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

ORIGINAL ARTICLE

Feasibility analysis for implementing CO_2 curing in a concrete block industry in the São Paulo Region

Análise de viabilidade para implantação de cura com CO_2 em uma indústria de blocos de concreto na região de São Paulo

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Received: 25 February 2022
Accepted: 17 October 2022

Abstract: The project feasibility analysis determines whether the project should be carried out from different spheres: strategic, technical, operational, legal, economic-financial, environmental, marketing, political, fiscal, location, among others. These are not excluding analyzes, all aspects must be assessed before implementing a new project or new process. This work will focus on the analysis of the technical feasibility of the innovative project to implement carbonation curing in a concrete block factory in the region of São Paulo. An overview of the CO_2 curing process and changing needs is presented, including identifying local CO_2 sources and delivering cost, gas consumption for chamber saturation, estimation of CO_2 uptake by masonry units during curing, estimation of consumption and monthly cost of CO_2, curing chamber changes needs, new equipment acquisition, estimation of cost for retrofit and new installations, potential best definitions on optimal temperature, humidity, and CO_2 concentration. International succeeded cases are presented. The study concludes that the technology can be easily implemented in the region, with few changes on a plant production process and on the curing chamber. There would be an increase of 4% to 14% on the block cost depending on the distance to the CO_2 supplier. Considering the Brazilian production of concrete blocks, up to 168,780 tons of CO_2 per year can be sequestered, this value is equivalent to the CO_2 sequestered by 21,100 trees.

Keywords: analysis, feasibility, technical, curing, CO_2.

Resumo: A análise de viabilidade de projetos determina se o projeto deve ou não ser colocado em prática e pode ser realizada a partir de diferentes esferas: estratégica, técnica, operacional, legal, econômico-financeira, ambiental, mercadológica, política, fiscal, localização, entre outras. As referidas análises não são excludentes, por conseguinte, é possível que para um único projeto sejam realizadas todas elas. No entanto, este trabalho terá enfoque na análise da viabilidade técnica do projeto inovador de implementação da cura química com CO_2 em fábrica de blocos de concreto na região de São Paulo. Para tanto, será apresentada uma visão geral do processo de cura com CO_2 e possíveis modificações para realizá-la na indústria, além da identificação de fontes locais de CO_2 e custo de entrega, necessidades de mudanças na câmara de cura, aquisição de novos equipamentos, possíveis melhores definições sobre temperatura ideal, umidade e concentração de CO_2. Casos de sucesso internacionais são apresentados. O estudo conclui que a tecnologia pode ser facilmente implantada na região, com poucas mudanças no processo produtivo da planta e na câmara de cura. Dependendo da distância da fábrica ao fornecedor de CO_2, poderá haver um aumento de 4% a 14% no custo do bloco. Considerando a produção brasileira de blocos de concreto, até 168.780 toneladas de CO_2 por ano podem ser sequestradas, este valor equivale ao sequestro de CO_2 realizado por 21.100 árvores.

Palavras-chave: Análise, viabilidade, técnica, cura, CO_2.

How to cite: L. R. Fortunato, G. A. Parsekian, and A. Neves Junior, "Feasibility analysis for implementing CO_2 curing in a concrete block industry in the São Paulo Region," *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 6, e15607, 2022, https://doi.org/10.1590/S1983-41952022000600007.

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Financial support: National Council for Scientific and Technological Development (CNPq) Grant (443831/2018-1).
Conflict of interest: Nothing to declare.
Data Availability: The data that support the findings of this study are available from the corresponding author, [FORTUNATO, L. R.], upon reasonable request.

1. INTRODUCTION

Accelerated carbonation curing or CO_2 chemical curing of concrete blocks is an innovation. According to the Oslo Manual [1], innovating means implementing a new or significantly improved product (good or service). However, chemical curing with CO_2 should not be considered just an innovation, but a sustainable innovation. According to Barbieri et al. [2] innovation and the sustainable development of organizations are one most important social movement today, since there is a global need to replace old means and practices with others that translate the principles, objectives, and guidelines new movement. When committing to sustainable development, the company must, at the very least, change the way it operates, to create strategies to reduce social and environmental impacts.

By implementing the sustainable innovation of accelerated carbonation curing, the Brazilian concrete block industries will contribute on a world scale to the reduction of global warming, reduction of water and electric energy consumption. Furthermore, they will have the benefit of reduced curing time and blocks will acquire final strength much more quickly, reducing waiting time in the industrial yard and providing faster production.

To carry out the chemical curing with CO_2, the newly manufactured unreinforced cementitious products are introduced into a carbonation chamber with adequate concentrations of CO_2, humidity, temperature, and pressure, and at the end, in a few hours, the advantages of said curing are verified that are the permanent absorption of CO_2 from the medium and premature gain in mechanical strength [3]–[6]. During curing, the CO_2 reacts with the main cement hydration product ($Ca(OH)_2$), C-S-H, and others) and is transformed into calcium carbonate ($CaCO_3$) and water. The formation of calcium carbonate promotes the permanent sequestration of CO_2 and the gain on mechanical strength, since calcium carbonate precipitates in the concrete pores, in the mineralogical form of calcite, vaterite and aragonite [7].

The idea is to capture the CO_2 emitted from the industries chimneys, use it during carbonation curing and store it permanently in unreinforced cement prefabrications. This cure type is already successfully done in countries such as the United States, Canada, and the United Kingdom, in industries like Carboclave, Solidia Technologies, CarbonBuilt and CarbiCrete [8]. Through this study we intend to analyze the technical and locational feasibility of introducing it in Brazil, more precisely in industries close to the Greater São Paulo area.

2. TECHNICAL FEASIBILITY ANALYSIS

In a technical feasibility study, also called engineering or technology study, it is necessary to understand the production processes to manufacture the product, as well as whether it is possible to produce the product or service to be commercialized in scale. As differentiated as the innovations may be, it is necessary to have coherence between the invention and its usability [9]. This technical feasibility and innovation study will comprise a) Characteristics of the innovation - description of the products, services, and technology to be used; b) Analysis of innovation process components; c) Research of similar processes and products – Success Cases.

2.1 Innovation characteristics

The concrete block industry is one of the links in the construction sector production chain, which includes cement companies, construction companies, equipment manufacturers, real estate companies linked to works and maintenance. The eco-friendly concrete block industry sector, in an unconventional way, embeds CO_2 suppliers.

Producing concrete blocks that store CO_2 is innovative. Through accelerated carbonation curing technology, carbon dioxide is chemically converted into a mineral, calcium carbonate, which definitively precipitates in the concrete pores [10]. It is sustainable, as it meets the need to reduce greenhouse gases in the atmosphere, minimizing the consequences of global warming. To the authors knowledge, technology is non-existent in the Brazilian market.

Some factors make concrete blocks ideal candidates for storing an CO_2. The block hollow geometry and thin walls facilitate the diffusivity of CO_2 inside the unit. Also, this is a large-scale product with increasing use in medium and large urban centers.

Concrete blocks that capture CO_2 also have the advantage of becoming "mature" early, that is, gaining the required compressive strength at an early age. This fact reduces the "dead time" in the industry yard and enables greater productivity. These factors benefit the possibility of practical implementing of chemical curing with CO_2, through which the blocks are placed inside the carbonation chamber with ideal conditions of temperature, pressure, humidity, and CO_2 concentration. At the end of the curing procedure, the block will permanently storage the CO_2 and with improved of mechanical resistance [6], [11].

It is a fact that non-reinforced cementitious precast can absorb CO_2 and gain strength prematurely when subjected to CO_2 curing. Fortunato [6] found that concrete paving pieces, when subjected to curing with carbon dioxide, stored 5.10% of the CO_2 present in the chamber atmosphere. Considering the consumption of cement by the Brazilian unreinforced precast industry in 2019 of 5.66 Mton [12], it would have been possible to capture approximately

290,000.00 ton of CO_2 if all production had been cured with CO_2. This value corresponds to the CO_2 sequestration of 36,250,000.00 trees in a year, since, according to the Totum Institute, a tree sequesters approximately eight kilograms of CO_2 in a year [13]. In addition, the carbonated concrete paving pieces showed superior axial compressive strength at 2-days age than the reference pieces (non-carbonated), although the 28-days were equivalent [6].

2.2 Analysis the innovation process components

2.2.1 Production of concrete blocks that sequester CO_2

The manufacturing process of concrete blocks involves the stages of mix design, in which the materials are proportioned; mixing, generally carried out in an orbital mixer; production (molding) of dry concrete in molds (forms), compaction and vibration through vibrating-pressing machines; curing and storage before delivery [14]. Concrete blocks that store CO_2 are produced in the same way as conventional concrete blocks, regardless of the industry that will produce them. It is not necessary to change the mix proportion, equipment and cycle time. The differentiation takes place in the curing procedure, which, unlike traditional industries, is not through steam or humidity, but with CO_2.

2.2.2 Innovative CO_2 chemical cure technology

The technology in question is a chemical cure that promotes the mineralization of CO_2, that is, the carbon dioxide through the cure is chemically transformed into a mineral, calcium carbonate. The permanent absorption of CO_2 in the pores of the concrete is possible due to the accelerated carbonation reaction. The main carbonation reaction occurs between $Ca(OH)_2$ and CO_2 in the presence of water, as shown in Equation 1.1; and in a second moment, when most of the calcium hydroxide has already been acquired, the occurrence of carbonation of hydrated calcium silicate is reported, as shown in Equation 1.2. These reactions are show below.

$$\mathrm{Ca(OH)_2} + CO_2 \rightarrow CaCO_3 + H_2\mathrm{O} \tag{1.1}$$

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 \cdot 2SiO_2 \cdot 3H_2O \tag{1.2}$$

2.2.3 Studies on the chemical curing process with CO_2 in precast concrete materials without steel reinforcement

According to Fortunato et al. [15] several studies involving the use of accelerated carbonation curing in non-reinforced precast cementitious products have been carried out to develop a curing process to use. Table 1 summaries the related research and the carbonation parameters used.

Table 1. Research involving accelerated carbonation curing in unreinforced cementitious precast.

Authors	Samples	Time and type of initial cure (h)	Carbonation curing time (h)	Carbonation Chamber				CO_2 absorption (%)	Compressive strength
				CO_2 concentration (%)	Pressure (MPa)	T (°C)	RH (%)		
[3]	Cubes (100×100mm) dry concrete	no initial cure	2	100	0.5	environment	-------	7.0 – 8.0	> 40 MPa after 2hs of carbonation
[16]	Concrete masonry units and concrete units for pavement (w/c=0,25)	no initial cure	2	100	0.5	45-95	-------	9.8	10.3 MPa after 2 hours of carbonation ~ 50% increase compared to the reference at 28 days)
[16]	Cement bead board comprised cement paste and expanded polyethylene beads (w/c=0,36)	no initial cure	2	100	0.5	45-95	-------	12.2	7.8 MPa after 2 hours of carbonation, same value was obtained for reference boards at 28 days
[4]	Concrete masonry units	no initial cure	2	100	0.15	environment	-------	8.2 – 10.6	Increase of compressive strength of 78% in relation to the reference
[5]	Concrete units for pavement (10x20x64mm) (w/c=0,4)	2 – 19 wet curing	4 - 5	99,5	0.15	56	65	3.4 -7.4	Tests done after 24 hours of production: 31MPa (after 4hs of carbonation) and 46 MPa (after 5hs of carbonation)
[5]	Zero slump concrete samples (127×76×20 mm)	no initial cure	2	99,5	0.15	40 - 56	65	11.7	9.6 MPa (after 2hs of carbonation) ~ 60% increase compared to the reference at 28 days)

Table 1. Continued…

Authors	Samples	Time and type of initial cure (h)	Carbonation curing time (h)	Carbonation Chamber				CO_2 absorption (%)	Compressive strength
				CO_2 concentration (%)	Pressure (MPa)	T (°C)	RH (%)		
[17]	Cement paste, (14×14×6mm) (w/c = 0.36)	18 wet curing	2	99,5	0.15	environment	-------	8.9	76.8 MPa without water spray and 123,7 MPa with water spray after carbonation
[18]	Zero slump concrete samples w/c = 0,36	18 air curing	2	100	0.15	25	-------	6.9 – 7.3	28.8 MPa without water spray and 38.9 MPa with water spray after carbonation
[19]	Concrete masonry unit w/c=0,40	0, 4, 6, 8, 18 air curing	2, 4, 96	100	0.01	25	50	9.0 – 35.0	Compressive strength with water spray after carbonation comparable to non-carbonated ones with thermal curing
[20]	Concrete masonry units with recycled aggregates	no initial cure	6, 12, 24	100	0.01	--------	-------	22.49- 43.96	Compressive strength gains ranging from 108% to 151% within 24 hours of carbonation
[21]	Concrete masonry unit with blast furnace slag produced in manual factory (127×76×38 mm)	0, 4, 6, 8, 18 thermal curing	2, 4, 96	100	0.1	25	50	8.3 – 35.1	Compressive strength with water spray after carbonation comparable to non-carbonated ones with thermal curing
[22]	Concrete Masonry Units	not executed	2	100	1.39	30	50	8.62	After 2 hours, net compressive strength of 35.72MPa carbonated Concrete masonry units and 10.14MPa steam cured concrete Masonry Units
[15]	Concrete unit for pavement (100×200×60 mm)	12 hours outdoor cure and 12 hours initial steam cure	4 and 16	20	0,1	23	65	1.5% - 5.1%	At 02 days, the compressive strength of the carbonated pieces was superior to the reference and at 28 days too

In Table 1, the non-reinforced cement precast elements that underwent a compaction process for their production were shaded in gray. It was found that only Shao and Lin [5] and Fortunato et al. [15] produced the sample in the industry using a vibro-pressing process, El-Hassan et al. [19] produced blocks in the laboratory using a manual machine. The other studies used samples produced in laboratory obtained by other compaction process rather than using a manual, pneumatic or hydraulic machines, not appropriate for concrete blocks or pavers production [23]. It was observed that in the studies of Shao et al. [4], El-Hassan et al. [19] and Zhan et al. [20] the concrete blocks did not have the dimensions specified by ABNT NBR 6136:2016 and are probably not hollow. It is known that the production/compaction process and the dimensions/formats of prefabricated cementitious products directly affect the speed of the carbonation reaction and the advance of the carbonation front, promoting important variability in the percentage of CO_2 absorbed.

In most studies the concentration of CO_2 inside the carbonation chamber was 100%. The maximum concentration of CO_2 inside the chamber allows the curing of the carbonation to be accelerated by maintaining its objective, which is the maximum production of CaCO3 in the cement matrix.

In the studies of Shao and Lin [5], Fortunato et al. [15], Rostami et al. [17], Boyd et al. [18], El-Hassan et al. [19], El-Hassan and Shao [21] it was possible to verify that the initial curing (open air curing or wet curing) carried out before the carbonation curing, directly interfered in the hydration of the non-reinforced cementitious product, and contributed to strength gain. Non-reinforced cementitious precast not subjected to initial cure absorbed more CO_2 than those submitted to initial wet curing. The hypothesis is that the non-performance of initial wet curing generated less hydration products, reducing the alkaline barrier, providing a greater advance of the carbonation front, allowing more CO_2 to be incorporated into the cement matrix. In all reported studies, the prefabricated cementitious non-reinforced carbonated yielded greater mechanical resistance when compared to the non-carbonated (reference) specimen at the earliest ages. This result is attributed to the fact that carbonation makes the sample premature, that is, its maturation is accelerated, and it gains the expected mechanical properties much faster. Among the unreinforced prefabricated samples reported tests, the concrete blocks absorbed the most CO_2.This is probably due to the smaller thickness of the block walls, allowing greater CO_2 diffusivity.

Further analyses on the literature review are reported in Fortunato et al. [[15]], that concludes the best conditions for carbon cure of concrete blocks are using a chamber at 100% of CO_2 concentration, to perform an initial air cure for at least two hours before carbon cure, the humidity shall be between 50 to 80%, temperature should be up to 60 ºC to maximize carbonation.

2.2.4 Based material – CO_2 captured

The carbon dioxide to be used in curing is captured by specialized companies as AirLiquide and WhiteMartins from emitting sources with high concentrations (> 90% CO_2) and high purity (absence of contaminants such as moisture and/or other gases).

After capture, the CO_2 is purified and liquefied and can be transported by pipeline within the industry itself, as in the case of cogeneration of utility systems in which the CO_2 customer itself uses the CO_2 produced, or else, the captured CO_2 is transported in tank trucks that will supply customers in bulk or go to a filling center, where the CO_2 will be discharged into a tank and later fill the cylinders [24], [25]. Figure 1 demonstrates in a simplified way the CO_2 path from capture to the final customer.

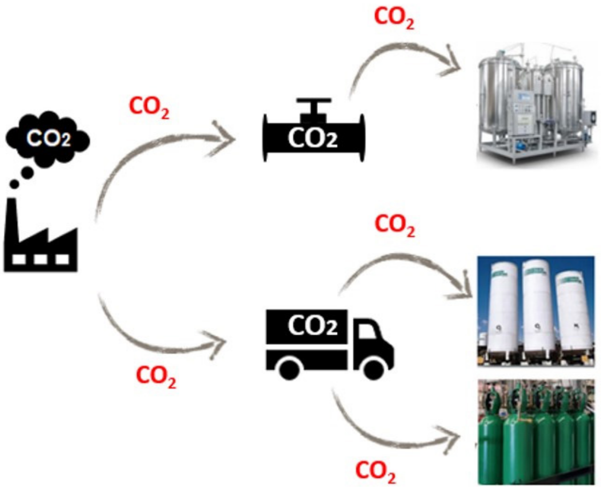

Figure 1. Transporting CO_2 to serve the industry that captured it and other customers (adapted from [[26]]).

To store CO_2 on the premises of Brazilian industries, there is no need for a government-issued environmental license. The supplying companies must only provide a safety data sheet. Since the CO_2 is an inert gas and heavier than air, it can occupy the air space. Every care must be taken to avoid cases of asphyxia. It is important that the tanks are in an open and ventilated place and that the chamber where the curing will be carried out has an efficient exhaustion system [24], [25].

2.2.5 Curing chamber facilities and parameter control equipment

In the case of an existing plant, there is the possibility of retrofitting the existing chambers, if they are perfectly sealed with the installation of appropriate doors, thus avoiding the risk of accidents due to CO_2 leakage. There is also the possibility of installing new designed CO_2 curing chamber, that can be make of masonry or appropriate containers can be used [24], [25]. The control of temperature, humidity, pressure, and CO_2 concentration parameters use equipment such as a manometer to check the internal pressure of the chamber a CO_2 sensor, a temperature sensor, a humidity sensor, among others [27], [28].

2.3 Research of technological processes and similar products – Success Cases

According to Castro [29], in a technical feasibility study, it is necessary to verify if the technology to be used is applied in practice and if the technical knowledge is available. Most companies choose to invest in already used mature technologies in which the problems and adjustment that certainly arise in the development process are already known and solved. Few companies choose to use the technology present only in the state of the art. Some successful cases of industries that apply CO_2 curing in non-reinforced cement prefabricated units are presented below.

2.3.1 Solidia Technologies

- **Company:**

The American start-up Solidia was founded in 2008, with an investment of around US$ 80 million, through investors such as LafargeHolcim, Total, Air Liquide, Oil & Gas Climate Initiative, BASF Venture Capital, BP Ventures, Kleiner Perkins Caufield &Byers, Bright Capital, among others [30].

- **Products sold:**

The company commercializes concrete masonry units and concrete paving pieces that store CO_2, as well as the CO_2 curing technology [31].

- **Manufacture and molding of prefabricated parts that store CO_2:**
The same equipment, trace, cycle time used in the production of traditional prefabricated products are used [32].
- **Accelerated carbonation cure:**
- **Based-material:** according to Meyer et al. [30] the CO_2 used by the company is supplied by AirLiquide and is usually stored in tanks like in Figure 2.

Figure 2. Tank for storing captured CO_2. Source: [33].

- **Installations:** according to Meyer et al. [30] as for the structure of the chamber, the company initially developed a prototype applied in several places of the world with more than 50 tests in companies interested in the technology. Figure 3 shows the test-chamber used by the company to carry out the cure with CO_2 on a small scale.


Figure 3. Solidia test chamber. Source: [33].

By proving the CO_2 absorption and mechanical strength improvements, the technology matured, and permanent carbonation chamber structures were developed across the world. Figure 4 shows carbonation chambers located in the United States, Canada, and the United Kingdom [30].

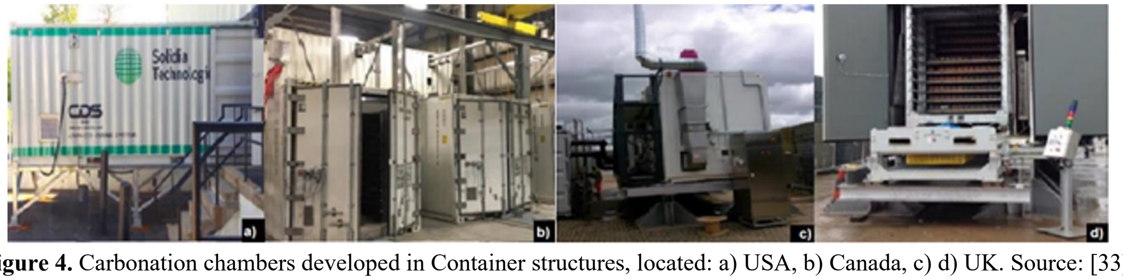

Figure 4. Carbonation chambers developed in Container structures, located: a) USA, b) Canada, c) d) UK. Source: [33].

- **Equipment and accessories:** according to Hall [34] the gas flow in the chamber occurs to ensure uniform evaporation on the surface of all products. This allows batch processing time to be minimized as the slowest curing-time product in the chamber defines the duration of the entire process.

Solidia has designed and built chambers 3.00 m wide x 6.00 m high x 23.00 m long [34]. The devices used for control and ventilation are shown in Figure 5.

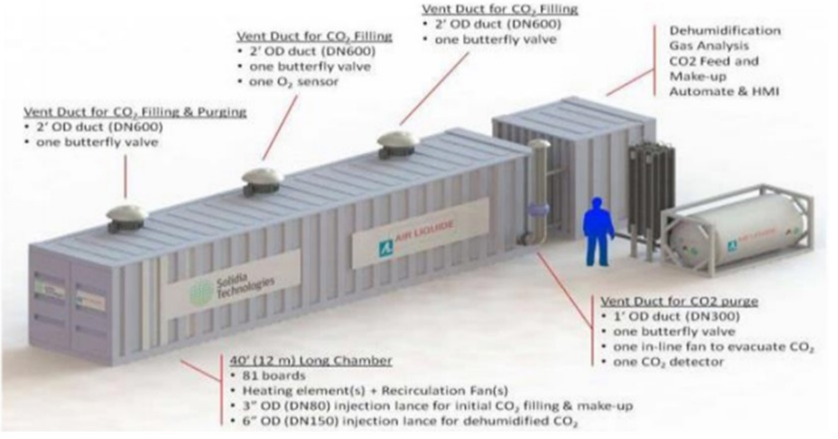

Figure 5. Solidia Carbonation Chamber. Source: [33].

- **Advantages of CO_2 curing:** Jang et al. [31], DeCristofaro et al. [32] and Meyer et al. [30] indicate the following advantages:
- It does not consume water, but CO_2;
- It takes advantage of existing factory facilities, production process, equipment, and raw materials;
- It is adaptable to existing production lines;
- Smart and fast curing, as the compressive strength results of non-reinforced precast cured with CO_2 obtained in 24 hours are equivalent to the compressive strength results of conventional unreinforced precast at 28 days;
- Reduced inventory, due to faster curing time, enabling just-in-time production and delivery;
- Better performance and greater durability than conventional concrete;
- No occurrence of primary efflorescence.

2.3.2 Carboclave

- **Company:**

The company is a Canadian start-up founded in 2016 after demonstrating a series of successes in the development, validation and expansion of the CO_2 curing processing, not only with autoclaving but with all other conventional concrete curing methods.

- **Products sold:**

The company commercializes concrete masonry units that store CO_2, as well as CO_2 curing technology that can be applied to masonry units and pavers [35].

- **Manufacture and molding of prefabricated parts that store CO_2:**

According to Hargest and Al-Ghouleh [35] the process for producing precast products in an airtight enclosure, which comprises the steps of a carbonation of pre-dried concrete precast units by feeding CO_2 , gas into a closed airtight enclosure under near ambient atmospheric pressure (psig between 0 and 2) and/or low pressure (between 2 and 15 psig) conditions, wherein said pre - dried concrete units have lost between 25 to 60% of their initial mix water content. The manufacturing and curing process is shown in Figure 6 below.

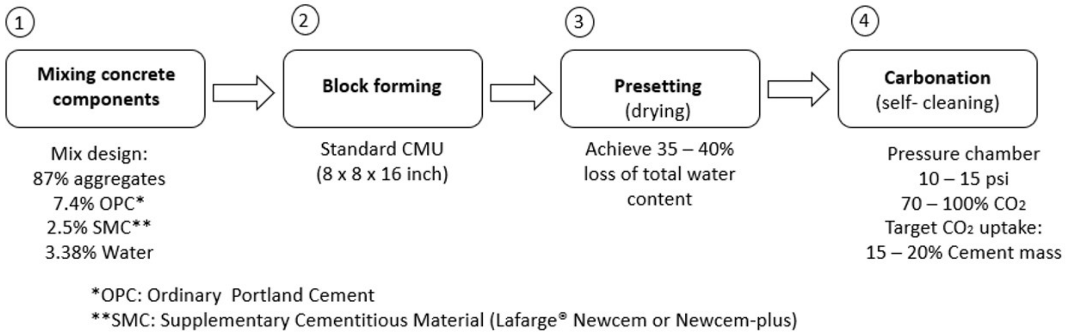

Figure 6. Manufacturing and curing process. Source: [35].

- **Accelerated carbonation cure:**
- **Based-material:** the CO_2 used by the company Carboclave is supplied by the partner Praxair.
- **Installations:** for the chamber structure , the company makes the technology available in two possibilities, retrofit and new installations. When the curing chamber already exist, it is used with adaptations, working with atmospheric pressure. The new chamber is specially designed and built for curing with CO_2 in an autoclave at high pressures. Figure 7 demonstrates a type of curing chamber used by Carboclave.

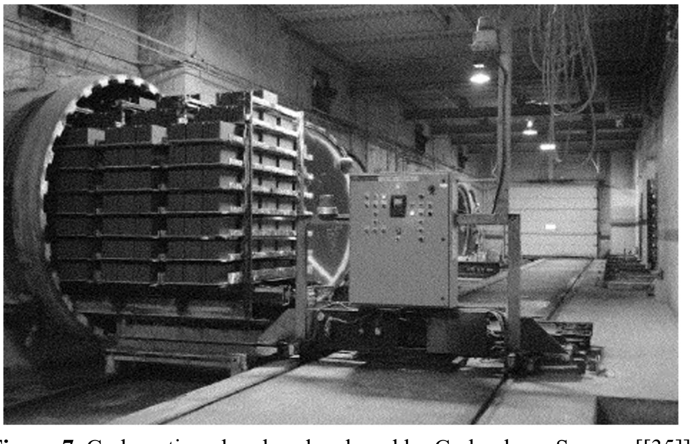

Figure 7. Carbonation chamber developed by Carboclave. Source: [[35]].

- **Equipment and accessories:** according to Hargest and Al-Ghouleh [35] before curing with CO_2, vacuum step is used to exhaust 50 to 90% of the volume of air initially present in the enclosure, then, after the CO_2 injection, applying a pressure greater than atmospheric, which is controlled by a manometer.
- **Advantages of CO_2 curing:** Hargest and Al-Ghouleh [35] verified:
- CarboClave concrete masonry units are 25% more ecological than concrete masonry units, as they absorb up to 250g of CO_2 per 19x19x39cm concrete masonry units;
- Non-reinforced CO_2-cured precast have greater resistance to axial compression than regular ones, greater resistance to freezing/thawing; greater resistance to sulfate attack; greater resistance to drying and atmospheric shrinkage; reduced sensitivity and permeability; and reduced efflorescence effect.

2.3.3 CarbonBuilt

- **Company:**

CarbonBuilt was created in 2014 at the Institute for Carbon Management at the University of California, Los Angeles (UCLA). In 2020, with support from the US Department of Energy and NRG COSIA Carbon XPRIZE, they took the prototype off paper and developed CO_2 curing in practice [36].

- **Products sold:**

The company sells reverse technologies for industries which seek to make a beneficial use of the CO_2. Accelerated carbonation curing is one of them. They are producing concrete masonry units that absorb CO_2 and soon they intend to expand the range of ecological non-reinforced prefabricated elements. They develop projects in the United States, Europe and India [37].

- **Manufacture and molding of prefabricated parts that store CO_2:**

The same equipment, mix proportion, cycle time used in the production of traditional prefabricated products are used [36].

- **Accelerated carbonation cure:**

- **Based-material:** the CO_2 used comes from the plant that emits it [37]. Figure 8 shows the CO_2 piping coming from a thermoelectric plant, the gas will be sent to the carbonation chamber installed on the thermoelectric plant infrastructure.

Figure 8. Pipe containing the CO_2 that will be injected into the carbonation chamber. Source: [[38]].

- **Installations:** for the structure of the chamber, an adapted container was used for the loading of concrete masonry units through forklifts. Figure 9 shows the container-chamber [38].

Figure 9. Container-chamber. Source: [38].

- **Equipment and accessories:** the chamber is controlled by CO_2, humidity, and temperature sensors [39]. Figure 10 demonstrates their inspection.

Figure 10. Chamber control: a) CO_2 injection configuration, b) temperature measurement. Source: [[38]].

- **Advantages of CO_2 curing verified by the company:**

The main advantage emphasized by the company is the definitive incorporation of CO_2 in the concrete and the removal of this environmental liability from the atmosphere [39].

2.3.4 Carbicrete

- **Company:**

CarbiCrete is a Canadian company that commercializes CO_2 absorption technology in concrete masonry units and pieces for paving through accelerated carbonation curing. The company's patented technology was developed at McGill University and includes the production of concrete by replacing cement with steel slag [40].

- **Products sold:**

The company licenses the technology to concrete masonry units (CMUs) and precast panels; and oversees the retrofit for implementation of the process in the industry [40].

- **Manufacture and molding of prefabricated parts that store CO_2:**

According to Hahn [40] the same equipment and cycle time used in the production of traditional prefabricated products are used. The composition has replacement of cement by steel slag.

- **Accelerated carbonation cure:**
- **Raw-material:** the CO_2 used by the company Carbicrete is supplied by the partner Praxair and is stored in tanks [41].
- **Installations:** the possibility of retrofitting existing chambers and new installations using an adapted container was reported. Figure 11 demonstrates the container-chamber [41].

Figure 11. Container-chamber. Source: [41].

- **Equipment and accessories:** the chamber is controlled by CO_2, pressure, humidity, and temperature sensors. It was reported that the curing procedure with CO_2 lasts from 5 hours to 6 hours [41].
- **Advantages of CO_2 curing:** according to [41]:
- High strength gain before 24 hours after curing with CO_2;
- Compressive strength of CO_2 cured concrete masonry units is 30% than conventionally cured concrete masonry units;
- According to the company, to produce a conventional concrete masonry unit, 2kg of CO_2 is generated, while the concrete masonry units cured with CO_2 is negative (-1kg), since the CO_2 is absorbed.

4. FEASIBILITY TO LOCATION

4.1 Location

According to Corrêa and Corrêa [42] decisions related to the location of the implementation of an enterprise are expensive and difficult to reverse, given that the location of an operation affects both its ability to compete and other internal and external aspects. The location directly affects the transport costs of inputs and final product, labor costs (since different regions may have different salary levels) and cost and availability of energy, in addition the choice of location influences directly on expenses, investments and even revenues. The location study has as main objective to determine the best place for the enterprise. This location, also known as the optimal location, can be understood as the one that gives the project the best cost/benefit ratio in an adequate period.

4.2 Location Variables

Location variables are factors that must be considered when choosing the ideal location for the enterprise. In general, the availability of raw materials, proximity to the consumer market and/or factors related to the production process must be considered. The analyzes must weigh between the main expenses and gains with these choices, and will be better described below [43]:

- As for the availability of raw materials: when this requires large volumes and transport is difficult or distant, it is recommended that the location of the enterprise is close to the sources of inputs;
- Regarding the consumer market: If the focus of the enterprise is the relationship with customers, the location must be close to the consumer market;
- Regarding the production process: some production processes may require certain conditions to take place, for example, they may need a source of water nearby for cooling or being close to a power substation for their perfect functioning, among others. However, it is desirable that the location of the unit is aligned with the needs of the production process.

5. TECHNICAL AND LOCATION FEASIBILITY FOR THE SÃO PAULO REGION

5.1 Methodology

In order to verify the technical feasibility and location for the implementation of CO_2 curing in concrete block factories located in the São Paulo region, several rounds of brainstorming were carried out with concrete block manufacturers, which were recruited by Associação Bloco Brasil, as well as meetings with Brazilian CO_2 suppliers. From the discussion, the equipment, material and other needs were assessed and listed, both for the case of a new or retrofit chamber. The CO_2 suppliers and block producers plant location were identified with the state. The materials, equipment, CO_2 and other supplies costs were assessed, as well as the estimated initial cost for a new or retrofit chamber. From the literature review the efficiency of the carbon cure was estimated. From this data it was possible to assess the technical and location feasibility for concrete block carbon cure implementation in the São Paulo region.

5.2 Based-material – captured CO_2

The supply of captured CO_2 is possible and viable to be carried out in the state of São Paulo, with more than one company supplying this gas. The carbon dioxide must be transported from the captured CO_2 producer to the concrete block plant using tank trucks. Then, it will be stored in tanks located in the concrete block plant premises and will later be transported through pipes provided and installed by the CO_2 supplier to the accelerated carbonation curing chambers.

For the installation and operation of the CO_2 tank, there is no need for a government environmental license. The gas is inert, does not explode and is not inflammable, but it must be stored in a well-ventilated place, as it can cause suffocation.

5.3 Installations

The CO_2 chamber can be new or can be adapted from the existing infraestructure. In both cases, airtightness must be guaranteed. Figure 12a shows a model of a new installation, like a cold chamber with temperature, humidity, and airtightness control, made in Brazil and which can be used, with the necessary adjustments, in the concrete masonry units manufacturing industry with the purpose of carrying out curing with CO_2.

Figure 12. Proposal for carbonation chambers: a) new installation; b) retrofit. Source: Author (2021).

Figure 12b shows a steam curing chamber used in an large concrete block plant located in the Great São Paulo region. To use this chamber there is the need of installing doors, control equipments, a exhaust system and the CO_2 supplier pipeline.

The analysis will be carried out considering a curing chamber with concrete masonry walls and reinforced concrete structure slab. For the installation of the CO_2 curing chamber, it must be ensured:

- **Airtight**

The airtightness of the chamber must be guaranteed by installing a guillotine door or sliding door in which carbon dioxide leakage is guaranteed no occurrence and the walls and ceiling must also be waterproofed to ensure that CO_2 does not escape through cracks or crevices. The indicated wall treatment is to apply a semi-flexible two-component waterproofing coating that shall also provide airtightness.

- Thermal insulation

Thermal insulation is important to standardize the curing procedure and prevent temperature changes from interfering with the process. Therefore, it is recommended that the walls and ceiling of the chamber be coated with insulating material such as isopanels composed of profiled steel sheets interspersed with polyisocyanurate.

- **CO_2 input**

The entry of CO_2 should occur in the lower region of the chamber. The pipeline from the tank to the chamber is designed by the CO_2 supplier. It is made of stainless steel and must have a pressure regulator before entering the chamber, since the pipeline will work at atmospheric pressure and the gas is pressurized to approximately 15 bar in the tank. The CO_2 supplier will design the chamber filling time according to the possible flow rate according to the pipeline diameter.

- **CO_2 and air output (exhaust)**

An exhaust system must be provided so that air is removed from the chamber when filling it with CO_2, as well as the CO_2 being expelled at the end of the curing procedure. It is recommended to use axial exhaust fans equipped with butterfly valves activated by hydraulic or pneumatic mechanisms, designer according to the dimensions of the chamber. A duct located in the lower region of the chamber must also be provided for the exhaustion of CO_2 after curing.

- **Ventilation**

Ventilation inside the chamber is essential so that the CO_2 is distributed evenly. The fans (blowers) must be positioned in the sides of the walls, in the upper region at one side and in the lower region on the other side, creating an air flow to promote greater contact between the CO_2 and the blocks.

- **Air conditioning**

The air in chamber must be conditioned to specific temperature and humidity. The system must contain an automation panel to make it possible to set the desired parameters. The air flow must be carried out through a buster interconnected in flexible and shielded pipe made with high performance material to prevent CO_2 from escaping. The humidification system must be coupled to the refrigeration equipment.

- **Safety**

An automated security panel equipped with red and green lights must be installed outside of the chamber, which will secure the opening of the chamber door. The red light will be directly related to the high concentration of CO_2 inside the chamber and the green light will indicate the low concentration of CO_2 in the chamber, communicating to the operator the prohibition or permission to open the door of the carbonation chamber.

5.4 Equipment and sensors for parameter control

The temperature, humidity, pressure, and CO_2 concentration parameters must be controlled using the equipment described below.

- **CO_2 sensor**

The sensor for evaluating carbon dioxide concentration must have an evaluation range between 0% and 100%. The sensor must be installed in the upper region of the chamber to verify that it is filled with CO_2. Since it is heavier than the air it tends to stay below reaching 100% at the top ensures the chamber is fully filled. Another CO_2 sensor must be installed in the lower region, close exhaustion duct . This will indicate when the CO_2 concentration inside the chamber is low, communicating the security system that will automatically turn on the green indicator light, allowing the door to be safely open.

- **Relative humidity sensor**

The Relative Humidity Sensor monitors the relative humidity in the range of 0 to 95% (± 5%). This sensor should be positioned in the center region of the chamber, as this location represents the average humidity of the chamber.

- **Temperature sensor**

The temperature sensor, in general must range between -40°C to 135°C. This sensor should also be positioned in the center region of the chamber.

- **Manometer**

The Bourdon type manometer, stainless steel case and brass alloy internals can be used, which controls the pressure from 0 to 20kgf/cm^2 and has an accuracy of 1.6%.

Figure 13 demonstrates the installations of the chamber and the supply of CO_2, as well as the equipment and sensors necessary to carry out the curing with CO_2 in the industry, both for chambers made for this purpose and for retrofit chambers.

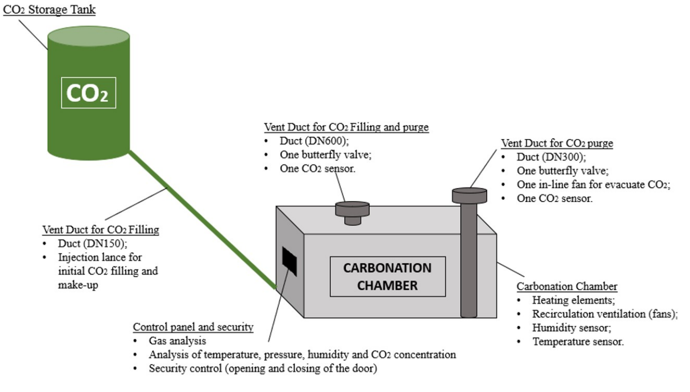

Figure 13. Chamber and CO_2 supply facilities, equipment, and sensors for carrying out CO_2 curing in the industry. Source: Author (2022).

5.5 Location

This study assesses industries consolidated in the market, within the state of São Paulo. The locational variable is related to the availability of raw material, CO_2. The industries that are closer located to the sources that generate CO_2 will have lower transport costs, not to mention the environmental issue related to lower gas emission due to transport. Figure 14 demonstrates the CO_2 gas sources sources and the concrete block plants in the state of São Paulo.

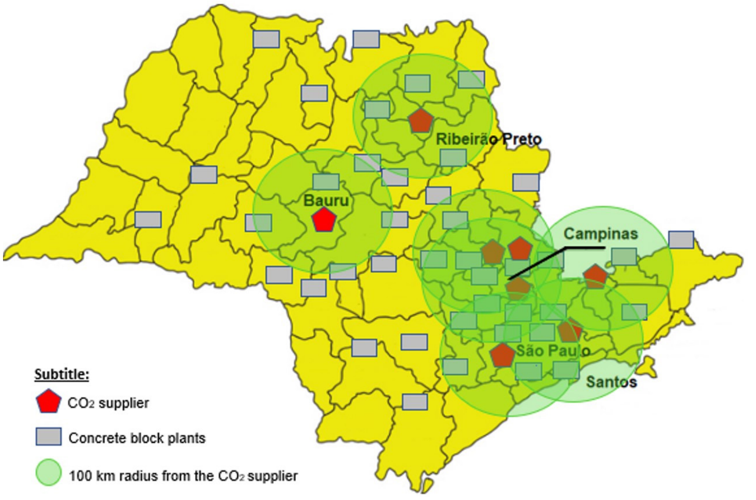

Figure 14. Radius of 100 km for CO_2 distribution. Source: Author (2022).

In Figure 14 it is possible to see that most of the main cities in the state of São Paulo have concrete block plants. CO_2 suppliers are more concentrated close to São Paulo city, with some suppliers in the inland part od the state. In this figure a radius of 100 km of the CO_2 suppliers was delimited. It is possible to observer that several concrete block plants that are within these perimeters.

5.6 Estimated CO_2 consumption for curing chamber saturation

To calculate the consumption of CO_2 for saturation of the curing chamber, the dimensions and storage capacity of concrete masonry units of an existing steam curing chamber in a concrete block plant, as shown by the Figure 15.

Figure 15. Steam curing chamber in a concrete block industry in the state of São Paulo. Source: Author (2022).

The following information was collected:

- Dimension of the curing chamber: 4.00 × 4.00 × 4.00 m (length × height × depth);
- Tray dimension: 0.66 × 0.54 × 0.03 m;
- Shelf dimension: 1.60 × 1.80 × 1.10 m;

The chamber accommodates 12 stacked shelves, 06 on the bottom and 06 on the top. Each shelf supports 20 trays and 80 concrete blocks with dimensions of 14×19×39 cm. Therefore, it is possible to cure 960 concrete masonry units per cycle, as calculated below:

- Curing chamber volume: 64.00 m^3;
- Net volume of one concrete block (14×19×39 cm): 0.0078 m^3;

- Net volume occupied by the concrete blocks in the chamber: 7.49 m^3;
- Volume occupied by the trays in the chamber: 2.57 m^3
- Volume occupied by the shelves in the chamber: 1.00 m^3

The calculation of the volume of CO_2 to be injected into the chamber for its saturation is demonstrated through Equations 2.1 and 2.2:

$$CO_{2\,\text{volume injected}} = Vol_{\text{chamber}} - Vol_{\text{net concrete masonry units}} - Vol_{\text{trays}} - Vol_{\text{shelves}} \tag{2.1}$$

$$CO_{2\,\text{volume injected}} = 52{,}94\ m^3 \tag{2.2}$$

One kilogram of CO_2 occupies 0.534m^3, then considering a 10%-waste, 109 kg of CO_2 will be needed to saturate the curing chamber.

Considering a production of three cycles per minute of the concrete block machine and eight hours worked per day, 5,760 concrete block units are produced per day. This production will fill six curing chambers/day, each cycle consuming 654 kg CO_2/day. Considering 22 workdays per month at total of and 14,388 kg CO_2/month for saturation of the curing chamber. A total of 126,720 blocks are produced per month.

5.7 Estimation of CO_2 absorption during curing by concrete masonry units

To calculate the monthly estimate of CO_2 absorption by the concrete masonry units, the mix proportion is considered as in Table 2.

Table 2. Mix proportion of the concrete blocks

Mix	Cement (kg)	Fine gravel (l)	Crushed sand (l)	Dust of stone (l)	Water (l)	Admixture (l)	Water/cement factor
Concrete masonry units	40	160	160	240	50	0,1	1,25

With this mix proportion, 64 concrete masonry units are produced, so block consumes 0.625 kg of cement. Considering the monthly production of 126,720 concrete masonry units, 79,200 kg of cement/month is consumed.

Considering the literature review, it was found that the lowest CO_2 absorption rate in concrete masonry units produced with natural aggregates, cured with 100% CO_2 concentration, is 8.62% for 2 hours of cure with CO_2 as (MacMaster and Tavares [22]). The highest reported absorption is 36.03% but with 24 hours of curing with CO_2 (Zhan et al. [20]). Considering the 2-hours cure and the smallest reported absorption, it is possible to sequester from 6,827 kg CO_2/month. Since six 2-hours cycles are necessary per day, two chambers will be necessary for the 8-hour workday.

5.8 Estimate of initial cost

For the new installation of the curing chamber, budgets were made considering a cold chamber with dimensions of 4.00 × 4.00 × 4.00 m (length × height × depth), equipped with a temperature, humidity, thermal insulation and tightness. The average value found was R$ 37,500.00. The devices for inlet and outlet of the pressure and CO_2 system, equipped with a pressure regulator and axial exhausters, cost around R$5,525.00. The CO_2, humidity, temperature, pressure gauge and interface sensors averaged R$ 8,760.00. Totaling R$ 51,786.00.

For retrofitting of an existing curing chamber with the same dimensions of 4.00 × 4.00 × 4.00 m (length × height × depth), it was verified through the SINAPI Price Bulletin (base date August/2022) that the waterproofing service walls and ceiling costs R$ 3,594.00. For thermal insulation, after budgeting with companies in the sector, the average value was R$18,697.00. The air conditioning system, including humidity and temperature control, has an average value of R$ 20,500.00. The devices required for the inlet and outlet of air and CO_2, equipped with a pressure regulator and axial exhaust fans with shutters to maintain the system's sealing, amounted to R$ 5,525.00. The CO_2, humidity, temperature, pressure gauge and interface sensors averaged R$ 8,760.00. Totaling R$57,076.00.

Considering that the chamber is a durable good, diluting the investment value for a minimum period of ten years. Considering that the production of concrete blocks for the same period is 15,206,400; the increase in cost per block will be R$0.0034 for a new installation and R$0.0037 for a retrofit, without impacting the final cost of the product.

5.8 Estimate of monthly CO_2 consumption and cost

To analyze the CO_2 cost to produce 126,720.00 concrete masonry units two situations were considered. The first scenario considers that concrete block plant is located 30 km from the CO_2 supplier. In the second case the plant is 100 km away from the CO_2 supplier. In the first situation, the cost of CO_2 will be R$ 14,000/month or R$ 0.11/ block. In the second case, the CO_2 cost will be R$ 46,673/month or R$ 0.37/block. According to a survey with the industries in May 2022, the conventionally cured 14×19×39 cm concrete masonry unit cost R$2.65 (not considering the delivering freight cost) each. Therefore, the concrete masonry units cured with CO_2 will present an extra cost that can vary from 4% to 14%, depending on the distance from the factory to the CO_2 supplier and the CO_2 absorption rate applied. The closer the industry is to the CO_2 supplier; the more viable the CO_2-cured concrete masonry units will be.

In any case, considering the environmental benefits this cost does not seem to be a barrier to the technology implementation. Also, it has already been discussed to monetary compensate the CO_2 sequestration. Although no practical regulation is in practice, this good environmental-friendly process may soon turn into a monetary profit.

The CO_2 emission related to cement production in 2020 in Brazil was approximately 34,907,896 tons [[44]]. In that year, 61,052,000 tons of cement were produced, of which 3,952,000 were representative of the non-reinforced prefabricated industry and 1,958,000 were for the manufacture of concrete masonry units [[45]]. This industry mainly uses CP-V cement which emits about 858 kg of CO_2 per cement tonne [[46]]. With the CO_2 absorption rate considered in this study, of 8.62%, it would have been possible to sequester approximately 168,780 ton of CO_2 per year if the entire production of concrete masonry units had been subjected to carbonation cure. This would correspond to ~ 0.5% of the total CO_2 emitted by the Brazilian cement production in 2020, or ~ 10% of the concrete masonry units industry, and equivalent to the sequestration of 21,100 trees in one year.

6 CONCLUSION

Carbonic curing is a sustainable innovation that helps to reduce global warming. According to the International Energy Agency [47], CO_2 capture and storage technology, by the year 2050, will be responsible for a reduction of up to 56% of CO_2 emissions in the cement sector. Therefore, accelerated carbonation curing technology becomes indispensable to achieve this objective.

This innovation is already successfully applied in countries such as Canada, the United States, and the United Kingdom. Cases of success are detailed in this paper.

According to the technical feasibility here reported, is possible to implement the technology in the state of São Paulo, with all of the innovative process need available in the region. A map showing CO_2 suppliers and concrete block plants located in the state is presented; the greater the distance between the supplier and the plant, the higher will be the cost.

An increase of R$ 0.11 and R$ 0.37 was estimated after implementing the carbonation cure if the plant is located 30km and 100 km from the CO_2 supplier, respectively. Those costs represent 4 to 14% of the concrete block production cost (not considering the delivering freight cost).

If all of the Brazilian concrete blocks industry implements the carbonation cure, considering the smallest absorption rate, it would have been possible to sequester approximately 168,780 ton of CO_2/year. This would correspond to ~ 0.5% of the annual total CO_2 emitted by the Brazilian cement production, or ~ 10% concrete block industry, and the sequestration equivalent to 21,100 trees in one year.

7 ACKNOWLEDGMENTS

The authors thank CNPq Project 443831/2018-1 - Academic Doctorate for Innovation at the Universidade Federal de São Carlos; CNPq - Process: 407060/2021-9 and to Associação Bloco Brasil for their encouragement and support.

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Author contributions: LRF: formal analysis, methodology, writing; GAP, ANJ: conceptualization, methodology, supervision.

Editors: Edna Possan, Mark Alexander.