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Developing an easy-to-build laboratory chamber for CO_2 experiments

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ABSTRACT

Carbonation chambers, in general, are used in civil engineering laboratories both for verification tests of the useful life of reinforced concrete, and for CO_2 curing tests of unreinforced cementitious materials. These chambers can be purchased from specialized manufacturers at a high cost, or they can be built by the researchers themselves. It so happens that in the literature there is no manual for making and operating an accelerated carbonation chamber. It is observed that its development and manufacture depend a lot on the needs and financial conditions of the research, with no standard or Technical Norm to be followed. This article presents a compilation of concepts related to the accelerated carbonation reaction and brings a bibliographical review about the different carbonation chambers made by researchers, in which it was possible to verify a great variation regarding the material to be used in the structure of the chamber, location of CO_2 and air inlet and outlet valves, temperature and humidity control, among others; and in addition, it presents a descriptive memorial for the construction of an automated and accessible carbonation chamber to be used in laboratories.

Keywords: Chamber; accelerated carbonation; operation; descriptive plan.

1. INTRODUCTION

The chemical reaction of carbonation can be analyzed on the basis of reinforced concrete structures' durability or sustainability when it relates only to unreinforced concrete. Considering the useful life of reinforced concrete structures, carbonation can be considered harmful depending on the aggressiveness of the environment in which it is inserted. This is because it promotes a reduction in the pH of the concrete, destroying the passivator film that involves the steel, leaving the material susceptible to corrosion [1–5]. However, in the case of unreinforced concrete, as is the case with non-reinforced cementitious precast elements (concrete blocks, units of concrete paving, tiles, cementitious slabs etc.), the carbonation reaction is considered beneficial. The accelerated carbonation curing highly enhances the mechanical strength and permanent absorption of CO_2 from the environment [6–9].

Several studies [10–20] have used a carbonation chamber to analyze the carbonation reaction under different conditions. In one condition (to assess the useful life [durability] of reinforced concrete), the chamber is set up by considering specific conditions like humidity, temperature, and CO_2 to accelerate the harmful effects. In the other condition, the chamber facilitates the CO_2 curing of pure concrete to assess the ideal conditions of CO_2 concentration, humidity, and temperature to maximize CO_2 absorption and enhance mechanical strength.

In both cases, the chamber is essential for analyzing the effects of carbonation reactions. In many cases, these chambers are made in the laboratory by the researchers themselves without the aid of an available technical standard. Therefore, this article compiles various reactions as well as the internal and external factors that can influence carbonation. It also conducts a review of different carbonation chambers. The lack of standardization can lead to varying test results and research conclusions that can significantly affect carbonation. In addition to this, the present article offers a step-by-step manual for the construction of an automated and cost-effective carbonation chamber to be used in carbonation experiments.

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2. LITERATURE REVIEW

2.1. Accelerated carbonation

Carbonation is a physicochemical phenomenon with an exothermic nature where the alkaline hydration products of cement, especially calcium hydroxide ($Ca(OH)_2$), react with CO_2, generating carbonated-based products and silica gel. The main carbonation reaction between $Ca(OH)_2$ and CO_2 can be illustrated as:

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O$$

The product formed is calcium carbonate ($CaCO_3$). It is insoluble and appears in a mineralogical form, such as calcite, vaterite and (rarely) aragonite [21, 22].

The hydrated calcium silicate phases (C-S-H) undergo structural changes due to the carbonation reaction, albeit more slowly. The reaction is shown below:

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 \cdot 2SiO_2 \cdot 3H_2O$$

According to PAPADAKIS *et al*. [23–25] gaseous reactions, dissolution and precipitation of solids involved in the carbonation processes comprise the following steps:

1. Initially, there is a diffusion of CO_2 to the pores of the cementitious material. Following this, it dissolves in the water present in the pores.
2. The solid $Ca(OH)_2$ undergoes dissolution in the aqueous film of the pore walls and the dissolved $Ca(OH)_2$ diffuses at a finite rate normal to the external surface of the porous concrete.
3. The dissolved CO_2 reacts with the $Ca(OH)_2$ dissolved in pore water.
4. The dissolved CO_2 reacts with the hydrated and unhydrated calcium silicate phases.
5. A reduction in the volume of the pores, caused by the precipitation of carbonation products, occurs.
6. Finally, condensed water forms on the pore walls of the cement matrix.

2.2. Factors that influence the carbonation process

Carbonation is directly influenced by the environment in which the sample is placed, as well as by its chemical composition. Therefore, the main factors that affect the reaction result are as described below, corroborating with the article by [26]:

- **Temperature:** The diffusion and carbonation reaction rates increase with the temperature [27, 28] concluded that the increase in temperature increases the mobility of molecules, i.e., the transport of substances. Higher temperatures increase the solubility of various substances, while at very low temperatures, the liquids freeze which prevents or hinders transport. For PAPADAKIS *et al*. [23] a temperature range between 20 and 40°C practically does not influence the carbonation, due to the diffusion-controlled process at this condition. According to LIU *et al*. [29], [30] the sequestration of CO_2 at atmospheric pressure increases until it reaches a temperature of 60°C. Following this, it begins to decrease. It was found that an increase in temperature up to 60°C increase the CO_2 diffusion into the pores as well as the leached amount of Ca^{2+} ions, promoting an increase in carbonation. On the other hand, temperatures higher than 60°C decrease the solubility of CO_2 in water, thus reducing the carbonation rate.
- **CO_2 concentration and pressure:** Environments with high pressure rates and CO_2 concentration increase the speed of CO_2 diffusion, favoring carbonation [31]. According to BUKOWSKI and BERGER [32], [33, 34], injecting high amounts of CO_2 at high pressure into the cementitious matrix before the pores close enhances the carbonation.
- **Relative humidity:** Water is not consumed during the carbonation reaction, but it is essential to trigger it. Therefore, a dry concrete does not carbonate due to the lack of water. In saturated conditions, the carbonation slows down due to the reduction of the gas diffusivity [27]. An ideal moisture content for carbonation, according to researchers, is cited below:
  - i. Between 65% and 85% [35]
  - ii. Between 50% and 65% [23]
  - iii. Between 50% and 70% [36]

iv. Between 50% and 70% [10]
v. Between 50% and 70% [11]

- **Cure:** According to PAULETTI [11], the cure is directly related to the pore structure of the cementitious material and the moisture content within, making it unsuitable for the carbonation reaction. LO and LEE [37] compared air curing with wet curing and observed that water-cured concrete had 72% of the carbonation of the air-cured concrete after 3 months of accelerated testing. The scholars [37] have concluded that air curing makes the pores favorable to reaction, which leads to an increase in the number of connected channels and a consequent increase in the speed of diffusion of CO_2.
- **Blended cement's chemical composition:** The elements Ca, Mg, K and Na considerably influence the carbonation reaction of the cementitious matrices. The calcium presented in the $Ca(OH)_2$, C-S-H and calcium silicate hydrates containing aluminum (C-A-S-H) phases are the main ones responsible for carbonation [22, 38, 39]. Moreover, the addition of complementary cementitious materials, such as coal ash, blast furnace slag, can result in the carbonation of components such as $Mg(OH)_2$, KOH and NaOH [40]. According to KOBAYASHI and UNO [41], HELENE [42] and STUMPP [31], mineral additions reduce porosity which halts the CO_2 diffusion. However, it promotes the acceleration of the carbonation depth due to the effect of the alkaline reserve. Thus, a small amount of $Ca(OH)_2$ leads to a small $CaCO_3$ "barrier", allowing a greater carbonation depth.
- **Porosity:** PAPADAKIS *et al*. [23] found that when considering the same type of cement, pore distribution is directly related to the w/c ratio. Therefore, increasing the w/c ratio increases porosity, consequently increasing diffusion and carbonation speed. ISHIDA and MAEKAWA [43] observed that pores become thinner after carbonation. The authors reported that the volume of the $CaCO_3$ crystal is about 11.7% larger than that of $Ca(OH)_2$.
- **Size and shape of specimens:** This refers to how the specimen shape can affect the depth of carbonation front. KULAKOWSKI [10] compared the carbonation depth of cylindrical specimens (diameter 50 mm and height of 100 mm) and prismatic specimens (40 mm × 40 mm × 160 mm) by referring to the same material (mortar) and conditions of exposure. The prismatic test caused an average carbonation depth of 9.23 mm, while for the cylindrical specimen, the average carbonation depth was 13.81 mm (approximately 50% greater).

The factors listed above refer to the environmental conditions in which the sample is inserted, as well as its chemical composition. All these factors combined can facilitate or hinder the occurrence of carbonation. Therefore, considering the curing of non-reinforced cementitious materials, the best combination must be sought so that the carbonation is maximized. The parameters related to the environment (chamber) can and should be controlled to obtain reliable results for a research's objectives.

2.3. Minimum parameters to be controlled in a carbonation chamber

In this section, in Tables 1, 2 and 3, different studies where the carbonation chambers were made by the researchers and the parameters that must be verified and controlled due to their influence on carbonation, are emphasized.

2.4. Guidelines for the construction of a carbonation chamber

From the literature review, it was observed that the construction of the carbonation chambers facilitated the experiments. However, the absence of standard procedures and automation can lead to results that are not comparable to each other, especially in chambers that work with low CO_2 concentrations. In this section, the different parameters from various studies will be discussed.

– **Chamber structure (materials):** In the research presented, it was observed that there is no standardization for the materials used to make the chambers; as some were built with glass, while others were made with stainless steel plate, acrylic, polycarbonate plate, wood or fiberglass. Each material has a different thermal conductivity coefficient which can affect the accelerated carbonation reaction if the internal temperature is not controlled. Therefore, the use of materials with a lower thermal conductivity coefficient is recommended for the construction of the chamber, such as acrylic. Or, if the researcher chooses to use metallic material, adding a layer composed of a material with low thermal conductivity, such as wood (Lucena, 2016), is recommended so that there is no interference from the external environment on the internal environment.

– **Chamber structure (dimensions):** The he dimensions of the chamber varied, owing to the different objectives of various studies and their different formats and quantities of specimens.

Table 1: Summary of different carbonation chambers, as reported in the literature.

AUTHOR		JOHN [12]	KULAWOSKI [10]	SILVA [13]	ABREU [14]
CHAMBER STRUCTURE	**MATERIAL**	No information	No information	Metal and glass	Internal structures and shelves made of wood with an iron and steel mesh
	DIMENSIONS (LENGTH × DEPTH × HEIGHT)	No information	50 cm × 81 cm× 117 cm	115 cm × 120 cm × 90 cm	82 cm × 52 cm × 126 cm
VENTILATION		Microcomputer fan	Two 9 cm × 9 cm fans installed in the lower region of the camera	No information	A 9 cm diameter fan located at the bottom of the chamber
INPUT AND OUTPUT OF CO_2 AND AIR		Entry of CO_2 and air in the upper region of the chamber and exit of CO_2 and air in the lower region	Needle valves and pressure reducers	No information	Entry of CO_2 and air in the upper region of the chamber and outflow of CO_2 and air in the lower region
CHAMBER CONFIGURATION	**CONCENTRATION OF CO_2**	5% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	5% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	0–100% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	5% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)
	TEMPERATURE	Controlled in an air-conditioned room	Controlled in an air-conditioned room	Controlled in an air-conditioned room	Not controlled, just registered
	HUMIDITY	Not controlled, just registered	Controlled with salts	Controlled through water container and automatic electric dehumidifier	Not controlled, just registered
	PRESSURE	Not internally verified	No information	No information	No information
SENSORS INCLUDED IN THE TEST		Temperature and humidity. There was no information if there was a CO_2 sensor	Temperature and humidity, but it was not informed if there was a CO_2 sensor	No information	Temperature and humidity, but it was not informed if there was a CO_2 sensor
AUTOMATION		Not performed	Not performed	No information	No information
AIRTIGHT		No information	No information	No information	No information

Table 2: Summary of different carbonation chambers, as reported in the literature (contd.).

AUTHOR		ABREU [14]	PAULETTI [11]	MCGRATH [15]	BARROS [16]
CHAMBER STRUCTURE	**MATERIAL**	Fiberglass	Chamber is made of acrylic and internal metal trays with holes	Two 200 liter drums (were not mentioned if they were metallic or plastic)	Metal and glass
	DIMENSIONS (LENGTH × DEPTH × HEIGHT)	80 cm × 50 cm × 50 cm	Volume of 245 liters	Height:85 cm; Diameter: 57 cm	No information
VENTILATION		Did not use ventilation	Two fans at the top and two more at the bottom for gas circulation	Low flow fans with up flow	Microcomputer fan
INPUT AND OUTPUT OF CO_2 AND AIR		Entry of CO_2 and air in the lower region of the chamber and exit of CO_2 and air in the upper region	CO_2 input is at the bottom and the purge at the top	Controlled by solenoid valve and needle valve	Entry of CO_2 and air in the upper region of the chamber and outflow of CO_2 and air in the lower region
CHAMBER CONFIGURATION	**CONCENTRATION OF CO_2**	50% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	60% or more – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	4% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	5% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)
	TEMPERATURE	Not controlled, just registered	Controlled in an air-conditioned room	Controlled by a 250W lamp connected to a control circuit and relay with a range between 23°C and 26°C	Not controlled, just registered
	HUMIDITY	Not controlled, just registered	~70% – controlled by sodium chloride (NaCl) ballast, recorded by hygrometers	Controlled with saturated salt solution composed of NaNO2 and water – ranged between 58% and 62%	Not controlled, just registered
	PRESSURE	No information	Atmospheric pressure controlled with a Bourbon Manometer	No information	No information
SENSORS INCLUDED IN THE TEST		Temperature and humidity, but it was not informed if there was a CO_2 sensor	Temperature and humidity, but it was not informed if there was a CO_2 sensor	Temperature and humidity, but it was not informed if there was a CO_2 sensor	Temperature and humidity, but it was not informed if there was a CO_2 sensor
AUTOMATION		No information	No information	No information	No information
AIRTIGHT		No information	No information	Sealing gaskets and clamps were used to make an almost airtight system	No information

Table 3: Summary of different carbonation chambers as reported in the literature (contd.).

AUTHOR		SALOMÃO AND SILVA [17]	SALDANHA [18]	LUCENA [19]	SOARES *ET AL.* [20]
CHAMBER STRUCTURE	**MATERIAL**	10 mm acrylic plates	Glass desiccator	Chamber made with plywood plate, expanding liquid polyurethane foam and stainless steel plate	Stainless steel sheets and polycarbonate sheet
	DIMENSIONS (LENGTH × DEPTH × HEIGHT)	100 cm × 60 cm × 65 cm	No information	100 cm × 60 cm × 85 cm	60 cm × 45 cm × 56 cm
VENTILATION		Did not use ventilation	12 Volt Fan	Two computer cooler fans	Two cooler-type fans installed on the sides, one on each level
INPUT AND OUTPUT OF CO_2 AND AIR		Only two valves located in the lower region of the chamber for CO_2 and air inlet and outlet	Entry and exit of CO_2 and events from the top of the desiccator	Four gas inlet and outlet devices (CO_2 and air) – solenoid valve for CO_2 inlet control	Two valves in the lower region for CO_2 and air inlet and outlet and one valve in the lower region for air outlet
CHAMBER CONFIGURATION	**CONCENTRATION OF CO_2**	5% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	The CO_2 flow comes from a cylinder that comes into contact with the air inside the desiccator, in order to obtain the intended concentrations for the test to be developed.	0% to 100% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)	0% to 100% – controlled by the proportion between CO_2 and air flow (open circuit and continuous supply)
	TEMPERATURE	Uncontrolled, recorded using a thermo-hygrometer	Controlled and recorded through a thermo-hygrometer	Not controlled, just registered	Not controlled, just registered
	HUMIDITY	Uncontrolled, recorded using a thermo-hygrometer	Controlled with salts and registered	Not controlled, just registered	Not controlled, just registered
	PRESSURE	Atmospheric pressure controlled with a Bourbon pressure gauge	Atmospheric pressure controlled with a Bourbon pressure gauge	Atmospheric pressure controlled with a Bourbon pressure gauge	Atmospheric pressure controlled with a Bourbon pressure gauge
SENSORS INCLUDED IN THE TEST		Temperature and humidity, but it was not informed if there was a CO_2 sensor	Temperature and humidity and CO_2 sensor	Temperature and humidity and CO_2 sensor	Temperature, humidity and oxygen meter
AUTOMATION		No information	Software DAS 100® and GasLab	Arduino e software GasLab	No information
AIRTIGHT		The seal is made like a chemical chapel	No information	Silicone rubber seal around the perimeter of the door and self-adjusting lock which provides adequate pressure to the rubber	Stainless steel weld and door with hermetic closure and butterfly type nuts and spongy fabric

- **Ventilation:** Some chambers did not have ventilation inside. This is quite concerning since it is essential for the uniformization of the CO_2 concentration and air inside the chamber. There was also great variation in the amount, size and location of fans in the chambers. The absence, excess or lack of ventilation can cause differences in CO_2 concentrations inside the chamber and affect carbonation. It is recommended that the chamber be ventilated strategically so that the air and CO_2 flow ideally (providing a greater contact surface between the CO_2 and the specimens). The number of fans must be in line with the dimensions and they should be distributed in an equally-spaced manner.
- **Input and output of CO_2 and air:** Many studies did not show whether there was a valve (or its type, if there was a valve) in the chamber. A variation was also observed in the fact that in some chambers, the CO_2 output occurred in the lower part of the chamber and in others, it occurred in the upper part. It is recommended that the air outlet be located at the top of the chamber, as CO_2 is denser than air. So, while injecting CO_2 at the bottom, the top valve must remain open for the air to exit as CO_2 enters. Doing it the other way around may reduce efficiency.
- **Chamber configuration (concentration of CO_2):** Most chambers do not work saturated (100% CO_2) and, instead, work with low concentrations of the gas. In some cases, the CO_2 concentration was often controlled by its volumetric proportion and air, while few used CO_2 cylinders. It is recommended that a CO_2 cylinder compatible with the particular research's objectives be used so that the analyzed parameter is strictly controlled. Buying a cylinder with 100% CO_2 concentration and an internal CO_2 sensor that indicates the CO_2 concentration in relation to the chamber volume is also advised.
- **Chamber configuration (temperature, humidity and pressure):** As for temperature and humidity, it was found that some studies did not control these parameters and only recorded them. This can cause variation in the results, as humidity and temperature directly affect carbonation. So, the author's suggestion is that in addition to the record, both the temperature and the humidity must be controlled inside the chamber through specific devices, such as humidifiers, dehumidifiers, heaters and air conditioners. Otherwise, the chamber must be installed in an acclimatized room for temperature control with distributed inside it to control the humidity. As for pressure, most studies (in general) worked with atmospheric pressure which was recorded through a Bourbon-type manometer.
- **Sensors:** Most studies [10–12, 14–20] used a humidity and temperature sensor while few reported the existence of a CO_2 sensor. Verifying the percentage of CO_2 through appropriate sensors gives greater credibility to the experiment instead of verifying through volumetric proportion formulas. It is recommended that these sensors be installed in the chamber, since they are feasible, are easily to install and allow the researcher to analyze important parameters for chamber configuration.
- **Automation**: Automation was only used in more recent cameras, such as Saldanha (2013) and Lucena (2016). They automated their cameras through arduino and specific software. It is recommended that chamber automation be used, as it is essential for controlling the chamber's configuration as well as obtaining reliable results.
- **Airtight:** A factor rarely mentioned in the research is related to the tightness of the chamber, and this is of fundamental importance since it can reduce the CO_2 concentration inside the chamber. Moreover, as it is a lethal gas, its escape must be prevented. Therefore, it is recommended that the chamber be perfectly sealed with glue, rubber, solder etc. and be checked for reliability with a tightness test.

Figures 1 and 2 shows some of the reported carbonation chambers with varying parameters.

From this review, it was possible to identify the pros and cons of each reference chamber and then propose a descriptive manual that lays out certain reliable designs and fabrication steps for creating and ensuring an accelerated carbonation chamber.

3. DESCRIPTIVE PLAN FOR CONSTRUCTION OF CARBONATION CHAMBER

This section presents the experimental methodology used to develop a prototype of a carbonation chamber for curing non-reinforced cementitious materials through accelerated carbonation. The chamber in question was built to work with a 100% concentration of CO_2, temperature of 25°C, humidity of 60%, 70% and 80%, and atmospheric pressure. It will perform the curing via the carbonation of the samples and concrete blocks (14 × 19 × 39 cm) with duration of 2h, 8h, 6h, 16h, 32h, and 64h.

The chamber's construction was carried out in three phases: The first phase comprised the development of the design project; defining the dimensions, the material to be used for making the chamber, the maximum number of samples to be tested, seals, hinges, door locks, ventilation, internal divisions, temperature, humidity,

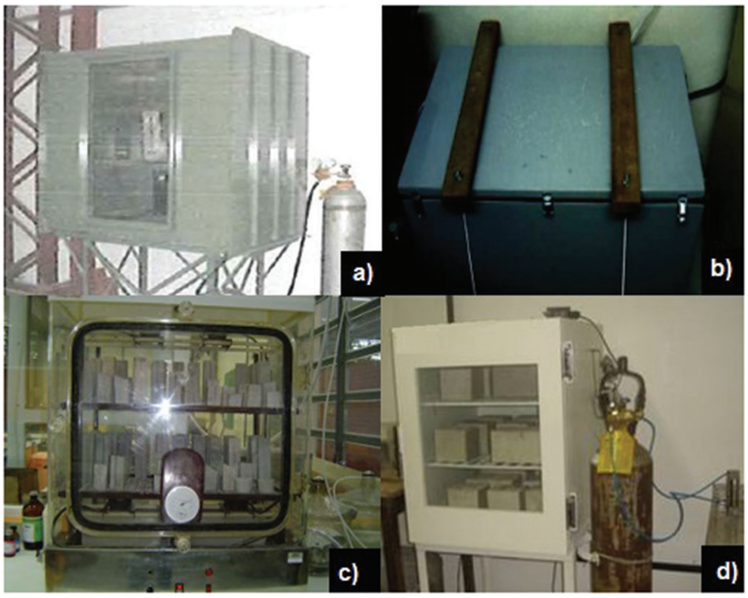

Figure 1: Carbonation chamber authors: a) SILVA [13] ; b) ABREU [14]; c) PAULETTI [11]; d) BARROS [16].

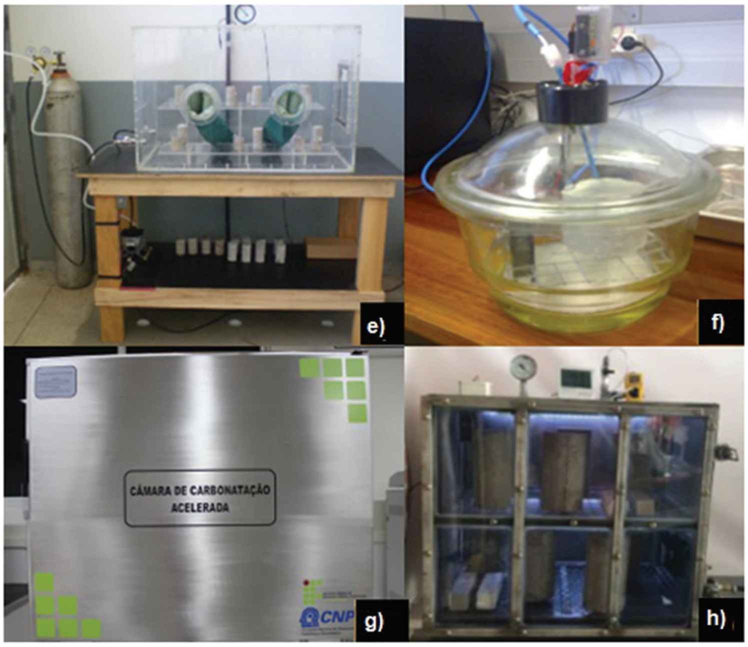

Figure 2: Continuation – Carbonation chamber authors: e) SALOMÃO and SILVA [17]; f) SALDANHA [18]; g) LUCENA [19]; h) SOARES *et al*. [20].

and CO_2 concentration probes The second phase focused on the construction of the accelerated carbonation chamber, and installation of the sensors, valves and pressure gauge. Finally, the third phase focused on the automation of the chamber through the installation of an interface and software compatible with the acquired probes, in addition to doing a sealing test. The development phases of the development are summarized in the flowchart illustrated in Figure 3.

3.1. Carbonation chamber project – 1st stage

This section provides information on the design of the carbonation chamber.

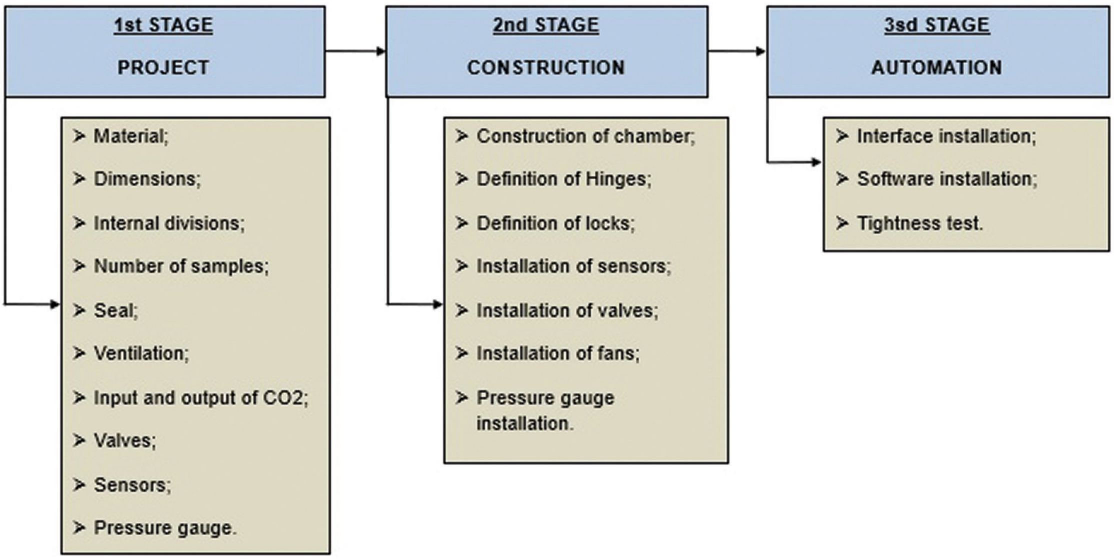

Figure 3: Design, construction, and automation of the carbonation chamber.
Source: Author (2020).

3.1.1. Materials, dimensions, internal divisions, and number of samples of the accelerated carbonation chamber

The accelerated carbonation chamber was designed using 10-mm acrylic sheets with internal dimensions 580 mm wide × 580 mm high × 490 mm deep, external dimensions 600 mm wide × 600 mm high × 500 mm deep. The 20 mm difference is due to the thickness of the acrylic sheet. The dimensions were determined as a function of the horizontal and vertical spacing to place the specimens, aiming for a better homogenization of the air as a function of height. The interior was designed with two shelves vertically separated from each other with 250 mm spacing. They are capable of supporting 72 prismatic concrete samples with dimensions 50 mm × 50 mm, separated from each other by 30 mm, to facilitate air circulation. The authors chose to work with acrylic sheets because it is a material that allows full visualization of the chamber's interiors. Moreover, it is more resistant and lighter than glass, has an abrasion resistance comparable to aluminum and has a thermal conductivity factor that is lower than that of glass and metal which makes it a good thermal insulator as well.

The shelves are also made of 10 mm thick acrylic sheets with dimensions 580 mm wide × 450 mm deep. Their surface was perforated by several 30 mm circular holes. To ease the air circulation inside the chamber, a spacing of 20 mm was left at the front and bottom. Figure 4 shows the top view of the shelf.

3.1.2. Ventilation of accelerated carbonation chamber

The accelerated carbonation chamber was designed to have two cooler-type fans inside the lower part of the chamber with the objective of favoring the equal CO_2 distribution inside it. This is because it is injected from the bottom and is heavier than regular air. It has a single opening door that is sealed with silicone rubber and locks, blocking any CO_2 leak from the chamber. Figure 5 shows the fans positioning.

3.1.3. Input and output of CO_2 and air

The chamber has a CO_2 inlet located on the left side that is 30 mm from the bottom and 250 mm from the front face, equipped with a valve to control the flow of CO_2. Moreover, it has an air outlet on the left side, 30 mm from the top and 250 mm from the front face that is also equipped with a valve to control the passage of air flow. The air outlet is located at the top of the chamber, as CO_2 is denser than air. So, while injecting CO_2 at the bottom, the upper valve remains open for controlling the air concentration. The accelerated carbonation chamber also has a CO_2 outlet, located on the left side, 30 mm from the bottom and 400 mm from the front face, and it will be used to empty the chamber when the tests are completed. In the experiments, it is predicted to work with a 100% CO_2 concentration. Figure 6 demonstrates the CO_2 input and output devices.

3.1.4. CO_2 sensor, humidity, and temperature

The probe to evaluate the CO_2 concentration works within a range between 0% and 100%. The sensor measures CO_2 levels through patented NDIR solid state LED technology that provides accurate CO_2 measurements over

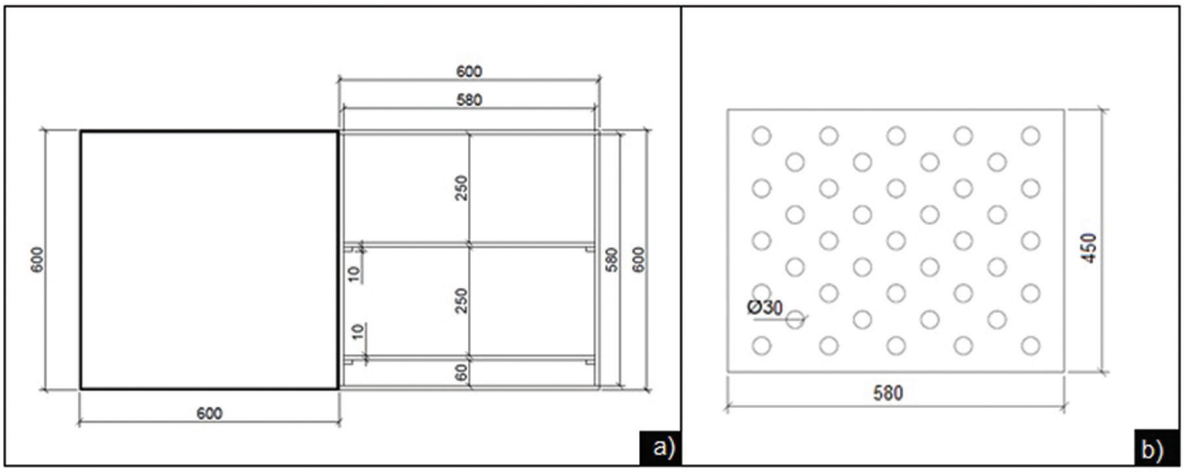

Figure 4: Project: a) Front views, shelves and carbonation chamber door; b) Shelves.
Source: Author (2020).

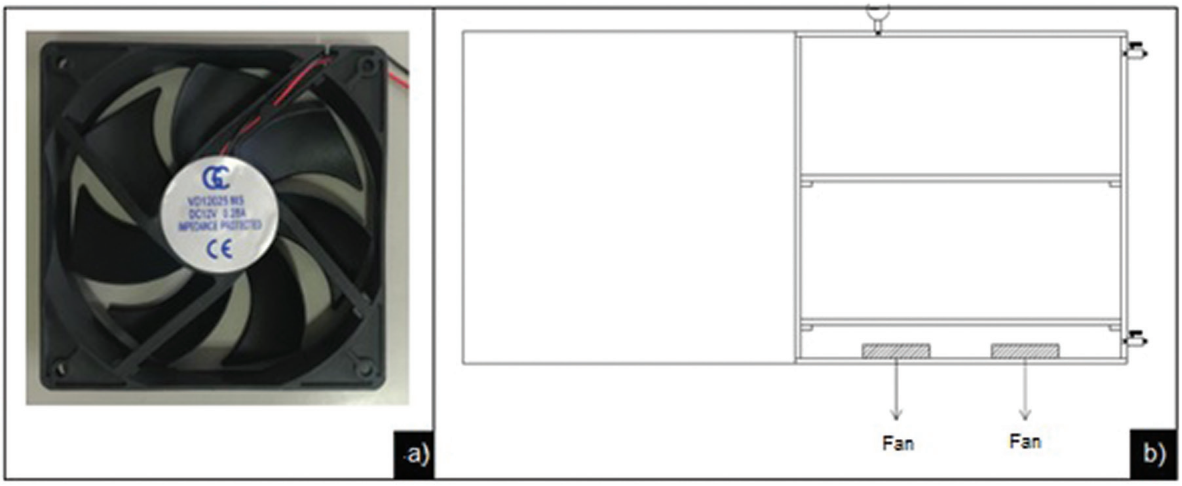

Figure 5: Fan: a) Description; b) position of fans in the chamber.
Source: Author (2020).

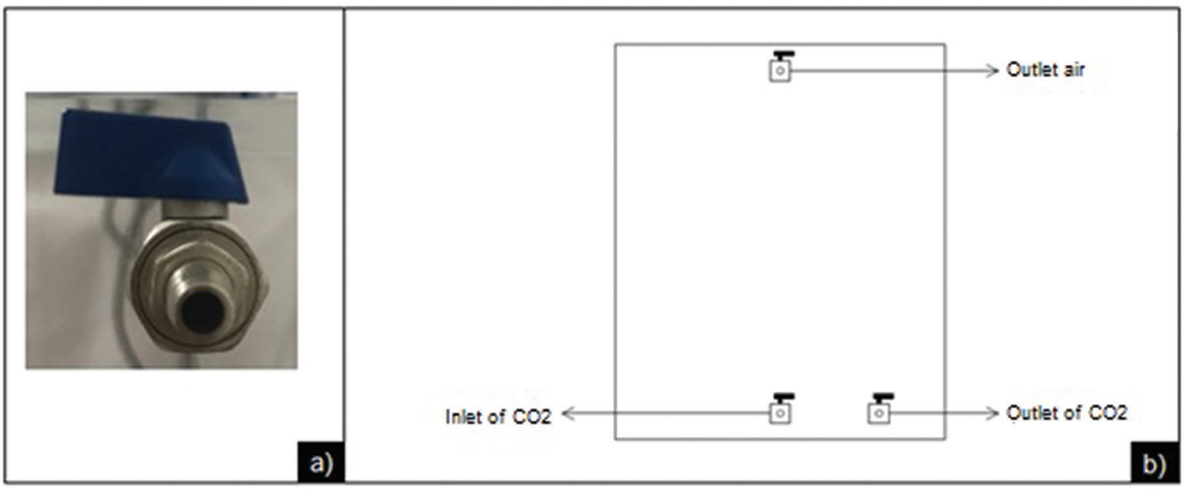

Figure 6: Valve to control the flow of carbon dioxide and air: a) Model; b) Left side view with CO_2 inlet device and air and CO_2 outlet.
Source: Author (2020).

a chamber's lifetime. The inlet nozzle for collecting the gas for analysis by the sensor was placed in the upper region of the chamber. This is because CO_2, being heavier than air, tends to get down. So when the reading is 100%, it means that the entire space of the chamber will be filled with CO_2. The relative humidity sensor contains an integrated circuit that monitors relative humidity in the range of 0 to 95% (± 5%). It uses a capacitive polymer to detect moisture. Following this, an integrated circuit produces an output voltage that varies with the relative humidity. The temperature probe evaluates the temperature inside the chamber, with an evaluation range between –40 and 135°C. This probe used a 20 k Ω NTC thermistor which is a variable resistor. When the temperature increases, the resistance decreases. The relative humidity and temperature probes were placed in the intermediate region of the chamber, as this location represents the average of the whole event. Figure 7 shows the probes for evaluating the CO_2 concentration, humidity, and temperature.

The relative humidity in the chamber can be obtained using salts. Each type of salt in an aqueous solution allows a specific relative humidity. Table 4 shows a list of commonly used salts and how each one contributes to a specific relative humidity [44]. The salts shall be placed on the carbonation chamber's base.

3.1.5. Pressure gauge

The manometer used has a Bourdon-type sensor with a stainless steel case and an interior made of brass alloy. It regulates pressure from 0 to 20 kgf/cm² and presents an accuracy of 1.6%. Figure 8 demonstrates the manometer to be used to check the pressure inside the chamber.

Figure 7: Sensors: a) CO_2 concentration; b) Humidity; c) Temperature.

Table 4: Relative humidity produced for different aqueous solutions.

SUPERSATURATED AQUEOUS SOLUTION		RELATIVE HUMIDITY OF SOLUTION AT 20 °C (%)
CHEMICAL COMPOST	CHEMICAL FORMULA	
Disodium phosphate	$Na_2HPO_4 \times 12\ H_2O$	95
Sodium carbonate	$Na_2CO_3 \times 10\ H_2O$	92
Zinc sulfate	$ZnSO_4 \times 7\ H_2O$	90
Potassium chloride	KCl	86
Ammonium sulfate	$(NH_4)2SO_4$	80
Sodium chloride	NaCl	76
Sodium nitrate	$NaNO_2$	65
Ammonium nitrate	NH_4NO_3	63
Calcium nitrate	$Ca\ (NO_3)_2 \times 4\ H_2O$	55
Potassium carbonate	K_2CO_3	45
Zinc nitrate	$Zn\ (NO_3)_2 \times 6\ H_2O$	42
Calcium chloride	$CaCl \times 6\ H_2O$	32
Lithium chloride	$Li \times H_2O$	15

Source: Adapted from [44].

Figure 8: Pressure gauge to control the pressure inside the chamber.
Source: Author (2020).

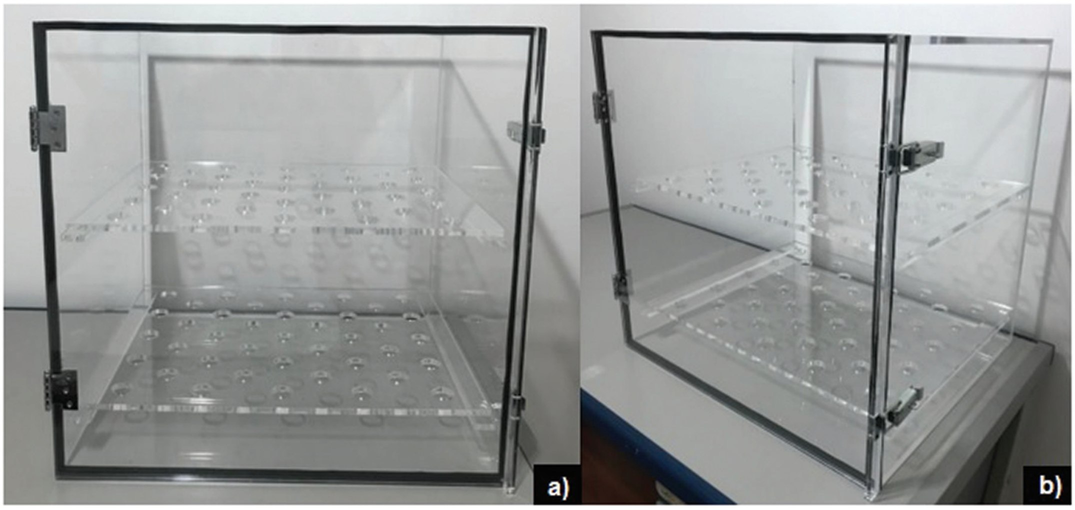

Figure 9: Carbonation chamber structure (acrylic box and shelves): a) front view; b) perspective view.

3.2. Construction of the carbonation chamber – 2nd stage

3.2.1. Chamber assemblage

The box and acrylic shelves are made by a specialized manufacturer. They are shown in Figure 9 below.

3.2.2. Sealing of the carbonation chamber

For perfect sealing of the carbonation door, the installation of five pivoting and self-adjusting hinges was designed. When the door is closed, they slide along its axis to avoid the guillotine effect on the sealing rubber; silicone rubber in contact region between the door and the chamber. It also avoids the same from happening on the two latches installed on the other sides of the door. Figure 10 demonstrates what was performed.

3.3. Automation of the carbonation chamber – 3rd stage

3.3.1. Software and interface installation

All the data collected by the probes were imported in specialized programs. In the case of the CO_2 sensor, the data were analyzed by a specific program provided by the manufacturer and graphically plotted as shown in Figure 11.

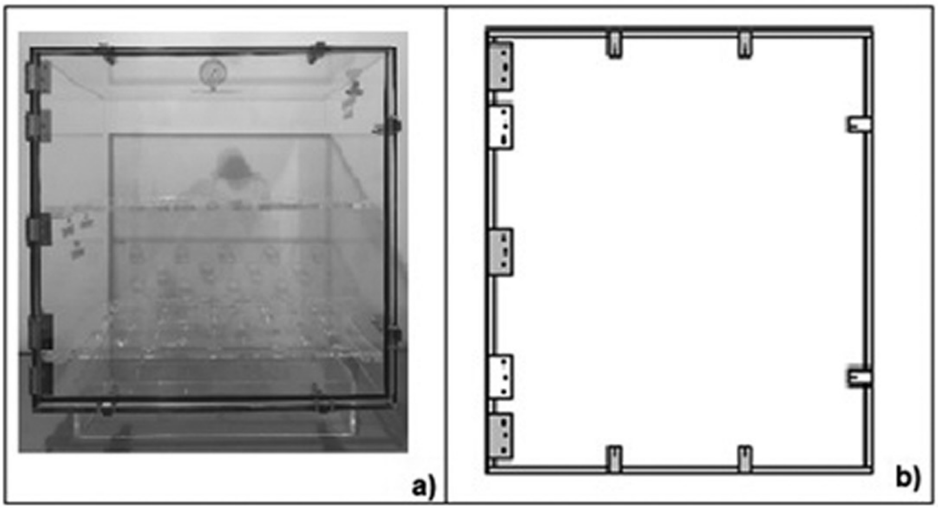

Figure 10: Hinges and latches installed for perfect sealing of the chamber: a) hinges and latches; b) project with emphasis on the new hinges and locks.

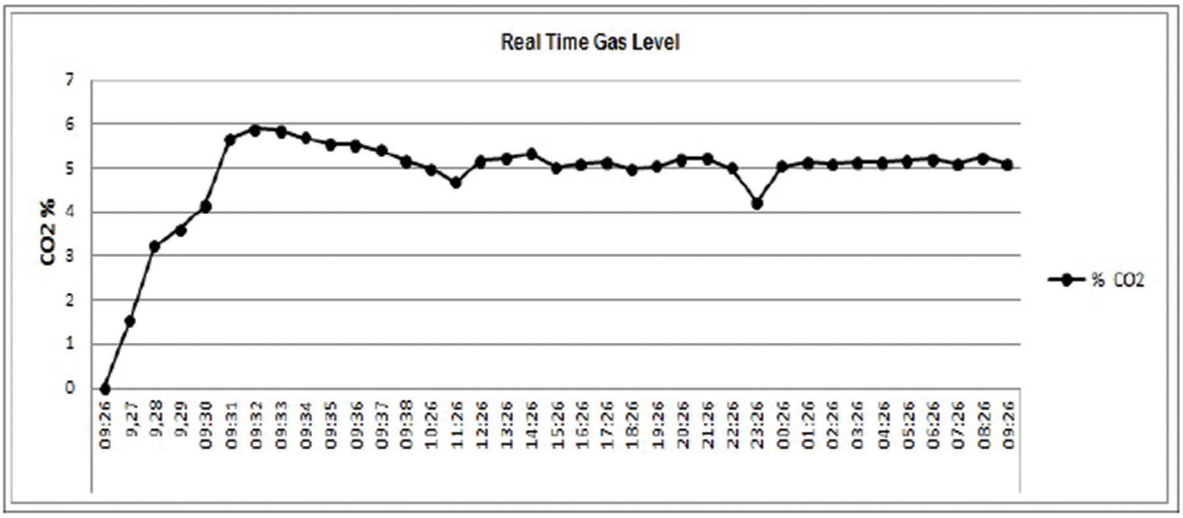

Figure 11: CO_2 concentration graph – reading history for 24 hours – experimental model.
Source: Author (2021).

For the data collection pertaining to temperature and relative humidity, an autonomous interface which features an integrated graphics and analysis application is used. These sensors are installed via a USB-type cable. Figure 12 demonstrates the autonomous interface.

3.3.2. Airtight test

Finally, with the aim of checking possible leaks, the carbonation chamber was sent to a workshop specialized in carrying out tests on pressure vessels and underwent a sealing test. The test consisted of connecting a compressor with a capacity of 16 kgf/cm^2 and a standard calibration manometer to one of the gas outlet valves of the carbonation chamber. After initiating the test, the pressure inside the reservoir as well as inside valves and pipelines of the carbonation chamber was recorded. In the end, an airtight certificate was issued.

3.3.3. Completion of the chamber

Figure 13 illustrates the carbonation chamber in operation with all the devices, sensors and connections installed.

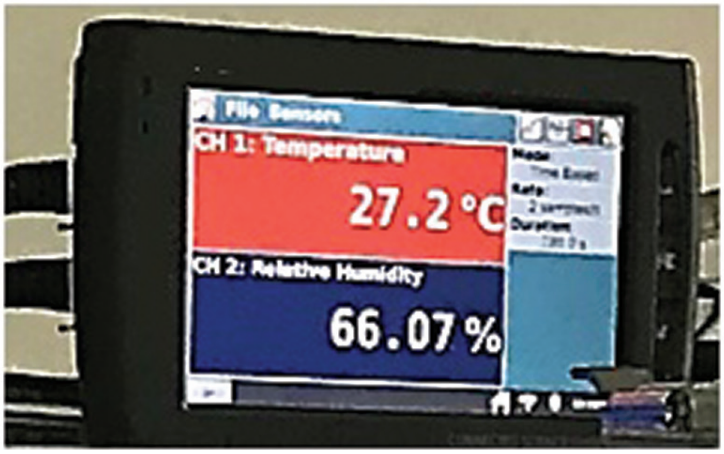

Figure 12: Standalone interface.
Source: Author (2020).

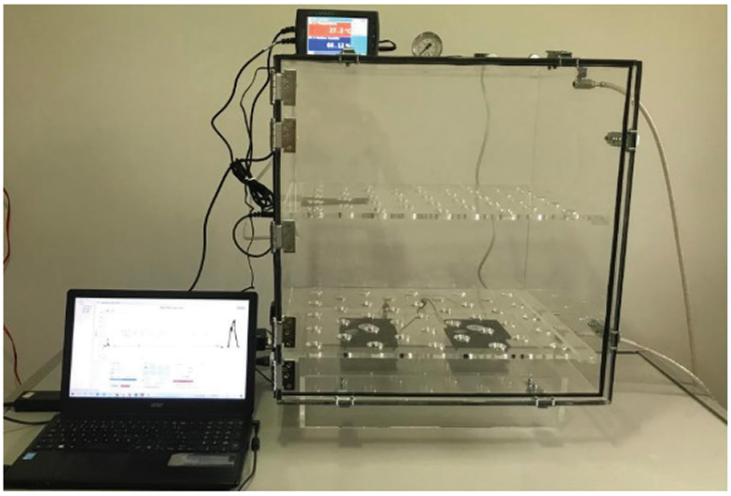

Figure 13: The completed carbonation chamber.

4. FINAL CONSIDERATIONS

The present article presented a compilation of the main concepts related to the accelerated carbonation curing, a literature review of the different carbonation chambers made by researchers and provided a descriptive manual for the construction of an alternative low-cost carbonation chamber. The developed chamber will be primarily used to cure concrete blocks although it can cure other non-reinforced cementitious materials. It can also be used to study the service life of reinforced concrete exposed to weathering carbonation. During the construction of the carbonation chamber, the challenge faced was the acquisition of a CO_2 sensor that could reach 100% CO_2 concentration since researchers, in general, work with low concentrations of CO_2 (as low as 20%). However, in the end, the chamber performed well and showed more advantages over the other projects presented in this article:

- **Chamber structure – Materials:** the chamber was construed with acrylic sheets. The authors choose this material because which is a crystalline and transparent material, with 92% light transmission, (superior to glass and other plastics), it also has better impact resistance at less than half the weight of glass. In addition, its abrasion resistance is comparable to that of aluminum, but when scratched it is fully recovered by polishing; It has good impact resistance and does not shatter like glass if dropped. In addition, its thermal conductivity factor is inferior to glass and metal, being considered a good thermal insulator.
- **Ventilation:** It were installed two fans, inside the lower part of the chamber, that allowed the circulation and homogenization of carbon dioxide inside the chamber. The location and position of the fans was determined considering the dimensions of the chamber and the size and shape of the samples.

- **Input and output of CO_2 and air:** The Input and output of CO_2 and air were performed through specific valves and located in strategics points on the chamber. The air outlet was located at the top of the chamber, as carbon dioxide is denser than air, and the CO_2 inlet was located at the bottom of the chamber.
- **Sensors and automation:** It were installed sensors of the temperature, humidity, and CO_2 concentration. They control and record the mentioned parameters through specific software.
- **Airtight:** For perfect sealing of the carbonation chamber, pivoting and self-adjusting hinges, silicone rubber and latches, were installed, with no leaks observed during operation.

Therefore, it can be concluded that the design, manufacture and automation of the carbonation chamber were successfully completed, being an economical and viable solution for use in carbonation tests on different materials.

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