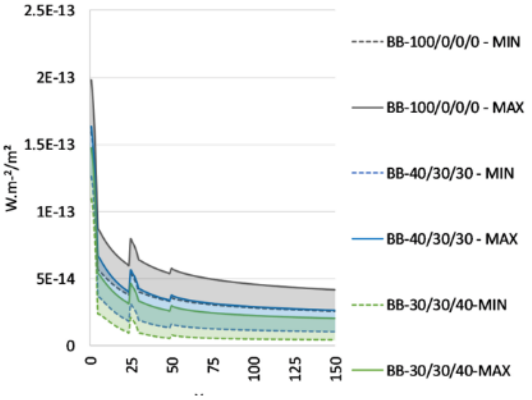

Fig. 8: Instantaneous radiative forcing for the three bio-concretes.

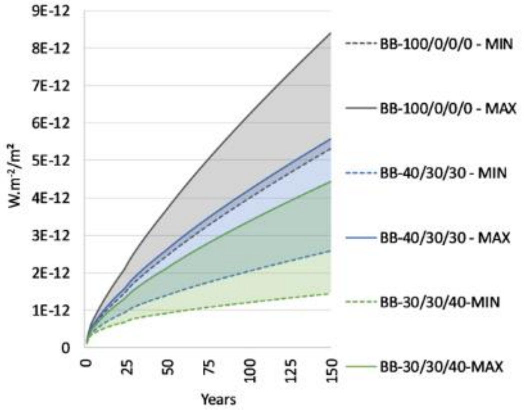

Fig. 9: Cumulative radiative forcing for the three bio-concretes.

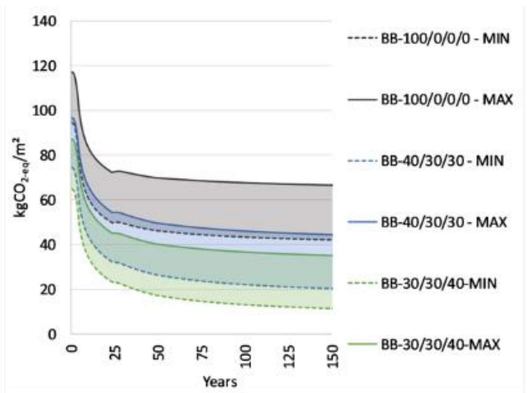

Fig. 10: Global warming potential for the three bio-concretes.

For the GWI_{inst} the first peak refers to the production of raw materials, transportation and the bio-concrete manufacturing (A1-A4). After this, the bamboo in plantation starts to regrow, following the scheme presented in Fig. 3, capturing and storing the same amount of CO_2 that is presented in bamboo particles of the bio-concretes, decreasing the GWI_{inst} impact. For the BB-30/30/40, and the minimum transportation distances, the balance until year 25 reaches nearly zero.

In the year 25, an expressive amount of GHG emissions are released in atmosphere due to the repair (B3) of the bio-concrete walls. In this stage is considered demolition of 10% of old bio-concrete, transportation of the waste to the landfill and transportation of new bio-concrete to the site. These results are similar to Fouquet [2015], when refurbishment was performed in their case studies.

Since the end-of-life considered is landfill, and the bio-concretes are inert materials due to the mineralization of bamboo fibers by cement and SCM, there are no emissions after this stage, as verified by Pittau [2018], in the case of hempcrete. It is important to say, that in terms of GWI, the landfill end-of-life is a good option as already verified by Fouquet et al. [2015] and Peñaloza [2016], since it allows the carbon stored indefinitely. However, this option could be less beneficial for other environmental impacts. Thus, material recycling, as investigated by Pittau [2018], could be an interesting alternative, although not evaluated in the present study.

The recycling benefits will be strongly influenced by which material the recycled material will replace. I.e. if the replaced material has a high environmental impact, the benefits will be higher. Since the bio-concretes are innovative materials, it is not yet known what their recycling potential is. In the future, with more experimental data available, it will be possible to evaluate other options for end-of-life and the benefits related to the avoided burdens.

The results for GWI_{cum} show that the BB-100/0/0 has the greatest impact on global warming, with a big difference between the SCM mixtures, 55% when compared to BB-40/30/30 and 77% with BB-30/30/40 for the scenario with lowest transportation distances. While, for the highest transportation distances the difference between the BB-100/0/0, BB-40/30/30 and BB-30/30/40 was 35% and 49%, respectively.

The consideration of different materials distances transportation also showed big differences, reaching 71% for BB-30/30/40. Since Brazil is a country with continental dimensions this range must be considered in LCA studies. These results agree with Lecompte [2017], which evaluated different transportation distances, with similar values that we adopted in this study, but considering the raw materials comes to different countries in Europe.

3.3 Comparison between Global Warming Potential and Mechanical Performance Indicator – Dynamic Life Cycle Carbon Assessment and IPCC at 100 years

In the below, the Global Warming Potential (GWP) calculated by the DLCCA model (at year 100) is compared with the IPCC method at 100 years. The differences between the two approaches are presented in Fig. 11.

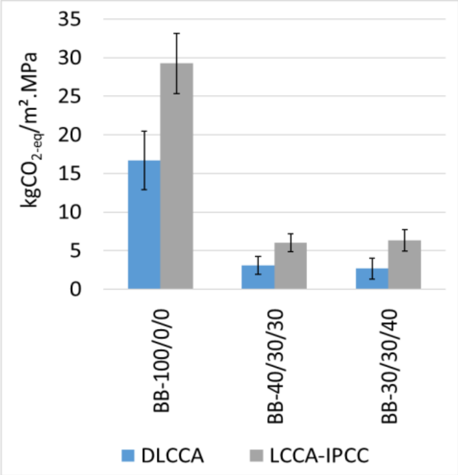

Fig. 11: Comparison between the Dynamic life cycle carbon assessment (DLCCA) and the conventional LCCA with the IPCC 100 (2013), considering the compressive strength per surface of wall as FU.

Similar to results presented by Pittau et al. [2018], there are important differences between the two methods for calculation of climate impacts. The different is larger for the BB-30/30/40, since the amount of biogenic carbon had a great impact on results in this mixture. Using the IPCC method, the biogenic carbon and the CO_2 captured during the bamboo growth were not accounted for, which drastically increases the GWP impact of the bio-concretes.

When the mechanical performance indicator is considered, the difference between the Portland cement bio-concrete (BB-100/0/0) and the alternative with SCMs (BB-40/30/30 and BB-30/30/40) increases. This occurs as the SCM mixtures have a lower GWI and a higher compressive strength. Using DLCA, the BB-30/30/40 performs as the most efficient mixture, with 1.48 to 4.14 $kgCO_{2\text{-eq}}/m^2 \cdot MPa$, while the BB-40/30/30 was the most efficient, with 5.04 to 7.32 $kgCO_{2\text{-eq}}/m^2.MPa$, using the IPCC method. The results considering just the surface of wall as FU is presented in Fig.12.

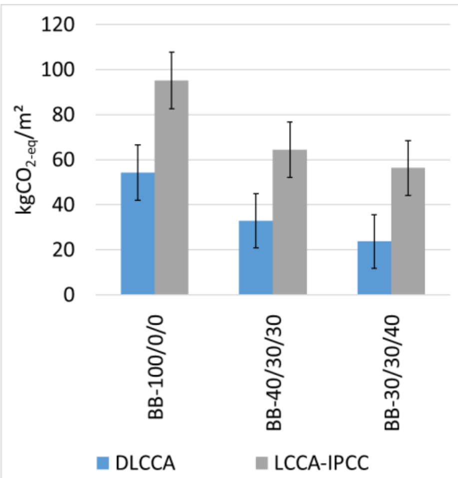

Fig. 12: Comparison between the Dynamic life cycle carbon assessment (DLCCA) and the conventional LCCA with the IPCC 100 (2013), considering just the surface of wall as FU.

4 CONCLUSIONS

In terms of the sum of all instantaneous global warming impact (GWI_{cum}), the bio-concrete with more fly ash content (BB-30/30/40) presented up to 77% better performance when compared to the 100% in mass of Ordinary Portland Cement bio-concrete (BB-100/0/0). When a mechanical performance indicator was considered, the difference increases, reaching 88% when the Dynamic Life Cycle Carbon Assessment (DLCCA) was used.

The consideration of biogenic carbon and the fast bamboo growth rate have a great influence on results, primarily when a landfill end-of-life scenario was considered, since this will have a positive effect in terms of permanent carbon sequestration. The IPCC method could not account for these aspects, and can therefore lead to an overestimated global warming impact for the bamboo bio-concretes.

The use of DLCCA in bio-concrete evaluation allowed a more consistent and informed assessment of life cycle GHG emissions flows and global warming impact of the bamboo bio-concretes, in terms of radiative forcing effects over time.

Materials transportation distances had a big influence on the results, reaching 71% between a minimum and maximum scenario for BB-30/30/40.

Other source of uncertainties related to bio-based materials, such as the bamboo carbon content and bamboo plantation rotation periods should be evaluated in future research, as well as the alternative method to allocate the impact of bamboo particles, since it is considered as waste material.

5 ACKNOWLEDGMENTS

Authors would like to express their gratitude to *Conselho Nacional de Desenvolvimento Científico e Tecnológico* - CNPq and *Centro Latinoamericano-Suizo* - Universität St.Gallen for their financial support in this research.

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