University of Beira Interior – Faculty of Engineering

Course:

Nature-Based Carbonation: From Biomass and Wool to Circular Construction Materials

1. Course Structure

The course was structured into four modules, as shown in Table1 .

Table1 : Course structure.

Module	Title	Objective
Module 1	Introduction to Natural and Accelerated Carbonation	Understand the scientific principles of carbonation and its role in sustainable construction.
Module 2	Biomass and Wool as Circular Resources	Explore the potential of regional waste (biomass and wool) as low-carbon raw materials.
Module 3	Carbonation Processes and Technologies	Understand laboratory and field methods to accelerate carbonation and reduce emissions.
Module 4	Practical part – Preparation and accelerated carbonation of mixtures with wool and biomass	Demonstrate the effectiveness of wool and biomass in the production of circular materials through accelerated carbonation and their application in modular construction components.
	Final Assessment	Assessment of acquired knowledge.

Module 1 — Introduction to Natural and Accelerated Carbonation

1.1 Introduction

The course "Nature-Based Carbonation: From Biomass and Wool to Circular Construction Materials" is part of the European Bauhaus Academy (NEBA — New European Bauhaus Academy Alliance), funded by the Circular Bio-based Europe Joint Undertaking (CBE JU) under the Horizon Europe programme (Grant Agreement No. 101160532).

It is a practical laboratory course, developed in the spirit of the New European Bauhaus, which promotes learning through experimentation, collaborative work and interdisciplinarity. It brings together students, researchers, companies, associations and architectural firms with the aim of exploring the collective capacity to develop circular innovation from regional materials and resources.

The course focuses on learning how to transform waste into circular materials — mixtures that harden with CO_2 absorption and incorporate wool and biomass. These materials, based on electric arc furnace slag and other by-products rich in calcium and magnesium, harden through a process called accelerated carbonation.

Wool and biomass do not participate directly in the chemical reaction, but play a key role in increasing the porosity of the material, promoting CO_2 diffusion and improving the thermal and mechanical properties of the parts produced.

1.2 What is mineralisation or carbonation?

On a geological scale, the carbonate-silicate cycle is a natural process that transforms atmospheric CO_2 into carbonic acid, which reacts with calcium and magnesium minerals to form stable carbonates, sedimentary rocks that store carbon for millions of years, Figure 1. The low reaction rate is due to the low concentration of atmospheric CO_2 [1]. This process is also known as mineral carbonation.

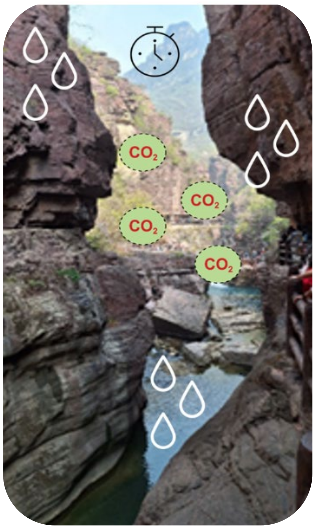

Figure 1: Illustration of limestone rock carbonated over thousands of years.

Reaction for the formation of carbonates and silica from silicates

$$(Ca, Mg)_xSi_yO_{x+2y} + zH_2O(l) + xCO_2(g) \rightarrow x(Ca, Mg)CO_3(s) + ySiO_2(s) + zH_2O(g/l) \quad (1)$$

Chemical equation (1) generally represents the mineral carbonation process, where silicate minerals react with water (H_2O) and carbon dioxide (CO_2) to form solid calcium and magnesium carbonates – $(Ca,Mg)CO_3$, solid silica – SiO_2 and water (in liquid or gaseous form) [2].

1.3 Difference between natural and accelerated carbonation.

Unlike natural carbonation, which can take thousands or millions of years, accelerated carbonation is a rapid process, inspired by the natural process, but carried out in just a few hours under controlled laboratory conditions.

Accelerated carbonation is based on the reaction between CO_2 and materials rich in calcium and magnesium. When exposed to gas under suitable conditions of temperature, pressure and humidity, stable carbonates ($CaCO_3$ and $MgCO_3$) are formed, which act as binders, giving the material strength and durability [3] .

For example, in the case of electric arc furnace slag, the presence of free calcium and magnesium oxides is crucial to the effectiveness of the process. Curing is carried out in a carbonation chamber, where temperature and pressure parameters are carefully adjusted to optimise CO_2 absorption [4].

1.4 Role of CO_2 and minerals in the process.

During the process, CO_2 diffuses into the moisture present in the pores of the material and forms carbonic acid (H_2CO_3). This ionises into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, which react with calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions to produce solid carbonates. This mechanism can occur through thin film carbonation, when CO_2 circulates around the particles, or in an aqueous medium, when the particles are partially immersed, as illustrated in Figure 2.

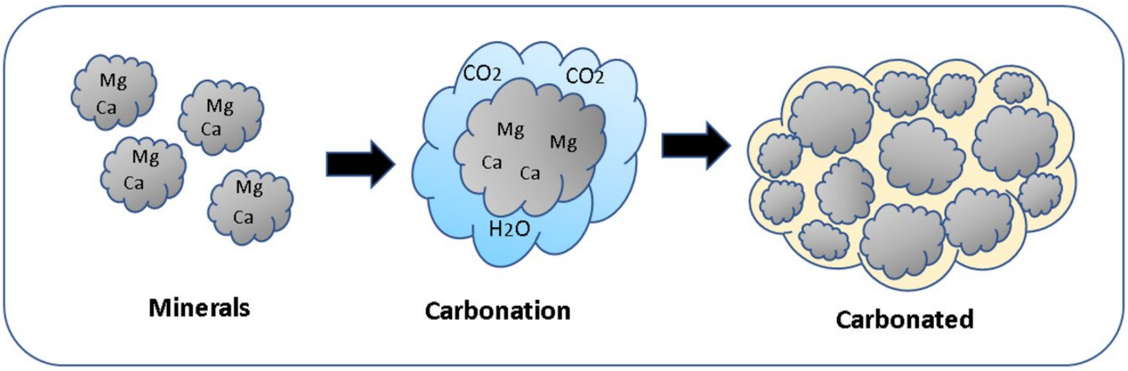

Figure 2: illustration of the water film reacting with CO_2 and minerals to form carbonates.

The technology can be applied to various industrial and mineral wastes rich in calcium and magnesium, such as steel slag (EAFS, BOFS, GGBFS), cement dust, biomass ash, and even brines from desalination processes. The principle is simple: reuse waste containing reactive oxides, transforming it into carbon-negative building materials [4].

The efficiency of carbonation depends on several parameters. Among the most important are CO_2 concentration, temperature, pressure, moisture content, particle size, surface area, and reaction time. Higher CO_2 concentrations and moderate temperatures promote faster and more complete reactions. Higher pressures increase the solubility of the gas, while adequate moisture is essential to dissolve the CO_2 and initiate the reaction. Finer, more porous particles offer a larger contact area and therefore greater efficiency [5].

One of the main challenges of the process is to ensure uniform carbonation. CO_2 reacts first on the surface, forming an outer layer that can hinder the penetration of gas into the inner zones.

Porosity and compaction pressure determine how easily CO_2 diffuses into the sample, as shown in Figure 3. It is necessary to find a balance between a structure that is open enough to allow diffusion and dense enough to ensure strength and durability.

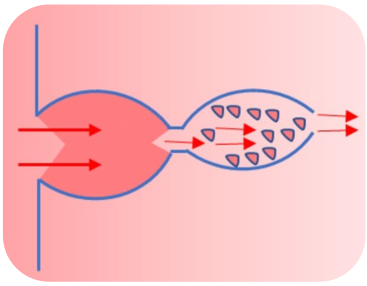

Figure 3: Dynamics of CO_2 penetrating the pores of the sample.

The use of different types of waste can significantly improve the process. Biomass fly ash, for example, helps to create a more balanced porosity, allowing CO_2 to penetrate the material better. This more open microstructure favours gas diffusion and increases the degree of carbonation.

The incorporation of natural fibres, such as wool, or recycled textiles, between 1 and 3%, also has an important effect. The fibres create additional diffusion paths for CO_2, increasing absorption and uniformity of the reaction. In addition, they act as micro-reinforcements, improving the mechanical strength and thermal behaviour of the materials.

1.5 How carbonation contributes to reducing emissions in construction.

Accelerated carbonation technology has the potential to be integrated into regional and national circular economy models. It allows the recovery of waste from the steel industry, biomass, construction and other sectors, generating new building materials with low environmental impact. This model promotes synergies between different industries and communities, reduces CO_2 emissions and creates local opportunities for sustainable innovation [6].

Accelerated carbonation demonstrates that it is possible to capture CO_2 and transform it into useful solid matter, integrating industrial and natural waste into a sustainable production cycle. The process combines scientific knowledge, technology and the recovery of local resources, reflecting the spirit of the New European Bauhaus — combining beauty, sustainability and inclusion in the creation of new materials for the construction of the future.

The development of new products in civil construction capable of capturing CO_2 is already a reality. For example, DarkCO₂ and ECOBLOCKS used slag and CO_2 to develop 25kg blocks [7], while Carbon8 used industrial waste to produce aggregates called CircaBuild [8].

Module 2 — Biomass and Wool as Circular Resources

2.1 Biomass

Biomass broadly refers to organic matter, including plants, animals, and microorganisms, making it an abundant, renewable, and low-pollution raw material [9].

2.2 Regional sources of biomass

- Forest biomass/forest residues: This is the most significant type of biomass in Portugal. It includes forestry residues such as branches, foliage, wood from tree felling, and residues from the pulp and paper industry. Figure 4 illustrates the process of preparing biomass for use in energy production.

Figure 4: Vegetation is shredded for use in energy production.

- Agricultural or agro-industrial/animal farming waste Biomass from agricultural crops, crop residues, agricultural or livestock production waste. For example, wool is a renewable organic resource from animals (mainly sheep), as shown in Figure 5. By nature, it falls into the category of animal biomass. In Portugal, wool production is mainly linked to regions with a tradition of sheep farming, such as Beira Interior (e.g. Covilhã — historic wool industry)

Figure 5: Sheep grazing.

Module 3 — Carbonation Processes and Technologies

3.1 The Carbonation Process

The accelerated carbonation process consists of several stages, each performing a specific function. The grinding stage, for example, consists of preparing the raw material, with the aim of making the binding material more reactive. This is followed by the mixing stage, which is intended to homogenise the materials, ensuring that the components are proportionally distributed in the final paste.

After mixing, the material is placed in moulds of the desired shape and subjected to static compaction, allowing the particles to bind together and form a cohesive mass (e.g. blocks or panels). These moulded elements are then placed in a chamber filled with CO2, under controlled conditions of pressure, temperature and humidity. It should be noted that each of these parameters directly influences the curing process of the test specimens.

After a curing period, usually 24 hours, the test specimens are removed and placed in an oven for the same period for stabilisation. Once this stage is complete, the test specimens are then subjected to laboratory tests and trials. The Figure 6 illustrates the step-by-step carbonation process.

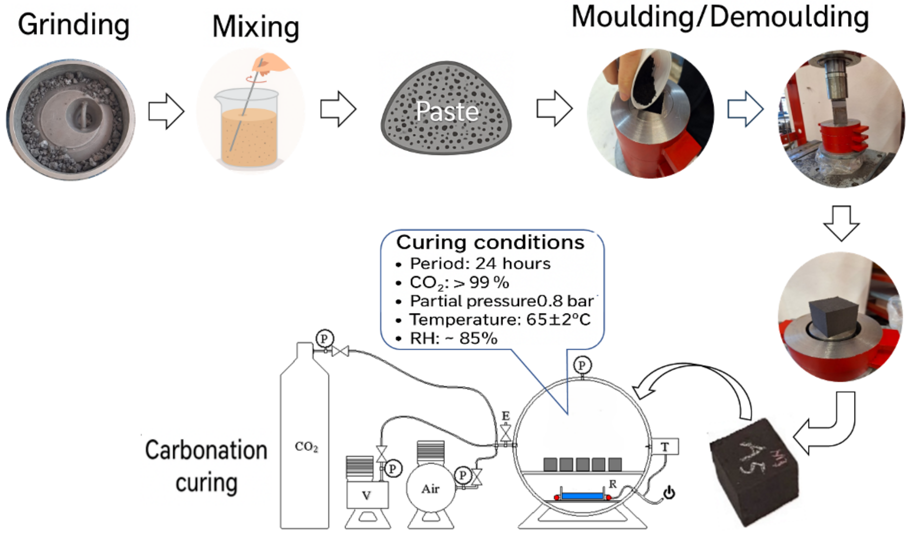

Figure 6: Step-by-step carbonation process.

Module 4 — Practical part — Preparation and accelerated carbonation of mixtures with wool and biomass

4.1 Introduction

In this module, participants learn how to prepare mixtures based on electric arc furnace slag and other by-products rich in calcium and magnesium, which harden with the absorption of CO_2 in a process called accelerated carbonation, also incorporating wool and biomass.

The process involves the preparation of mixtures, shaping and static compaction, and direct carbonation, carried out in a carbonation chamber under controlled conditions of humidity, temperature and CO_2 concentration, as studied in the previous module.

Different compositions will be produced and tested in small-scale prototypes, integrating materials and knowledge from the local community. The activity aims to exemplify how circular materials can be developed from waste and by- ble to harden by absorbing CO_2, incorporating regional by-products and generating lightweight and resistant pieces, suitable for modular construction.

The presence of wool fibres, biochar and other plant fibres alters the properties of the pieces, increasing porosity and internal pathways for CO_2 diffusion, which facilitates carbonation. On the other hand, it can improve their mechanical properties.

The mixtures can be prepared without the need for drinking water; the water used is not absorbed by the slag or mineral residues and can be fully recovered, and can even be seawater or waste water.

During the experimental component, simple measurements will be carried out to verify CO_2 absorption, qualitatively assess heat transfer resistance and quantitatively assess compressive strength, with the aim of understanding the behaviour and potential of these materials.

Overall objective: to demonstrate the effectiveness of wool and biomass in the production of circular materials through accelerated carbonation and their application in modular construction components capable of sequestering CO_2, reducing environmental impact and improving the thermal performance of buildings.

4.2 Experimental procedures

4.2.1 Preparation of raw materials

At this stage, the binder (slag) is ground in a disc mill (Figure 7) to make it finer and more reactive, while the aggregates (e.g., wool and biomass) are processed to increase the porosity of the mixture, an essential characteristic for CO2 penetration. To this end, the wool and biomass undergo a cutting process in a blade mill, Figure 7 .

Figure 7: Grinding of slag and cutting of wool.

4.2.2 Mixtures to be produced

Table 2 below illustrates the mixtures for the production of pieces measuring approximately 30 x 16 cm with a thickness of 1.5 cm.

Table 2 : Experimental Formulations and Mixing Parameters.

Mixture	Electric arc furnace slag	River sand	Wool	Biomass fibres	Reactive magnesium oxide	Slag sand	Water
M1	700g	18g	45g/45g	-	200g	-	240g
M2	500g	-	70g	-	120g	200g	200g
M3	500g	-	-	60g	120g	200g	200g

4.2.3 Preparation and moulding of mixtures

The first step is to select one or two formulations from the table above. Next, weigh and mix the components, homogenising them dry before adding the wool, biochar and/or fibres. Here is an example of mixture M3 (see Figure 8).

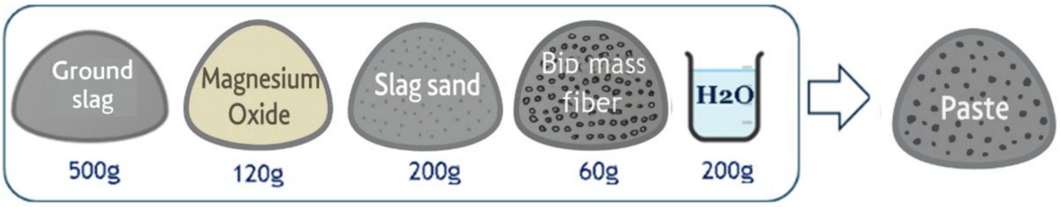

Figure 8: Paste formulation.

After homogenisation (Figure 9) of the dry materials, water is added according to the chosen formulation. Non-potable water or wastewater may be used.

Figure 9: Homogenisation of the material.

Next, the mixture is placed in moulds or plates (Figure 10), where static compaction is performed, followed by surface finishing (see Figure 11).

Figure 10: Preparation of moulds.

Figure 11: Prepared test specimens.

4.2.4 Accelerated carbonation

The pieces are placed in the carbonation chamber with humidity, temperature and CO_2 concentration control, as shown in Figure 12 .

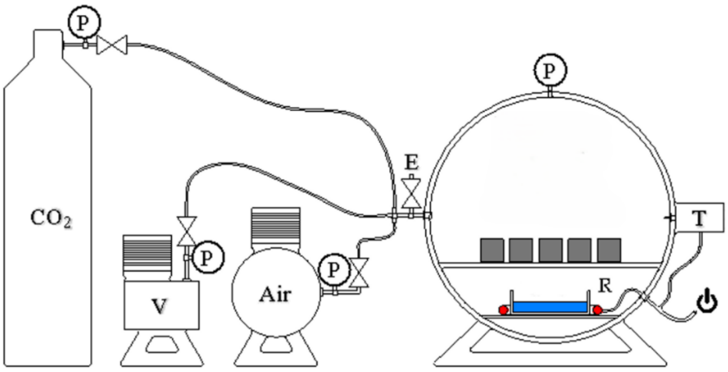

Figure 12: Carbonation curing system.

The operating conditions are 0.8 bar differential pressure, 60ºC temperature and 24 hours of exposure.

After the carbonation process, adequate ventilation must be ensured when opening the chamber, and personal protective equipment (PPE) must always be used.

4.2.5 Verification and measurements after carbonation

The next day, after 24 hours of exposure, check the produced parts and observe whether they have gained strength (see Figure 13).

Figure 13: Opening the chamber and checking the test specimens.

Then place the pieces in an oven at 60-70°C for 1 hour, allow to cool and weigh the mass of the pieces after carbonation, as shown in Figure 14.

Figure 14: Stabilisation of the test specimens in an oven.

In order to determine the difference in mass resulting from the carbonation process (Δm), it is necessary to calculate the difference between the final mass (m_f) of the sample after the test and the initial mass of the mixture (m_i), disregarding the water initially present (m_{H_2O}).

$$\Delta m = m_f - (m_i - m_{H_2O})$$

Conclude based on the observed results and discuss the mass gain associated with CO_2 absorption. It should be noted that the value of Δm represents the mass gain or loss associated with the carbonation reaction. If $\Delta m > 0$, there is a mass gain, usually due to the incorporation of carbon dioxide (CO_2) into the sample. On the other hand, if $\Delta m < 0$, there is a loss of mass, indicating the release of volatile components or decomposition of products.

In parallel, perform compressive strength tests on the small specimens produced, as shown in Figure 15.

Figure 15: Compression tests.

Also carry out a comparative assessment of thermal resistance, using a heating plate set at 40–50 °C. After 5 minutes in contact with the heat source, measure the surface temperature with a laser thermometer on two comparable plates and record which one shows the lowest temperature increase, as per Figure 16.

Figure 16: Thermal resistance test.

Record all data relating to masses, exposure conditions, mechanical resistance, thermal behaviour and visual observations.

4.2.6 Expected Results and Analysis

The addition of wool and biomass is expected to increase the degree of slag carbonation due to greater porosity and more effective CO_2 diffusion.

Samples treated with wool and biomass may have lower density and slightly reduced mechanical strength, but will still maintain good mechanical strength.

Improved thermal behaviour and greater insulation and heat retention capacity are expected.

4.2.7 Conclusion

Conclude on the effectiveness of wool and biomass in slag carbonation and on the implications of this process for the sustainable construction industry, considering its potential use as a coating material, thermal insulation and modular components with low environmental impact.

5. Final Assessment

Objective: To consolidate the knowledge acquired and assess understanding.

Final Quiz (10 Questions)

1. What is accelerated carbonation?

(A) Process of water evaporation in cementitious materials

(B) A natural process that occurs only in sedimentary rocks

(C) Rapid reaction between CO_2 and calcium/magnesium-rich materials under controlled conditions

(D) Technique for heating waste to produce energy

✓ Correct answer: C

2. What differentiates natural carbonation from accelerated carbonation?

(A) Natural carbonation uses only liquid CO_2, while accelerated carbonation uses gaseous CO_2

(B) Accelerated carbonation occurs in hours, while natural carbonation takes thousands of years

(C) Natural carbonation requires high temperatures, while accelerated carbonation occurs at low temperatures

(D) Accelerated carbonation occurs exclusively in marine environments

✓ Correct answer: B

3. What is the main role of wool in carbonated mixtures?

(A) To increase the final mass of the test specimens

(B) To participate directly in the chemical reaction of carbonation

(C) To increase porosity and facilitate CO_2 diffusion

(D) To reduce the need for slag in the mixture

✓ Correct answer: C

4. Which of the options below is an example of regional biomass in Portugal?

(A) River sand

(B) Coal ash

(C) Wool from sheep

(D) Steel slag

✓ Correct answer: C

5. What is the main environmental benefit of accelerated carbonation?

(A) It increases fossil fuel consumption

(B) Generates toxic waste during curing

(C) Captures CO_2 and transforms it into a stable solid

(D) Reduces the mechanical strength of materials

✓ Correct answer: C

6. Which parameter does NOT directly influence the efficiency of accelerated carbonation?

(A) CO_2 concentration

(B) Particle size

(C) Temperature

(D) Colour of materials used

✓ Correct answer: D

7. During the carbonation reaction, CO_2 initially:

(A) Reacts with magnesium to produce hydrogen gas

(B) Dissolves in the pores, forming carbonic acid

(C) Evaporates from the surface of the material

(D) Replaces water in the binder structure

✓ Correct answer: B

8. Why is the slag used as a binder ground beforehand?

(A) To reduce its alkalinity

(B) To lower the curing temperature

(C) To increase its reactivity and surface area

(D) To remove organic impurities

✓ Correct answer: C

9. During the preparation of mixtures, why is it important to perform dry homogenisation before adding water?

(A) To reduce the temperature of the material

(B) To ensure uniform distribution of solid components

(C) To improve the aesthetics of the final piece

(D) To avoid the need for compaction

✓ Correct answer: B

10. Which of the following represents one of the challenges of accelerated carbonation?

(A) The reaction occurs too quickly to be controlled

(B) The formation of an external carbonated layer that hinders CO_2 penetration

(C) The need to use only potable water

(D) The impossibility of using natural fibres

✓ Correct answer: B

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