Feasibility analysis for implementing CO2 curing in a concrete block industry in the São Paulo Region

Lívia Regueira Fortunato
Guilherme Aris Parsekian
Alex Neves Junior

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 CO2 curing process and changing needs is presented, including identifying local CO2 sources and delivering cost, gas consumption for chamber saturation, estimation of CO2 uptake by masonry units during curing, estimation of consumption and monthly cost of CO2, curing chamber changes needs, new equipment acquisition, estimation of cost for retrofit and new installations, potential best definitions on optimal temperature, humidity, and CO2 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 CO2 supplier. Considering the Brazilian production of concrete blocks, up to 168,780 tons of CO2 per year can be sequestered, this value is equivalent to the CO2 sequestered by 21,100 trees.

Keywords: analysis, feasibility, technical, curing, CO2.

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 CO2 em fábrica de blocos de concreto na região de São Paulo. Para tanto, será apresentada uma visão geral do processo de cura com CO2 e possíveis modificações para realizá-la na indústria, além da identificação de fontes locais de CO2 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 CO2. 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 CO2, 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 CO2 por ano podem ser sequestradas, este valor equivale ao sequestro de CO2 realizado por 21.100 árvores.

Palavras-chave: análise, viabilidade, técnica, cura, CO2.
1. INTRODUCTION

Accelerated carbonation curing or CO\textsubscript{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\textsubscript{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\textsubscript{2}, the newly manufactured unreinforced cementitious products are introduced into a carbonation chamber with adequate concentrations of CO\textsubscript{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\textsubscript{2} from the medium and premature gain in mechanical strength [3]–[6]. During curing, the CO\textsubscript{2} reacts with the main cement hydration product (Ca(OH)\textsubscript{2}), C-S-H, and others) and is transformed into calcium carbonate (CaCO\textsubscript{3}) and water. The formation of calcium carbonate promotes the permanent sequestration of CO\textsubscript{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\textsubscript{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\textsubscript{2} suppliers.

Producing concrete blocks that store CO\textsubscript{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\textsubscript{2}. The block hollow geometry and thin walls facilitate the diffusivity of CO\textsubscript{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\textsubscript{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\textsubscript{2}, through which the blocks are placed inside the carbonation chamber with ideal conditions of temperature, pressure, humidity, and CO\textsubscript{2} concentration. At the end of the curing procedure, the block will permanently store the CO\textsubscript{2} and with improved of mechanical resistance [6], [11].

It is a fact that non-reinforced cementitious precast can absorb CO\textsubscript{2} and gain strength prematurely when subjected to CO\textsubscript{2} curing. Fortunato [6] found that concrete paving pieces, when subjected to curing with carbon dioxide, stored 5.10\% of the CO\textsubscript{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 CO₂ if all production had been cured with CO₂. This value corresponds to the CO₂ sequestration of 36,250,000.00 trees in a year, since, according to the Totum Institute, a tree sequesters approximately eight kilograms of CO₂ 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 CO₂

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 CO₂ 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 CO₂.

2.2.2 Innovative CO₂ chemical cure technology

The technology in question is a chemical cure that promotes the mineralization of CO₂, that is, the carbon dioxide through the cure is chemically transformed into a mineral, calcium carbonate. The permanent absorption of CO₂ in the pores of the concrete is possible due to the accelerated carbonation reaction. The main carbonation reaction occurs between Ca(OH)₂ and CO₂ 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.

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (1.1)
\]

\[
3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{CO}_2 \rightarrow 3\text{CaCO}_3 \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} \quad (1.2)
\]

2.2.3 Studies on the chemical curing process with CO₂ 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>
<thead>
<tr>
<th>Authors</th>
<th>Samples</th>
<th>Time and type of initial cure (h)</th>
<th>Carbonation curing time (h)</th>
<th>Carbonation Chamber</th>
<th>CO₂ concentration (%)</th>
<th>Pressure (MPa)</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>CO₂ absorption (%)</th>
<th>Compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>Cubes (100×100mm) dry concrete</td>
<td>no initial cure</td>
<td>2</td>
<td>100</td>
<td>0.5</td>
<td>environment</td>
<td>------</td>
<td>7.0 – 8.0</td>
<td>&gt; 40 MPa after 2hs of carbonation</td>
<td></td>
</tr>
<tr>
<td>[16]</td>
<td>Concrete masonry units and concrete units for pavement (w/c=0.25)</td>
<td>no initial cure</td>
<td>2</td>
<td>100</td>
<td>0.5</td>
<td>45-95</td>
<td>------</td>
<td>9.8</td>
<td>10.3 MPa after 2 hours of carbonation (~ 50% increase compared to the reference at 28 days)</td>
<td></td>
</tr>
<tr>
<td>[16]</td>
<td>Cement bead board comprised cement paste and expanded polyethylene beads (w/c=0.36)</td>
<td>no initial cure</td>
<td>2</td>
<td>100</td>
<td>0.5</td>
<td>45-95</td>
<td>------</td>
<td>12.2</td>
<td>7.8 MPa after 2 hours of carbonation, same value was obtained for reference boards at 28 days</td>
<td></td>
</tr>
<tr>
<td>[4]</td>
<td>Concrete masonry units</td>
<td>no initial cure</td>
<td>2</td>
<td>100</td>
<td>0.15</td>
<td>environment</td>
<td>------</td>
<td>8.2 – 10.6</td>
<td>Increase of compressive strength of 78% in relation to the reference</td>
<td></td>
</tr>
<tr>
<td>[5]</td>
<td>Concrete units for pavement (10x20x64mm) (w/c=0.4)</td>
<td>2 – 19 wet curing</td>
<td>4 - 5</td>
<td>99,5</td>
<td>0.15</td>
<td>56</td>
<td>65</td>
<td>3.4 - 7.4</td>
<td>Tests done after 24 hours of production: 31 MPa (after 4hs of carbonation) and 46 MPa (after 5hs of carbonation)</td>
<td></td>
</tr>
<tr>
<td>[5]</td>
<td>Zero slump concrete samples (127×76×20 mm)</td>
<td>no initial cure</td>
<td>2</td>
<td>99,5</td>
<td>0.15</td>
<td>40 - 56</td>
<td>65</td>
<td>11.7</td>
<td>9.6 MPa (after 2hs of carbonation) (~ 60% increase compared to the reference at 28 days)</td>
<td></td>
</tr>
</tbody>
</table>
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 fungi in the production environment had a significant impact on the mechanical properties of the samples.

In most studies the concentration of CO2 inside the carbonation chamber was 100%. The maximum concentration of CO2 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 CO2 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 CO2 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 CO2. This is probably due to the smaller thickness of the block walls, allowing greater CO2 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 CO2 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 °C to maximize carbonation.

### Compressive strength

<table>
<thead>
<tr>
<th>Authors</th>
<th>Samples</th>
<th>Time and type of initial cure (h)</th>
<th>Carbonation curing time (h)</th>
<th>CO2 concentration (%)</th>
<th>Pressure (MPa)</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>CO2 absorption (%)</th>
<th>Compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>[17]</td>
<td>Cement paste, (14×14×60mm) (w/c ~ 0.36)</td>
<td>18 wet curing</td>
<td>2</td>
<td>99.5</td>
<td>0.15</td>
<td>25</td>
<td>--------</td>
<td>--------</td>
<td>8.9</td>
</tr>
<tr>
<td>[18]</td>
<td>Zero slump concrete samples (w/c ~ 0.36)</td>
<td>18 air curing</td>
<td>2</td>
<td>100</td>
<td>0.15</td>
<td>25</td>
<td>--------</td>
<td>6.9 – 7.3</td>
<td>28.8 MPa without water spray and 38.9 MPa with water spray after carbonation</td>
</tr>
<tr>
<td>[19]</td>
<td>Concrete masonry unit (w/c=0.40)</td>
<td>0, 4, 6, 8, 18 air curing</td>
<td>2, 4, 96</td>
<td>100</td>
<td>0.01</td>
<td>25</td>
<td>50</td>
<td>9.0 – 35.0</td>
<td>Compressive strength with water spray after carbonation comparable to non-carbonated ones with thermal curing</td>
</tr>
<tr>
<td>[20]</td>
<td>Concrete masonry units with recycled aggregates</td>
<td>no initial cure</td>
<td>6, 12, 24</td>
<td>100</td>
<td>0.01</td>
<td>--------</td>
<td>22.49-43.96</td>
<td>Compressive strength with water spray after carbonation comparable to non-carbonated ones with thermal curing</td>
<td></td>
</tr>
<tr>
<td>[21]</td>
<td>Concrete masonry unit with blast furnace slag produced in manual factory (127×76×38 mm)</td>
<td>0, 4, 6, 8, 18 thermal curing</td>
<td>2, 4, 96</td>
<td>100</td>
<td>0.1</td>
<td>25</td>
<td>50</td>
<td>8.3 – 35.1</td>
<td>Compressive strength with water spray after carbonation comparable to non-carbonated ones with thermal curing</td>
</tr>
<tr>
<td>[22]</td>
<td>Concrete Masonry Units</td>
<td>not executed</td>
<td>2</td>
<td>100</td>
<td>1.39</td>
<td>30</td>
<td>50</td>
<td>8.62</td>
<td>After 2 hours, net compressive strength of 35.72MPa carbonated Concrete masonry units and 10.14MPa steam cured concrete Masonry Units</td>
</tr>
<tr>
<td>[15]</td>
<td>Concrete unit for pavement (100×200×60 mm)</td>
<td>12 hours outdoor cure and 12 hours initial steam cure</td>
<td>4 and 16</td>
<td>20</td>
<td>0.1</td>
<td>23</td>
<td>65</td>
<td>1.5% - 5.1%</td>
<td>At 62 days, the compressive strength of the carbonated pieces was superior to the reference and at 28 days too</td>
</tr>
</tbody>
</table>

### 2.2.4 Based material – CO2 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% CO2) and high purity (absence of contaminants such as moisture and/or other gases).
After capture, the CO₂ 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 CO₂ customer itself uses the CO₂ produced, or else, the captured CO₂ is transported in tank trucks that will supply customers in bulk or go to a filling center, where the CO₂ will be discharged into a tank and later fill the cylinders [24], [25]. Figure 1 demonstrates in a simplified way the CO₂ path from capture to the final customer.

![Figure 1. Transporting CO₂ to serve the industry that captured it and other customers (adapted from [[26]]).](image-url)

To store CO₂ 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 CO₂ 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 CO₂ leakage. There is also the possibility of installing new designed CO₂ curing chamber, that can be made of masonry or appropriate containers can be used [24], [25]. The control of temperature, humidity, pressure, and CO₂ concentration parameters use equipment such as a manometer to check the internal pressure of the chamber a CO₂ 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 CO₂ 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 CO₂, as well as the CO₂ curing technology [31].
- **Manufacture and molding of prefabricated parts that store CO₂:**
  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 CO₂ used by the company is supplied by AirLiquide and is usually stored in tanks like in Figure 2.

![Figure 2. Tank for storing captured CO₂. Source: [33].](image1)

- **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 CO₂ on a small scale.

![Figure 3. Solidia test chamber. Source: [33].](image2)

By proving the CO₂ 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].](image3)
- **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].](image)

- **Advantages of CO₂ curing:** Jang et al. [31], DeCristofaro et al. [32] and Meyer et al. [30] indicate the following advantages:
  - It does not consume water, but CO₂;
  - 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 CO₂ 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 CO₂ curing processing, not only with autoclaving but with all other conventional concrete curing methods.

- **Products sold:**
  
The company commercializes concrete masonry units that store CO₂, as well as CO₂ curing technology that can be applied to masonry units and pavers [35].

- **Manufacture and molding of prefabricated parts that store CO₂:**
  
  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 CO₂, 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.
Accelerated carbonation cure:
- **Based-material:** the CO₂ 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 CO₂ in an autoclave at high pressures. Figure 7 demonstrates a type of curing chamber used by Carboclave.

Equipment and accessories: according to Hargest and Al-Ghouleh [35] before curing with CO₂, vacuum step is used to exhaust 50 to 90% of the volume of air initially present in the enclosure, then, after the CO₂ injection, applying a pressure greater than atmospheric, which is controlled by a manometer.

Advantages of CO₂ 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 CO₂ per 19x19x39cm concrete masonry units;
- Non-reinforced CO₂-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 CO₂ curing in practice [36].
- **Products sold:**

  The company sells reverse technologies for industries which seek to make a beneficial use of the CO₂. Accelerated carbonation curing is one of them. They are producing concrete masonry units that absorb CO₂ 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 CO₂:**

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

- **Accelerated carbonation cure:**

  - **Based-material:** the CO₂ used comes from the plant that emits it [37]. Figure 8 shows the CO₂ 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 CO₂ that will be injected into the carbonation chamber. Source: [[38]].](image)

  - **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].](image)

  - **Equipment and accessories:** the chamber is controlled by CO₂, humidity, and temperature sensors [39]. Figure 10 demonstrates their inspection.
Advantages of CO2 curing verified by the company:
The main advantage emphasized by the company is the definitive incorporation of CO2 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 CO2 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 CO2:
  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 CO2 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].

Advantages of CO2 curing:
- High strength gain before 24 hours after curing with CO2;
- Compressive strength of CO2 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 CO2 is generated, while the concrete masonry units cured with CO2 is negative (-1kg), since the CO2 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 CO₂ 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 CO₂ 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 CO₂ suppliers and block producers plant location were identified with the state. The materials, equipment, CO₂ 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 CO₂

The supply of captured CO₂ 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 CO₂ 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 CO₂ supplier to the accelerated carbonation curing chambers.

For the installation and operation of the CO₂ 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 CO₂ chamber can be new or can be adapted from the existing infrastructure. 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 CO₂.
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.
- **CO₂ 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 CO₂. Since it is heavier than the air it tends to stay below reaching 100% at the top ensures the chamber is fully filled. Another CO₂ sensor must be installed in the lower region, close exhaustion duct. This will indicate when the CO₂ 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/cm² and has an accuracy of 1.6%.

  Figure 13 demonstrates the installations of the chamber and the supply of CO₂, as well as the equipment and sensors necessary to carry out the curing with CO₂ in the industry, both for chambers made for this purpose and for retrofit chambers.

  ![Figure 13. Chamber and CO₂ supply facilities, equipment, and sensors for carrying out CO₂ curing in the industry. Source: Author (2022).](image)

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, CO₂. The industries that are closer located to the sources that generate CO₂ will have lower transport costs, not to mention the environmental issue related to lower gas emission due to transport. Figure 14 demonstrates the CO₂ gas sources sources and the concrete block plants in the state of São Paulo.
In Figure 14 it is possible to see that most of the main cities in the state of São Paulo have concrete block plants. CO₂ suppliers are more concentrated close to São Paulo city, with some suppliers in the inland part of the state. In this figure a radius of 100 km of the CO₂ suppliers was delimited. It is possible to observe that several concrete block plants that are within these perimeters.

5.6 Estimated CO₂ consumption for curing chamber saturation

To calculate the consumption of CO₂ 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.

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 m³;
- Net volume of one concrete block (14×19×39 cm): 0.0078 m³;
- Net volume occupied by the concrete blocks in the chamber: 7.49 m³;
- Volume occupied by the trays in the chamber: 2.57 m³
- Volume occupied by the shelves in the chamber: 1.00 m³

The calculation of the volume of CO₂ to be injected into the chamber for its saturation is demonstrated through Equations 2.1 and 2.2:

\[
CO_2 \text{ volume injected} = V_{\text{chamber}} - V_{\text{net concrete masonry units}} - V_{\text{trays}} - V_{\text{shelves}}
\]  
(2.1)

\[
CO_2 \text{ volume injected} = 52.94 \text{ m}^3
\]  
(2.2)

One kilogram of CO₂ occupies 0.534m³, then considering a 10%-waste, 109 kg of CO₂ 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 CO₂/day. Considering 22 workdays per month at total of and 14,388 kg CO₂/month for saturation of the curing chamber. A total of 126,720 blocks are produced per month.

5.7 Estimation of CO₂ absorption during curing by concrete masonry units

To calculate the monthly estimate of CO₂ absorption by the concrete masonry units, the mix proportion is considered as in Table 2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete masonry units</td>
<td>40</td>
<td>160</td>
<td>160</td>
<td>240</td>
<td>50</td>
<td>0.1</td>
<td>1.25</td>
</tr>
</tbody>
</table>

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 CO₂ absorption rate in concrete masonry units produced with natural aggregates, cured with 100% CO₂ concentration, is 8.62% for 2 hours of cure with CO₂ as (MacMaster and Tavares [22]). The highest reported absorption is 36.03% but with 24 hours of curing with CO₂ (Zhan et al. [20]). Considering the 2-hours cure and the smallest reported absorption, it is possible to sequester from 6,827 kg CO₂/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 CO₂ system, equipped with a pressure regulator and axial exhausters, cost around R$5,525.00. The CO₂, humidity, temperature, pressure gauge and interface sensors averaged R$ 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 CO₂, equipped with a pressure regulator and axial exhaust fans with shutters to maintain the system's sealing, amounted to R$ 5,525.00. The CO₂, 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 CO2 consumption and cost

To analyze the CO2 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 CO2 supplier. In the second case the plant is 100 km away from the CO2 supplier. In the first situation, the cost of CO2 will be R$ 14,000/month or R$ 0.11/block. In the second case, the CO2 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 CO2 will present an extra cost that can vary from 4% to 14%, depending on the distance from the factory to the CO2 supplier and the CO2 absorption rate applied. The closer the industry is to the CO2 supplier; the more viable the CO2-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 CO2 sequestration. Although no practical regulation is in practice, this good environmental-friendly process may soon turn into a monetary profit.

The CO2 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 CO2 per cement tonne ([46]). With the CO2 absorption rate considered in this study, of 8.62%, it would have been possible to sequester approximately 168,780 ton of CO2 per year if the entire production of concrete masonry units had been exposed to carbonation cure. This would correspond to ~ 0.5% of the total CO2 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], CO2 capture and storage technology, by the year 2050, will be responsible for a reduction of up to 56% of CO2 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 CO2 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 CO2 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 CO2/year. This would correspond to ~ 0.5% of the annual total CO2 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.

8 REFERENCES


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

**Editors:** Edna Possan, Mark Alexander.