IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Transportation impact on CO_2 emissions of concrete: a case study in Rio Branco/Brazil

Impacto do transporte nas emissões de CO_2 do concreto: um estudo de caso em Rio Branco/Brasil

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Received 23 March 2022
Accepted 17 October 2022

Abstract: Due to the scarcity of crystalline massifs in the north of Brazil, concrete producers have been using crushed stone and cement from suppliers located hundreds of kilometers away. In this case, CO_2 emissions related to material transportation for concrete production may become significant. Thus, this study aims to analyze the influence of the transportation of the materials in CO_2 emissions of ready-mix concrete production in Rio Branco (Acre). Concrete compositions were obtained from a local concrete producer. Brazilian methods of dosage were not applicable due to the high fineness of the regional sand available; the mix designs were adjusted empirically. Two types of cement (CP V-ARI and CP IV) were considered to create the studied scenarios. Transportation distances of the raw materials (cement and aggregates) ranged from 20 km (local sand supplier) to 3,592 km (cement supplier from Sete Lagoas, MG). CO_2 emissions to produce concrete (f_{ck} of 25 MPa, cement consumption of 426 kg/m^3) ranged from 208 $kgCO_2/m^3$ to 573 $kgCO_2/m^3$. Transportation was responsible for up to 20% of total emissions. The emissions in this study are considerably higher than the national data of concrete production available in the Construction Environmental Performance Information System (Sidac) due to the higher cement consumption and higher transportation distances. Although cement consumption in Acre represents less than 1% of Brazilian consumption, the results reveal the impact of transportation distances in CO_2 emissions of concrete in cities that deal with local scarcity.

Keywords: concrete, CO_2 emission, transportation, construction materials.

Resumo: Devido à escassez de maciços cristalinos no norte do Brasil, produtores de concreto têm usado pedra britada e cimento de fornecedores localizados a centenas de quilômetros. Nesse caso, as emissões de CO_2 relacionadas ao transporte de materiais na produção de concreto podem ser significativas. Assim, este estudo tem como objetivo analisar a influência do transporte dos materiais nas emissões de CO_2 da produção de concreto usinado em Rio Branco (Acre). As composições de concreto foram obtidas de um produtor de concreto local. Os métodos brasileiros de dosagem não foram aplicáveis devido à alta finura da areia regional disponível; os traços foram ajustados empiricamente. Dois tipos de cimento (CP V-ARI e CP IV) foram considerados para criar os cenários estudados. As distâncias de transporte das matérias-primas (cimento e agregados) variaram de 20 km (fornecedor local de areia) a 3.592 km (fornecedor de cimento de Sete Lagoas, MG). As emissões de CO_2 para a produção de concreto (f_{ck} de 25 MPa, consumo de cimento de 426 kg/m^3) variaram de 208 $kgCO_2/m^3$ a 573 $kgCO_2/m^3$. O transporte foi responsável por até 20% do total de emissões. As emissões neste estudo são consideravelmente maiores do que os dados nacional de produção de concreto disponíveis no Sistema de Informação do Desempenho Ambiental da Construção (Sidac) devido ao maior consumo de cimento e maiores distâncias de transporte. Embora o consumo de cimento no Acre represente menos de 1% do consumo

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Financial support: CNPq grant number 140054/2020-0 and CAPES grant number 88887.463874/2019-00.
Conflict of interest: Nothing to declare.
Data Availability: The data that support the findings of this study are available from the corresponding author, A. A. L. Pacheco, upon reasonable request.

brasileiro, os resultados revelam o impacto das distâncias de transporte nas emissões de CO_2 do concreto em cidades que lidam com a escassez local.

Palavras-chave: concreto, emissão de CO_2, transporte, materiais de construção.

How to cite: A. A. L. Pacheco, L. S. Oliveira, V. M. John, and S. C. Angulo, "Transportation impact on CO_2 emissions of concrete: a case study in Rio Branco/Brazil", *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 6, e15609, 2022, https://doi.org/10.1590/S1983-41952022000600009

1 INTRODUCTION

The growing need of concrete for habitation and urban infrastructure leads to increasing consumption of minerals for construction [1]. This happens in great part because concrete, the most consumed construction material in the world, has approximately 75% of its volume composed of aggregates [2], [3]. In the last decades, BRIC countries (Brazil, Russia, India and China) were responsible for the extraction of one third of global resources, which includes Brazil [4]. In Brazil, more than 600 million of tons of minerals have been consumed in 2016 [5], and around 50% of it was used for concrete [6], [7].

The fabrication of Portland cement also depends on the extraction of minerals as limestone (in which part of it is converted in CO_2 during production [8]) and clay, its main raw materials. Although the cement consumption decreased in the country from 2015 to 2018, consequence of the economic crisis, since 2019 it has been observed the increasing in its consumption [9] as in many other BRIC countries. The same is happening in the northern region of Brazil, which has population growth above the national average and a growing need for infrastructure in transportation, sanitation and housing for the population [9], [10].

Although the minerals used in civil construction are considered abundant in nature [11], [12], in many regions of Brazil or abroad [13], [14] these resources are far away. Areas located in sedimentary basins generally do not have hard rocks for crushing. In the northern region of Brazil, states such as Amapá, Roraima and Amazonas have rare crystalline massifs, depending on alternative materials and long-distance transportation [15], [16]. As an example, in the city of Manaus (state of Amazonas, AM) gravel is frequently used as a substitute material for crushed stone [17]. Also, in the Southern and Southeast regions, many cities located in the Paraná sedimentary basin require the transportation of coarse aggregates over distances greater than 100 km [15]. Globally, the scarcity of aggregates due to geological restrictions was also observed in the Netherlands [18], and in the central region of United States [19].

The state of Acre stands out in this scenario due to the absence of mineral deposits (Figure 1). The construction industry in this state depends mainly on coarse aggregates from the state of Rondônia. This makes the price of crushed stone the highest in Brazil, up to R$ 286.54/m^3 in April of 2022 [20]. In addition, due to the lack of limestone reserves in the region, Acre does not have cement production [21] and this material needs to be transported from neighboring states over distances that can reach up to 3,500 km.

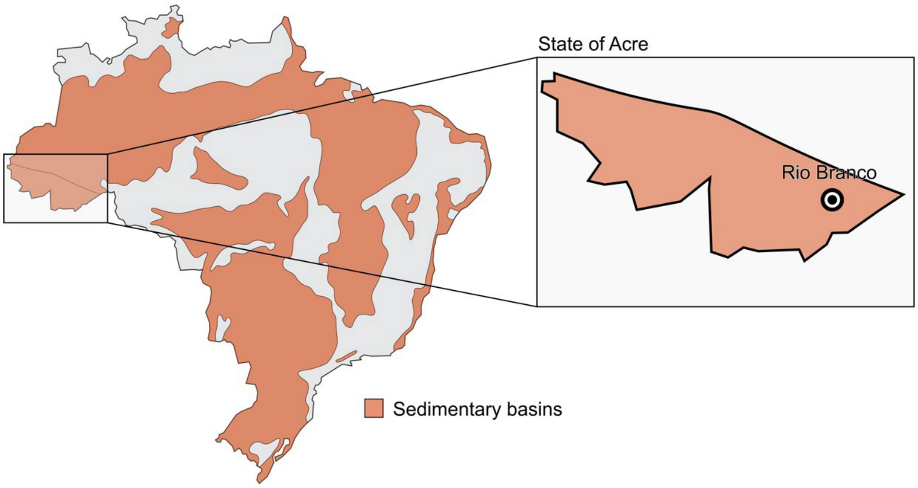

Figure 1. Map of Brazil identifying the sedimentary basins and the State of Acre.

Cement production is the main responsible for environmental impacts of concrete, especially in CO_2 emissions from limestone decarbonation and energy consumption [22]. According to the Global Cement and Concrete Association [23], [24], the average cement emission in 2019 was 564 kg CO_2/t in Brazil and 635 kg CO_2/t in the world. The emission due to the transportation of concrete materials differs depending on the region and the means of transportation [8], being generally adopted as less than 5% of the total emissions. However, most studies consider distances of aggregates transportation between 20 and 400 km and cement transportation between 100 and 900 km [25], [26], values much lower than those found in the northern region of Brazil.

Based on this context, the objective of this work is to quantitatively analyze the impact of the material transportation stage on the CO_2 emission of the ready-mix concrete produced in the city of Rio Branco, state of Acre, in Brazil. The results were compared to the national data of concrete production available in the Construction Environmental Performance Information System (Sidac), a platform for the assessment and calculation of environmental performance indexes of Brazilian construction products.

2 METHODOLOGY

The methodology used in this work is based on the Life Cycle Assessment (LCA) framework, using a simplified approach that focus more on the inventory (quantity of natural resource extraction, and CO_2 footprint), similar to the methodology adopted by the Environmental Performance in Construction Assessment (ADAC is its acronym in Portuguese[1]) [27]. It consists of an inventory analysis with the objective of quantifying the CO_2 emission of the production of concrete in the city of Rio Branco, with emphasis on the materials transportation impact.

The methodology for calculating the CO_2 emissions of concrete considered the material's production and transportation to Rio Branco, as shown in Figure 2. All emission factors were adopted from Sidac database, as the data is up to date. The details for the method are described in item 2.1. Thus, first, it was assessed the CO_2 emissions for cement and aggregates production and transportation to Rio Branco. Then, the CO_2 emissions of a local mix design of concrete grade C25 (f_{ck} = 25 MPa) was calculated from the present methodology and the results were compared to the same mix design of C25 calculated using Sidac product calculator (details in item 2.2). Finally, it was calculated the maximum and minimum CO_2 emissions of concretes C15 to C35 and the results were compared to generic ready-mix concrete (C20 to C35) products available in Sidac database.

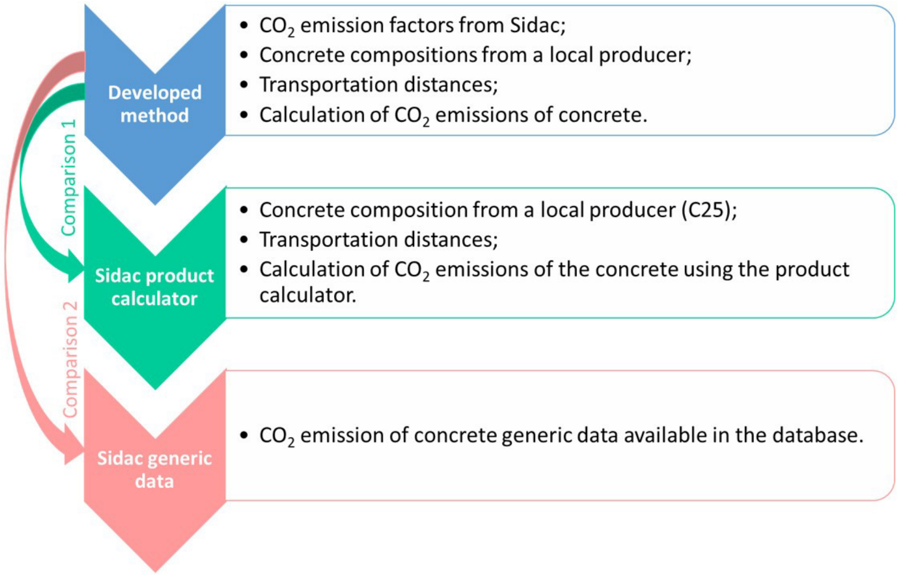

Figure 2. Flowchart of the methodology adopted in this study.

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[1] Avaliação do Desempenho Ambiental da Construção.

2.1 Method to calculate CO_2 emissions of concrete

CO_2 emissions of concrete comprise the emission of the materials' production ($E_{CO2,M}$) and their transportation to the place where concrete will be produced ($E_{CO2,T}$), a "cradle-to-gate" framework, like it is presented by the Equation 1.

$$E_{CO2,conc} = E_{CO2,M} + E_{CO2,T} \tag{1}$$

In the assessment, Rio Branco was considered the only destination of the materials, whereas their origins were defined consulting local concrete plants. The materials analyzed in transportation over long distances were cement and crushed stone, as they are constituents of concrete which are not produced in the city. The transportation distance of the sand was considered fixed (one single value) because its extraction takes place within Rio Branco, not being transported over long distances. The road modal was adopted as the only means of transportation.

2.1.1 CO_2 emission factors

CO_2 emissions from raw materials used to produce concrete are the sum of the emissions from energy consumed in the production of the materials, electricity and fuels, and the emissions originated in the process due to chemical reactions [28], when they occur.

The unitary emission of cement ($E_{CO2,cem}$), given in $kgCO_2/t_{cement}$, was calculated from Equation 2.

$$E_{CO2,cem} = \%_{clinker} \cdot EF_{clinker} + \%_{SCMs} \cdot EF_{SCMs} + E_{energy,cem} \tag{2}$$

Where: $\%_{clinker}$ is the clinker content and $EF_{clinker}$ is the emission factor from clinker production, which includes the emission from limestone decarbonation and the energy to produce clinker (fossil fuels and electricity); $\%_{SCMs}$ is the content of supplementary cementitious materials (SCMs) and EF_{SCMs} is the emission factor of SCMs, which includes the energy to produce SCMs (fossil fuels and electricity); and $E_{energy,cem}$ is the emission from electricity used in cement production during milling of clinker with SCMs.

This study limited the analysis to two types of cement with different clinker content according to the Brazilian standard, shown in Table 1. Emission factors of clinker, calcined clay and limestone fillers, such as the CO_2 emissions from energy used in cement production were adopted from Sidac data [30] and are presented in Table 2. When blast furnace slags and fly ash are used as SCMs, the emission of SCMs is considered zero.

Table 1. Cement types and their proportions according to the Brazilian standard NBR 16697 [29].

Cement ID	Cement type	Clinker content	Addition	Addition content
C1	CP V – ARI	90 – 100%	Limestone filler	0 – 10%
C2	CP IV	45 – 85%	Calcined clay	15 – 50%

Table 2. Emission factors of raw materials and energy consumed. Range (min-max) values from Sidac database [30].

CO_2 emission source	Emission factor ($kgCO_2/t_{material}$)
Clinker	845.1 – 1049
Calcined clay	144.4 – 435.6
Limestone filler	0.6 – 7.2
Sand	0 – 12.51
Crushed stone	0 – 4.67
Energy - cement	2.5 – 4.6 [2]

Besides cement, the other materials composing concrete are fine and coarse aggregates, and water. The emission of the aggregates production was also collected from Sidac database [30]. CO_2 emissions from aggregates include the energy

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[2] Calculated considering the electricity consumption of 51 kWh/t of cement ± 2 times the standard deviation of 7.3, and 0.07 $kgCO_2/kWh$ [31].

consumed during the extraction and production process, once there is no chemical reaction like in the cement production. CO_2 emissions related to water extraction and its availability to consumption are not considered in this study.

The fuel emission factor adopted in this study was 2.29 $kgCO_2/L_{diesel}$ from Sidac database [30], which considered the emission by direct diesel combustion and the percentage of biodiesel present in Brazilian diesel (defined as 13%). For the electricity use it was considered 0.07 $kgCO_2/kWh$, published by Sidac [30], which considers the Brazilian electric matrix composition.

2.1.2 Material's consumption of concrete

According to the local ready-mix concrete producers, some of the Brazilian methods of mix design for determining the materials consumption, as ABCP method, are not applicable for the concrete of the region, which uses sand from Acre River (Rio Acre). The granulometry of sand is fine (fineness of 0.9), implying in a greater demand of water and, consequently, a greater consumption of cement in experimental dosage concrete mixes. Thus, this study considered the mix designs of a local concrete plant for different concrete grades, varying from C15 to C35. The materials were cement, sand and crushed stone (0 – 6.3 mm) as fine aggregates, crushed stone (9.5 – 19 mm) as coarse aggregate and superplasticizer admixture. The granulometries of aggregates are similar to the work of Santos [32].

Table 3 presents the material consumptions for each mix design based on the estimated f_{ck} (characteristic of compressive strength) at 28 curing days. In this work, the same materials consumption of concrete was adopted for the two different types of cement considered. It seems reasonable since the effect of granulometry of the aggregates will be the mandatory and it is constant for both cements used.

Table 3. Materials consumption for one cubic meter of concrete

Concrete grade	**Estimated f_{ck} (MPa)**	$C_{i,conc}$ **(t/m³)**			
		Cement	**Fine Sand**	**Crushed stone (0-6.3 mm)**	**Crushed stone (9.5 – 19 mm)**
C15	15	0.350	0.484	0.322	1.023
C20	20	0.400	0.456	0.304	1.029
C25	25	0.426	0.438	0.294	1.026
C30	30	0.450	0.423	0.279	1.017
C35	35	0.464	0.409	0.265	1.017

2.1.3 Fuel consumption in transportation

The CO_2 emission during the materials transportation by road was determined by the fuel consumption multiplied by its emission factor. Many factors can influence the fuel consumption, such as the travel distance, vehicle efficiency, load capacity, fuel type, road conditions, driving preferences, weather, and others [33]. In this study, the fuel consumption was simplified as the traveled distance divided by the efficiency of the vehicle. Diesel was considered the only fuel type. The distances included the round trip with loaded truck in the way out and empty truck on the way back.

Minimum and maximum emission conditions were considered for vehicle efficiency, from two types of road train trucks (*bitrem*) with different diesel consumptions based on the work of Campos [34], as shown in Table 4. The information about considered load weights were obtained from concrete plant producers, adopting the maximum load weight for the minimum emission condition and the minimum load weight for the maximum emission condition. Furthermore, according to concrete producers in the region, there is no supply of bulk cement to Rio Branco.

Table 4. Load weight and efficiency of vehicles.

Emission condition	**Vehicle type**	**Load weight, P_v (t)**	**Truck weight (t)**	**Diesel consumption factor (L_{diesel}/t.km)**	**Vehicle efficiency (km/L_{diesel})**	
					Empty, $e_{f.e}$	**Loaded, $e_{f.l}$**
Minimum	Volvo FH 440 6x2	48.0	9.2	0.004	27.17	4.37
Maximum	Volvo FH 520 6x4	38.0	9.2	0.015	7.25	1.41

Table 5 presents the main cities of origin of the materials. This study considered the two types of cement presented in the previous section (C1 and C2))), each one from a different city of origin, and two cities of origin of crushed stone (B1 and B2). Road distances were collected using GoogleMaps [35], considering the shortest route simulated by the website. It was established a fixed distance for sand because its transportation takes place within Rio Branco. The cement C2 is constituted by clinker from Nobres (MT), which is transported to Porto Velho (RO) where it is mixed with calcined clay from the region, packed and distributed. Thus, the considered distance was from Nobres to Rio Branco. Figure 3 shows a map including the states of origin and destination of the materials and the transportation roads.

Table 5. Cities of origin of the materials and their distances to Rio Branco

Material	City of origin	Distance to destination (km)
Sand A	Rio Branco (AC)	20
Crushed stone B1	Porto Velho (RO)	510
Crushed stone B2	Vista Alegre do Abunã (RO)	250
Cement C1	Sete Lagoas (MG)	3,592
Cement C2	Nobres (MT) (clinker)	1,844
	Porto Velho (RO) (calcined clay)	510

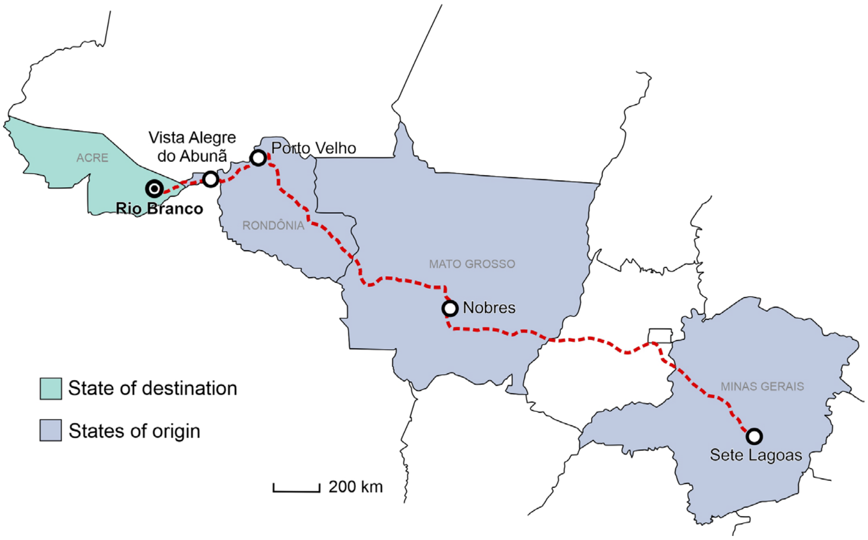

Figure 3. Map of Brazil showing the states of origin and destination of the materials and the transportation roads collected using GoogleMaps (2022).

2.1.4 CO_2 emissions from transportation

Based on the methodology presented above, Equation 3 is proposed to determine the CO_2 emissions from the transportation of concrete materials ($E_{CO2,T}$), given in kgCO_2/m^3 of concrete. The development of the equation is detailed in Appendix A.

$$E_{CO2,T} = EF_F \cdot \frac{e_{f,l}+e_{f,e}}{e_{f,l} \cdot e_{f,e} \cdot P_v} \sum_{i=1}^{n=3} \left(C_{i,conc} \cdot d_i \right) \tag{3}$$

Where, EF_F is the fuel emission factor (kg CO_2/L), $e_{f,e}$ is the efficiency of the empty vehicle (km/L), $e_{f,l}$ is the efficiency of the loaded vehicle (km/L), P_v is the maximum load capacity of the vehicle (t), i is the type of material (cement, sand or gravel), $C_{i,conc}$ is the consumption of material i necessary to produce 1 m^3 of concrete (t/m^3) and d_i is the transportation distance of the material i (km).

2.2 CO_2 emissions of concrete C25 using Sidac product calculator

The CO_2 emissions of concrete C25 were calculated using the Sidac product calculator from the data adopted in this study, i.e., type of materials, mix proportions of the local concrete C25 and transportation distances. The objective was to assess the variation in CO_2 emissions resulting from different methodologies between this study and Sidac product calculator. The main differences relied on the materials emission factors, in which Sidac uses a medium value, and the transportation method of calculation, in which it is used a single vehicle efficiency and consider the same efficiency for empty and loaded trucks.

3 RESULTS AND DISCUSSION

3.1 CO_2 emission of cement and aggregates

The results of CO_2 emission from each cement are shown in Figure 4. Cement C1 presented minimum and maximum emissions of 809 and 1,237 $kgCO_2/t$ of cement respectively, whereas cement C2 had a lower emission range, from 478 to 1,056 $kgCO_2/t$. The difference between cements relies on both production and transportation stages. In the production stage, cement C1 had a greater emission range due to the higher clinker content of the CP V-ARI cement type, compared to cement C2 (CP IV), which had higher substitution of clinker for calcined clay. In Brazil, 63% of the CO_2 emissions of the cement production process, without accounting the transport, it occurs in consequence of the chemical reactions [28]. Regarding the transportation stage, the distance from the factory to Rio Branco is greater for cement C1 as well, reaching 3,592 km, thus the transportation can contribute with up to 15% of the emissions from this cement.

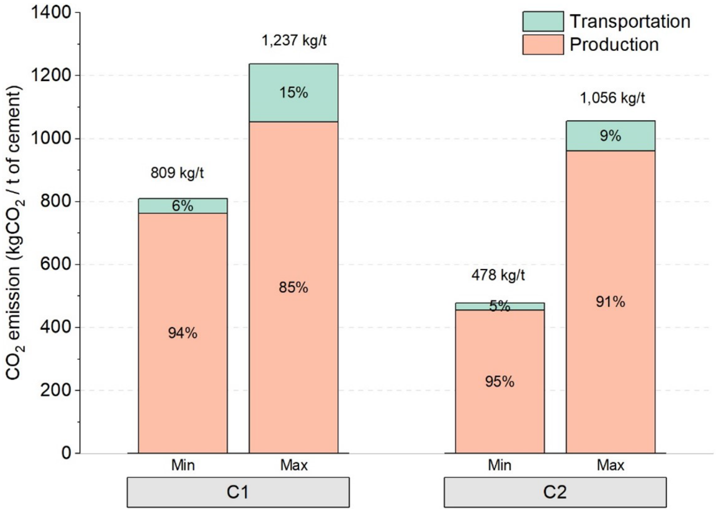

Figure 4. Minimum and maximum CO_2 emissions of cements considered in this study.

The values found in this study differ significantly from the emissions reported in the literature. In the Brazilian scenario, Lima [25] indicated a total cement emission in the range of 603 to 714 $kgCO_2/t$ of cement. Souza [31] calculated 590 and 840 $kgCO_2/t$ of cement for low and high emission cement, respectively, where the materials' transportation in São Paulo did not reach 1% of the total CO_2 emissions. In an international scenario the values found also differ significantly. In China, for example, a blended Portland cement emits around 543 $kgCO_2/t$ of cement, and transportation is responsible for 2.5% of the total emission.

For the aggregates, the calculated emission ranges are displayed in Figure 5. The minimum CO_2 emission from sand was 0.25 $kgCO_2/t$ because it was considered zero emission from production. For the maximum CO_2 emission from sand (13.5 $kgCO_2/t$), production was responsible for 92% of the total emission. The difference between minimum and maximum CO_2 emissions of the crushed stones (3.17 to 30.7 $kgCO_2/t$) consisted mostly of the transportation stage, which was responsible for 85% of the maximum value, in which the aggregate was transported for 512 km. Similar to cement, the aggregate emissions in this work were higher than other values founded in Brazilian studies, such as 2.75 $kgCO_2/t$ obtained by Souza [31] and 23.0 $kgCO_2/t$ calculated by Lima [25] and Marcos [36]. This is mainly due to transportation distances considered in this study, which are far above to the ones of the Southern region of Brazil.

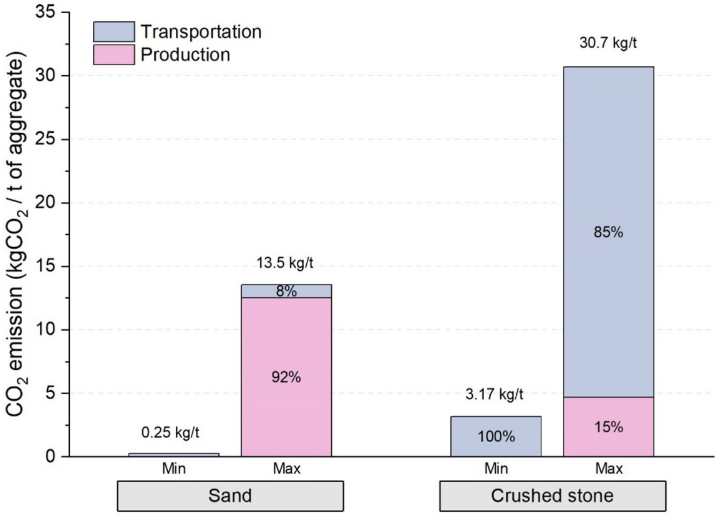

Figure 5. Minimum and maximum CO_2 emissions of aggregates.

3.2 Analysis of CO_2 emission from concrete C25

Figure 6 presents the CO_2 emissions per cubic meter of concrete for C25 concrete produced with C1 and C2 cements. Cement production was the factor that most contributed to concrete emissions, regardless the type of cement. However, in the case of concrete produced with C1, the transportation of cement and aggregates were together responsible for up to 20% of the total concrete emissions, which added up 113 $kgCO_2/m^3$ of concrete to a maximum of 573 $kgCO_2/m^3$. This value is far above the emission ranges of Brazilian references [37], which point to a maximum emission of approximately 350 $kgCO_2/m^3$ of concrete for this concrete grade. The concrete produced with C2 cement showed lower emissions, in the range of 208 to 496 kg CO_2/m^3 of concrete. Thus, in this study case, the value of 5% generally adopted to concrete emissions from raw materials transportation does not apply.

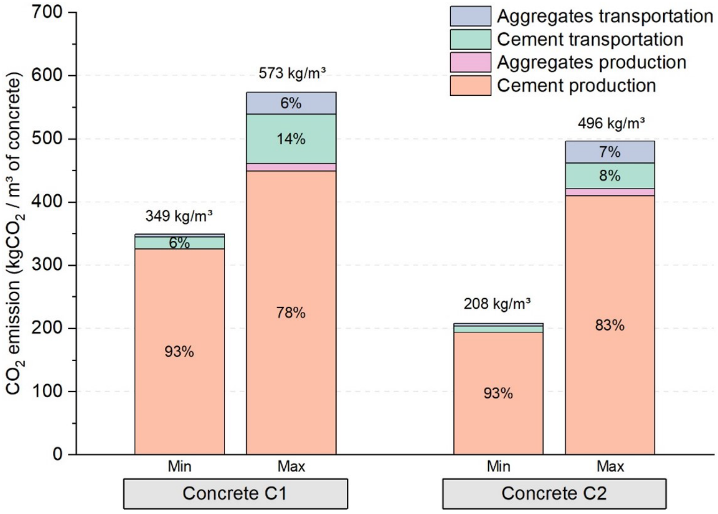

Figure 6. Minimum and maximum CO_2 emissions from C25 concrete with C1 and C2 cements.

The large variation between the minimum and maximum emissions found in Figure 6 is mainly due to the range of emissions from cement production. However, in the maximum emission conditions, the transportation stage was considerable. The parameter with the larger influence in the transport emission is the fuel consumption factor, a value that depends on the transportation distances, type of vehicle, vehicle efficiency, transported load and others [33]. For long distances, the difference in fuel consumption accentuates emissions.

Figure 7 presents the values of CO_2 emissions from the same C25 concrete but estimated from Sidac calculator tool and its database, available in its website[3] [30]. It is observed that the maximum emission values of both concrete produced with cement C1 and C2 were similar to the ones calculated in this study. However, the minimum values estimated by Sidac calculator were considerably higher than from this study calculation, for both production and transportation stages. In the production stage, this happened because Sidac database considers a medium value of clinker in the composition of the cements, while in this study was consider the minimum and maximum clinker content indicated by the Brazilian standard for Portland cement, ABNT NBR 16697 [29]. In the transportation stage, Sidac database considers only one type of vehicle, differently what was considered in this study, and simplifies the calculation by adopting the same vehicle efficiency for empty or loaded trucks.

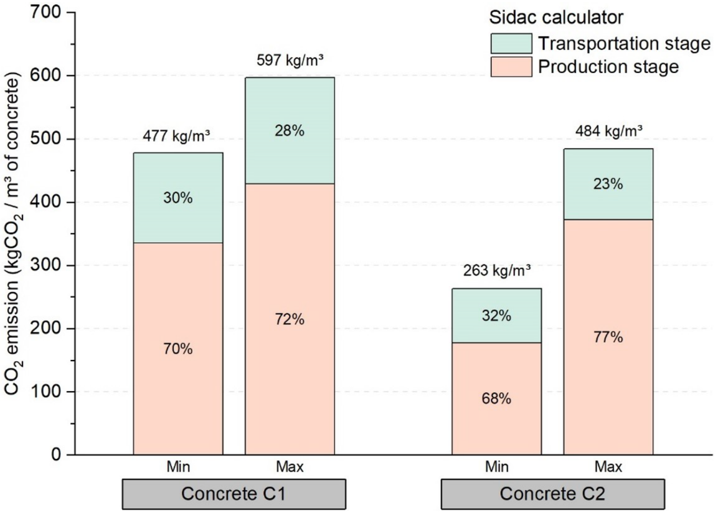

Figure 7. Minimum and maximum CO_2 emissions from C25 concrete estimated using the Sidac calculator and its database.

3.3 CO_2 emissions of different concrete strength: comparison with Sidac database

The emissions for concretes of different strength with C1 cement are calculated. There is an increase in the emissions with increasing strength (Figure 8). C15 concrete has a maximum emission of 481 $kgCO_2/m^3$, while C35 concrete has a maximum emission of 619 $kgCO_2/m^3$. The increase in emissions was due to increasing cement consumption. For all strength values, the transportation stage obtained similar proportions in relation to the total emission of concrete, approximately 7% for the minimum emissions and 20% for the maximum emissions of each mix.

Figure 8 also presents the CO_2 emissions of different concrete grades obtained in Sidac products, as being an average of Brazilian data. Even the concrete with the lowest strength (and the lowest consumption of cement) presented a maximum emission higher than the Brazilian Sidac estimates [37]. This difference is attributed to two main factors. First, the high cement consumption in the mix design for concretes produced in Rio Branco, since Brazilian methods of dosage were not applicable, being adjusted empirically because of the characteristics of the regional sand (fineness of 0.9) [32]. The cement consumptions of concretes C20 to C35 of Sidac products varied from 0.260 to 0.385 ton of cement per cubic meter of concrete; values much lower than those generally adopted in Rio Branco. Secondly, for the emission in the transportation of materials, a medium value of transportation distances of 564 km for cement and 80 km for crushed stone were considered by Sidac, far below than those found in this study case. Thus, it is possible to conclude that the range of CO_2 emissions from concrete calculated by Sidac Brazilian averages does not include the reality of the city of Rio Branco.

Most of the data considered to calculate the indicators of Sidac's concrete processes refer to the Southeast region of Brazil, which represents 47% of ready-mix concrete production in the country [38]. Thus, although the Sidac database has a representative sample, it does not include extreme conditions observed in specific regions of Brazil, where there is a shortage of some minerals, such as in Acre. Because the cement consumption in this state represents only 1% of the national cement consumption, the impact on national data may be insignificant. Nevertheless, the adoption of the data available in Sidac must be done with caution and analysis of data consistency must be done for specific regions and cases.

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[3] https://sidac.org.br/

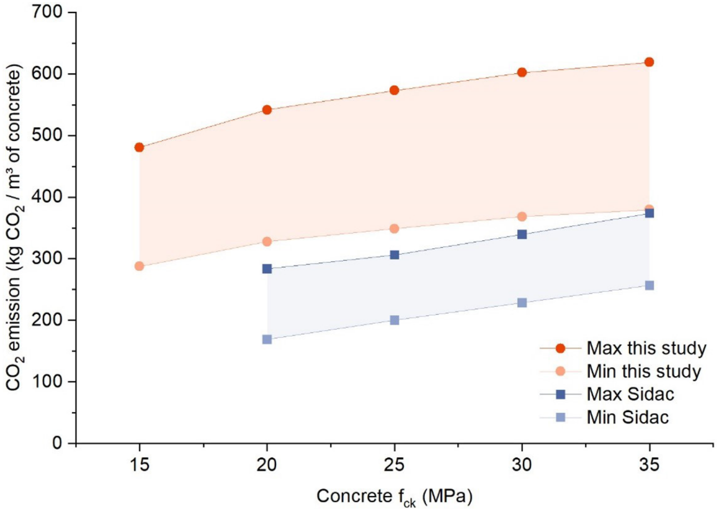

Figure 8. CO_2 emissions for concretes of different grades produced in Acre calculated using the methodology developed in the study in comparison with CO_2 emissions for similar concretes available in the Sidac database.

Thus, because of both higher cement consumption and longer transportation distances, CO_2 emissions of concrete produced in Acre are substantially higher than usual from Brazil. Comparing the results of CO_2 emissions of concrete calculated in this study with some which can be found in Brazilian literature, none are representative to Acre. Oliveira presents the maximum emission for concrete with 20 MPa as 270 $kgCO_2/m^3$ and with 40 MPa as 392 $kgCO_2/m^3$ [39]. Santoro and Kripka present 123 $kgCO_2/m^3$ to concrete with 20 MPa and 168 $kgCO_2/m^3$ to concrete with 40 MPa [40]. The use of generic data must be avoided if possible. Sidac offers cradle-to-gate emission data for different cement types and aggregates, emission factors for various transportation modals as well as a convenient calculator to make the estimative. This certainly allows a more accurate estimative considering actual formulation, transportation distances.

4 CONCLUSIONS

Considering the compositions analyzed in this study, ready-mixed concrete produced in Rio Branco has higher CO_2 emissions than concrete produced in other regions of Brazil. Cement content and transportation of materials contribute significantly to CO_2 emissions in all concrete strength. We estimate emissions of up to 573 $kgCO_2/m^3$ of C25 concrete, where transportation was responsible for 20% of the total emissions. The CO_2 emissions will increase with concrete strength increases.

The transportation fuel consumption is the most influencing factor on the transportation emissions. This value depends on the transportation distances, type of vehicle, vehicle efficiency, transported load and others.

Therefore, Sidac's generic Brazilian data is not representative for the case of the city of Rio Branco and possible other regions with long transportation distances for aggregate or higher cement consumption associated to aggregate characteristics.

We recommend care on use generic data and always consider use other Sidac information to make accurate estimative considering actual transportation distances and cement consumption.

ACKNOWLEDGEMENTS

A. A. L. Pacheco acknowledges CNPq grant number 140054/2020-0 and L. S. Oliveira acknowledges CAPES grant number 88887.463874/2019-00. The authors would like to thank the local specialist who helped with information about the region.

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Author contributions: AALP: conceptualization, formal analysis, investigation, methodology, visualization, writing – original draft; LSO: conceptualization, formal analysis, investigation, methodology, visualization, writing – review and editing; VMJ, SCA: conceptualization, investigation, supervision, writing – review and editing.

Editors: Edna Possan, Mark Alexander

APPENDIX A – Development of the equation of CO_2 emissions from materials transportation

This Appendix presents the development of the equations for calculating CO_2 emissions from materials transportation.

First, it is understood that the CO_2 emission from transportation of a material i ($E_{CO2,Ti}$), in $kgCO_2$, occurs from burning the fuel and it is obtained by the fuel consumption multiplied by its emission factor, as shown in Equation A1.

$$E_{CO2,Ti} = EF_F \cdot C_F \tag{A1}$$

where, EF_F is the fuel emission factor ($kgCO_2/L$) and C_F is the fuel consumption (L).

The fuel consumption (C_F), in liter (L), modeled for the round trip of the vehicle, can be written as shown in Equation A2.

$$C_F = \frac{d}{e_{f,l}} + \frac{d}{e_{f,e}} \tag{A2}$$

where, d is the traveled distance (km) and $e_{f,l}$ and $e_{f,e}$ are the efficiencies of the loaded and empty vehicle, respectively (km/L_{diesel}).

To determine the fuel consumption of transporting each material to produce one cubic meter of concrete ($C_{F,i}$), in L/m^3, the fuel consumption should be multiplied by the number of trucks needed for transporting this material. The estimate of the number of trucks is made by the consumption of the material *i* necessary to produce one cubic meter of concrete as function of the vehicle's load capacity, as shown in Equation A3.

$$C_{F,i} = \frac{C_{i,conc}}{P_v}\left(\frac{d_i}{e_{f,l}} + \frac{d_i}{e_{f,e}}\right) \tag{A3}$$

where, i is the type of material (cement, sando or gravel), $C_{i,conc}$ is the consumption of a material *i* necessary to produce 1 m^3 of concrete (t/m^3), P_v is the maximum load capacity of the vehicle (t) and d_i is the transportation distance of the material *i* (km).

Finally, as the CO_2 emission from the transportation of concrete materials ($E_{CO2,T}$), given in $kgCO_2/m^3$ of concrete, is the sum of the emission of transporting each material, we arrive at Equation A4 and its simplification, Equation A5, the last one presented in the body of the work.

$$E_{CO2,T} = EF_F \cdot \sum_{i=1}^{n=3}\left(\frac{C_{i,conc} \cdot d_i}{P_v \cdot e_{f,l}} + \frac{C_{i,conc} \cdot d_i}{P_v \cdot e_{f,e}}\right) \tag{A4}$$

$$E_{CO2,T} = EF_F \cdot \frac{e_{f,l} + e_{f,e}}{e_{f,l} \cdot e_{f,e} \cdot P_v} \sum_{i=1}^{n=3}\left(C_{i,conc} \cdot d_i\right) \tag{A5}$$