

# EFFECT OF DIFFERENT CURING CONDITIONS ON THE PROPERTIES OF HARDENED CONCRETE

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## Article history

Received 17 December 2025

Revised 07 May 2026

Accepted 14 May 2026

## Abstract

*This paper focuses on the sustainable materials introduced as a response to the NET ZERO ROADMAP proposed by the European Cement Association (CEMBUREAU). This process involves the use of composite binders with a limiting clinker fraction in the final product. As this is a different approach, we may expect different behaviour under severe conditions, and this question needs to be addressed. This research investigates the behaviour of concrete and various binders under different curing conditions, which simulate the long-term effects of carbonation by exposing the samples to climate conditions with ultra-high CO<sub>2</sub> content in the air. The testing of the specimens includes compression and flexure strength, the dynamic elastic modulus, and thermal analysis of the binders. The specimens cured with an CO<sub>2</sub> demonstrated comparable early-age compressive strength and achieved values that were approximately 4 % greater at 2 days in comparison to those cured with water. By 7 days, the strength advantage of the CO<sub>2</sub> cured specimens increased to 18 %. Finally at 28 days, significantly higher strengths for the CO<sub>2</sub>-cured samples, with values exceeding those of the water-cured samples by 30 % had resulted. The development in strength observed in the CO<sub>2</sub> curing is attributed to the rapid precipitation of the CaCO<sub>3</sub> and the refinement of the pores, while the water curing facilitated a slower yet continuous gain in strength due to the ongoing process of hydration. The results from the Derivative Thermogravimetry (DTG) indicated significant changes in the oxide composition of binders, which are related to changes in the structural behaviour of materials.*

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## Key words

- Concrete,
- Cement,
- Composite cements,
- Sustainability,
- Carbonation.

## 1 INTRODUCTION

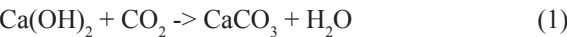
Concrete is a complex material composed of relatively few constituents, yet it is highly sensitive to proportions of the mixture and the boundary conditions. While preparing concrete mixtures under controlled laboratory conditions is

relatively straightforward, the surrounding environment is an additional critical factor that influences the performance of the material. In the context of contemporary climate challenges, sustainability has become a central concern and the development of new materials with a reduced environmental impact should be considered a priority. Ordinary Portland

cement (OPC) production generates substantial amounts of CO<sub>2</sub>; however, this greenhouse gas can also undergo secondary reactions with clinker phases by forming stable carbonate products and thereby indirectly contributing to the reduced carbon footprint of the material (Poon et al. 2004).

Previous studies have demonstrated that the application of CO<sub>2</sub> during the early stages of setting and hardening can lead to a refined microstructure, increased matrix density, and improved physico-mechanical properties, such as enhanced compressive strength and reduced water permeability (Liu et al. 2021; Thomas et al. 2013). Given the crucial role of hydration, two distinct curing regimes were employed in the present study. The first involved exposure to 100 % relative humidity and served as the reference condition; the second group was placed in a chamber with an elevated CO<sub>2</sub> concentration in the atmosphere (Poon et al. 2004; Tam and Tam 2007). By comparing the results across these two regimes, it is possible to determine whether controlled CO<sub>2</sub> exposure during the initial curing phases is a promising strategy for developing sustainable concrete mixtures with reduced environmental impact and improved material performance.

Acceleration carbonation curing is based on the reaction between carbon dioxide and hydration products formed during hydration of the cement. The main reactions involve calcium hydroxide (portlandite) and partially hydrated calcium silicate hydrate (C-S-H) phases, which leads to the precipitation of calcium carbonate (CaCO<sub>3</sub>) according to the following simplified reactions for calcium hydroxide (1) and C-S-H gel (2):



Despite the significant progress achieved in recent years, several unresolved questions remain regarding the combined effects of carbonation curing, moisture transport, hydration kinetics, and long-term durability. Most previous studies focused either on cement pastes or on conventional OPC systems, while relatively limited information is available concerning fine-grained concretes prepared with optimized particle packing and exposed to elevated CO<sub>2</sub> concentrations during early curing stages. In particular, the relationship between carbonation-induced microstructural refinement, dynamic modulus of elasticity, shrinkage development, and mineral phase evolution remains insufficiently understood.

The originality of the current research is found in the integrated assessment of the mechanical, physical, and thermal properties of fine-grained concrete subjected to controlled curing conditions with increased CO<sub>2</sub> levels. Beyond the development of compressive and flexural strength, this study examines the dynamic modulus of elasticity, shrinkage behaviour, changes in density, and the derivative thermogravimetric (DTG) characteristics of hydration products. Consequently, this research enhances the understanding of the interplay between accelerated carbonation and hydration processes in cement-based materials intended for low-carbon construction applications.

2 MATERIALS AND METHODS

2.1 Materials

OPC ExtraCem CEM I 42,5 R (Danucem, a. s., Slovakia) was used for the production. We tested the OPC density with a gas pycnometer Pentapyc™ 5200e and the specific surface area (SSA) with a Blain apparatus Dyckerhoff system. We conducted chemical analysis using ED RFS Energy-dispersive X-Ray Fluorescence Spectrometer from SPECTO type SPECTROXEPOS HE equipped with an X-ray lamp and a oxide composition analysis using Phillips PW-1800 X-ray fluorescence (XRF) as found in Table 1.

Tab. 1 Characterisation of OPC

| Oxide composition<br>[wt%] |                  |                                |                                |      |                 | Density<br>[kg m <sup>-3</sup> ] | SSA<br>[m <sup>2</sup> kg <sup>-1</sup> ] |
|----------------------------|------------------|--------------------------------|--------------------------------|------|-----------------|----------------------------------|-------------------------------------------|
| CaO                        | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | MgO  | SO <sub>3</sub> |                                  | 1456<br>(BET)                             |
| 64.24                      | 19.73            | 4.4                            | 2.51                           | 1.85 | 2.95            | 3110                             | 472.5<br>(Blaine)                         |

Aggregates

We used a normal-weight granite aggregate (Danucem, Slovakia). The testing of the aggregates consisted of measuring the density of magnetite using a gas pycnometer Pentapyc™ 5200e and analysing the geometric properties of the aggregate using the SIKA Sand App. The density of the aggregate was 2670 kg/m<sup>3</sup>; the aggregates were screened and mixed to suit optimum curvature according to Andreassen.

Additives

The superplasticizer STACHEMENT 2063 (Stachema Bratislava a.s. Slovakia) was employed

2.2 Methods

2.2.1 Preparation of the samples

The carbonation process transpires in three distinct phases, i.e., vapor, liquid, and solid. In this context, the liquid phase that resides on the surface of the solid phase acts as a solvent by facilitating the carbonation reaction. It is important to note that the excessive presence of water on the solid surface can impede the carbonation reaction. Therefore, it is essential to maintain an optimal water level to ensure efficient progression of the carbonation reaction (Goto et al. 1998). All the river aggregates were processed using square sieves of sizes 0.063, 0.125, 0.25, 0.5, 1.0, 2.0, and 4.0 mm. This procedure enabled us to achieve the required curvature and aggregate distribution. The mixtures were formulated in accordance with the specifications outlined in Table 2. Normal-weight fine-grained concrete mixes were prepared following the Slovak National Annex of EN 206 (EN 206+A2 2021) and adhered to the limits defined by lines A and B as illustrated in Figure 1. The proportions of cement, water, and additives were consistently maintained relative to the mass of the aggregates

across all the experiments. The OPC properties are stated in Table 1. Samples with dimensions of 40 x 40 x 160 mm were prepared to enable accelerated testing of the curing conditions in a climatic chamber with an elevated CO<sub>2</sub> concentration (Kuzielová et al. 2023; R. Yang et al. 2024).

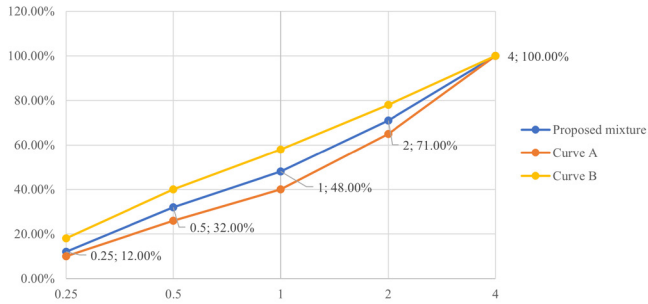


Fig. 1 Proposed granulometry of the aggregates

Tab. 2 Material composition for fine grained concrete mix

| Material                  | Mass (kg) per mixture | Mass (kg) per m <sup>3</sup> |
|---------------------------|-----------------------|------------------------------|
| Cement (CEM I 42.5 R)     | 6.056                 | 400                          |
| Aggregate 0–0.25 mm       | 3.171                 | 209                          |
| Aggregate 0.25–0.5 mm     | 5.285                 | 349                          |
| Aggregate 0.5–1 mm        | 4.228                 | 279                          |
| Aggregate 1–2 mm          | 6.078                 | 401                          |
| Aggregate 2–4 mm          | 7.664                 | 506                          |
| Water                     | 2.423                 | 160                          |
| Stachema 2014 Plasticiser | 0.080                 | 5                            |

All the dry materials were placed in a bucket mixer and processed for 2 minutes to homogenize the material. Half of the water was added; the material was mixed with the superplasticizer for 3 minutes; and the remaining water was subsequently added. It was mixed for a further 2 minutes. Once the material was well mixed, it was poured into moulds, and 15 40 x 40 x 160 mm prism specimens were made. This procedure was repeated 2 times.

2.2.2 Curing and testings

The moulds, which were covered with plastic foil, were stored at 20 °C until the next day, when all the specimens were released.

Two different curing conditions (W) were chosen for the comparison. The first group consisted of 100 % humidity and 20 °C; the second group was stored in a chamber with 20 vol. % CO<sub>2</sub>, 70 % humidity, and an ambient temperature of 20 °C (CO<sub>2</sub>). They were cured until the specific days of testing at 2, 7, and 28 days. At each testing day, 3 samples were taken from each group.

Measurements of the compressive strength, flexural tensile strength, and dynamic modulus of elasticity were performed (EN 12504-4 2021; EN 12390-1 2021; EN 12390-2 2019; EN 12390-3 2019; EN 12390-5 2019).

The specimens were subjected to the following tests and measurements: dimensional measurements, mass measurements, ultrasonic measurement of the dynamic modulus of elasticity with Ultrasonic meter 02.00.001 (MATEST), and a test of their compressive strength using a ZDM by U30t hydraulic press (VEB WPM, Germany).

3 RESULTS

As shown in Figure 2, the specimens exposed to water exhibited an initial expansion during the early curing period and reached a relative change in length on the order of  $1.5\text{--}2.0 \times 10^{-4}$  during the first 20–30 days. After this initial increase, the expansion stabilized and showed only minor fluctuations over the remainder of the observation period up to 149 days. This behaviour is consistent with the uptake of moisture and continued hydration, thereby leading to dimensional stabilization at later stages.

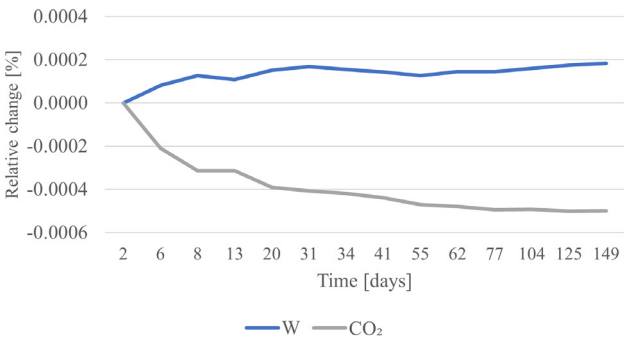


Fig. 2 Relative changes in length of the fine-grained concrete

In contrast, the specimens exposed to CO<sub>2</sub> exhibited pronounced and continuous shrinkage over time (Neville 1995). A rapid decrease in relative length was observed during the early stages, which was followed by a more gradual, yet persistent, shrinkage thereafter. By the end of the monitoring period, the total shrinkage had reached approximately  $-5.0 \times 10^{-4}$ . This trend suggests that CO<sub>2</sub> exposure significantly accelerates mechanisms associated with dimensional reduction, such as carbonation-induced densification and moisture loss (Bacharz et al. 2025; Yang et al. 2024).

Figure 3 shows the development of the compressive strength of the concrete cured under supercritical CO<sub>2</sub> (CO<sub>2</sub>).

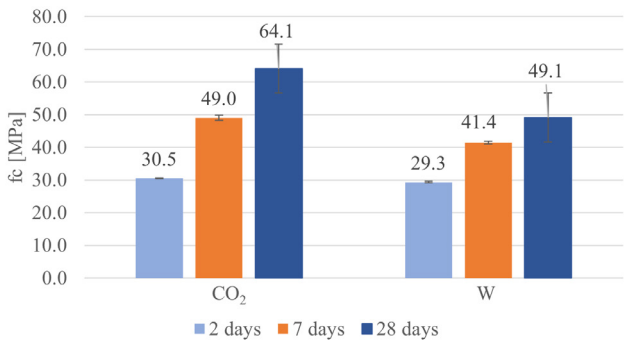


Fig. 3 Compressive strength of fine-grained concrete

and water curing conditions (W) at 2, 7, and 28 days. At 2 days, both curing regimes exhibit similar compressive strengths: 30.5 MPa for CO<sub>2</sub> and 29.3 MPa for W, which indicates the minimal effect of the curing environment at an early stage. At 7 days, the CO<sub>2</sub> curing results in a compressive strength of 49.0 MPa, compared with 41.4 MPa for the water curing, thereby representing an increase of approximately 18 %. This difference becomes more pronounced at 28 days, where the CO<sub>2</sub> specimens achieve 64.1 MPa, while the W specimens reach 49.1 MPa, which correspond to an improvement of about 30 % (Chang Liu et al. 2024).

Under the controlled curing conditions of the 20 vol.% CO<sub>2</sub> concentration and 70 % relative humidity, the natural aggregate concrete exhibited a notable increase in compressive strength compared to the conventionally water-cured specimens. This enhancement is primarily attributed to accelerated carbonation reactions, where the CO<sub>2</sub> reacts with the calcium-bearing phases (particularly Ca(OH)<sub>2</sub> and C-S-H etc.) to form CaCO<sub>3</sub>, which leads to refinement of the pores and densification of the cementitious matrix. The presence of intermediate relative humidity (~60-70 %) is particularly critical, as it ensures sufficient moisture for the carbonation reactions, while maintaining adequate CO<sub>2</sub> diffusivity. It thereby optimizes the reaction kinetics and microstructural development. This observation is consistent with established findings that carbonation efficiency and the resulting mechanical improvements are maximized under moderate humidity conditions, where both the transport, and reaction processes are balanced (Scrivener et al. 2018).

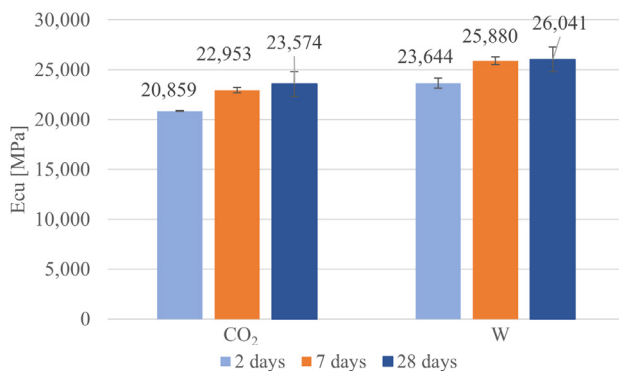


Fig. 4 Dynamic modulus of elasticity of the fine-grained concrete

Figure 4 illustrates the development of the dynamic modulus of elasticity ( $E_{cu}$ ) of the concrete cured under CO<sub>2</sub> and the water conditions at 2, 7, and 28 days. For both curing regimes,  $E_{cu}$  increases with the stage of the curing, which indicates progressive stiffening of the concrete matrix.

At 2 days, the water-cured specimens exhibit a higher dynamic modulus 23,644 MPa compared to the CO<sub>2</sub> cured specimens at 20,859 MPa. This trend persists at 7 days, with values of 25,880 MPa for the water curing and 22,953 MPa for the CO<sub>2</sub> curing. At 28 days, the dynamic modulus reaches 26,041 MPa under the water curing and remains higher than the corresponding value of 23,574 MPa under the CO<sub>2</sub> curing.

The observed increase in compressive strength accompanied by a reduction in the dynamic modulus of elasticity can be

attributed to the different sensitivities of these parameters to the microstructural features. While the compressive strength benefits from pore refinement and microstructural densification improves due to carbonation, the dynamic modulus is more sensitive to microcracking, which reduces the velocity of the wave propagation (Kim et al. 2024).

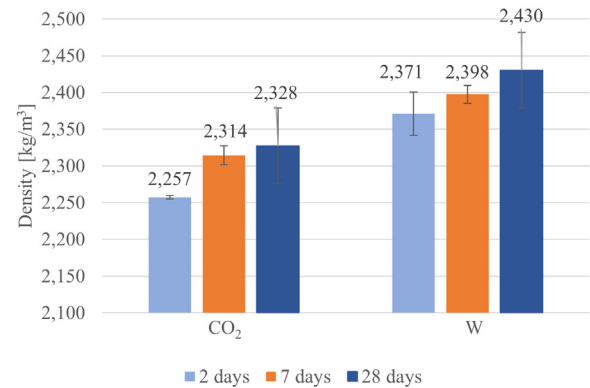


Fig. 5 Density of the fine-grained concrete

Figure 5 illustrates the evolution of the density of the concrete cured under CO<sub>2</sub> and the water conditions over periods of 2, 7, and 28 days. In both curing methods, the density shows an upward trend with the increased curing stage, which signifies the gradual stiffening of the concrete matrix.

At the 2 day mark, the specimens cured with water demonstrate a greater density of 2,371 kg/m<sup>3</sup> in comparison to those cured with CO<sub>2</sub>, which have a density of 2,257 kg/m<sup>3</sup>. This pattern continues at 7 days, where the water-cured specimens show densities of 2,398 kg/m<sup>3</sup>, while the CO<sub>2</sub> cured specimens exhibit densities of 2,314 kg/m<sup>3</sup>. By the 28 day period, the density under the water curing reaches 2,430 kg/m<sup>3</sup>, which remains higher than the corresponding density of 2,328 kg/m<sup>3</sup> observed under the CO<sub>2</sub> curing.

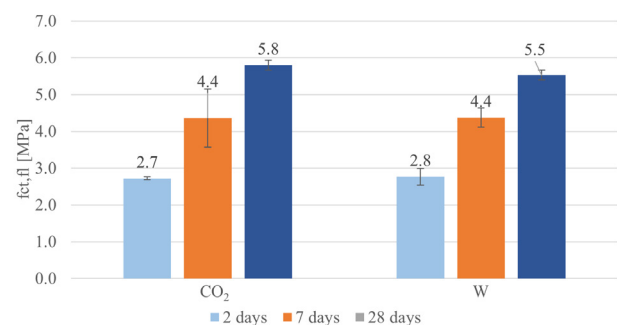


Fig. 6 Flexural tensile strength of the fine-grained concrete

Figure 6 illustrates the development of the flexural tensile strength in the concrete. At the 2 day mark, both curing methods demonstrate comparable compressive strengths, i.e., 2.7 MPa for the CO<sub>2</sub> and 2.8 MPa for the water, which suggests that the curing environment has a negligible effect at this early stage. By 7 days, the CO<sub>2</sub> curing method yields a flexural tensile strength of 4.4 MPa. The disparity between the two curing methods becomes more evident at 28 days, with the CO<sub>2</sub> specimens achieving a strength of 5.8 MPa, compared with 5.5 MPa for the water-cured specimens, which reflects an approximately 5 % increase (Urbonas et al. 2016).

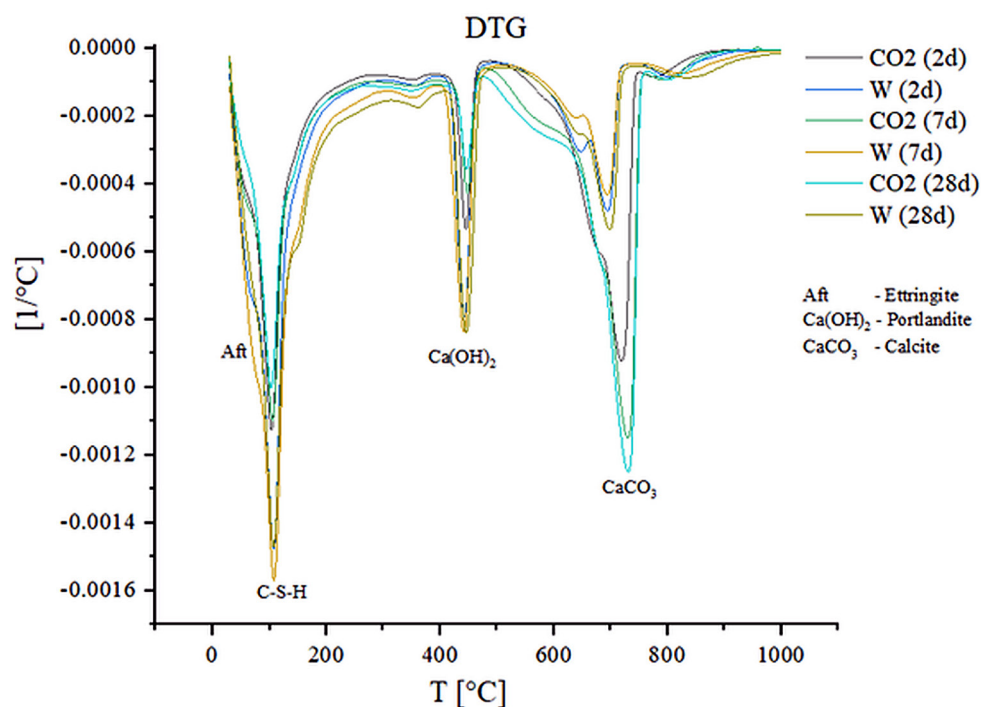


Fig. 7 DTG curves of all the samples

Figure 7 indicates the derivative thermogravimetric (DTG) curves of the cement pastes obtained from the concrete samples that were cured for durations of 2, 7, and 28 days. The thermal decomposition profiles indicate the advancement of the hydration reactions and the assemblage of the changing phase within the cement matrix. At the early stage (2 days), the DTG curve displays a significant endothermic peak in the range of 64–72 °C, which is associated with the dehydration of the early-formed AFt phases (ettringite and its carbonated variety). This peak gradually decreases with the extended curing time and signifies the transformation of the AFt into more stable AFm phases, along with a redistribution of sulfate-bearing hydration products, as evidenced by an increasing peak observed at around 145 °C. The broad signal centred around 102–107 °C is linked to the release of bound water from the poorly crystalline C-S-H gels and from the monocarboaluminate (Čepčianska et al. 2025; Chen Liu et al. 2024). The rising intensity and sharpness of this peak over time indicate the continuous densification and polymerization of the gel network, which directly contribute to the enhancement of the strength and the microstructural refinement.

A notable endothermic event that occurs around 157 °C is likely associated with the decomposition of the C-A-S-H gels and strätlingite ( $C_2ASH_8$ ), a secondary hydrate formed through pozzolanic interactions or ongoing aluminate reactions (Santacruz et al. 2015). The system's appearance indicates that it continues to experience microstructural reorganization, even after the initial hydration phases. At elevated temperatures, a small shoulder at around 240–250 °C and a subsequently broad peak observed in the 340–370 °C range is associated with the two-step decomposition of the hydrogarnet (Hg), an calcium aluminate hydrate that forms during later hydration stages. The development of this phase is indicative of the alumina's reactivity and serves as an indirect marker of the system's

advancement towards thermodynamic stability. Additionally, the significant peak observed between 446–448 °C is typical of the decomposition of portlandite ( $Ca(OH)_2$ ). The steady increase of this peak over a period of 28 days implies a dynamic equilibrium between the formation of the portlandite and its consumption, which is likely influenced by internal carbonation or secondary pozzolanic reactions resulting from interactions with the finer aggregates (Gabrovšek et al. 2006). Ultimately, the endothermic reaction observed at temperatures between 694–730 °C indicates the breakdown of calcium carbonate ( $CaCO_3$ ) (Trnik et al. 2016), which is a by-product of the ongoing carbonation processes. The thermal analysis provides essential insights into the internal evolution of the hydration phases that are fundamental to the mechanical properties of concrete. The gradual conversion of the early ettringite into stable AFm phases, the densification of the C-(A-)S-H gels and the regulated development of the portlandite and carbonates collectively suggest a well-managed hydration process. The existence of stable, mature hydration products at the later stages corroborates the observed enhancements in strength and stiffness, which affirms that aggregate gradation not only affects the physical packing but also the chemistry and kinetics of the hydration, thereby directly contributing to the durability and performance of the concrete.

The microstructural analysis and mechanism of the carbonation  $CO_2$  penetrates the pore structure of cement paste and reacts with the calcium hydroxide ( $Ca(OH)_2$ ) as well as with the C-S-H phases. This leads to the precipitation of calcium carbonate ( $CaCO_3$ ) within the microstructure. This process results in the densification of the interfacial transition zones (ITZ) and the partial blockage of the pore networks (Ravikumar et al. 2021; D. Zhang et al. 2017; J. Zhang et al. 2015).

It has been shown that CO<sub>2</sub> curing can mitigate certain shrinkage-related effects. Rapid carbonation may initially induce chemically-driven shrinkage (carbonation-induced shrinkage) due to dehydration and the volumetric changes of hydration products; however, the subsequent pore filling by CaCO<sub>3</sub> contributes to a longer-term reduction in shrinkage (Xian et al. 2022). The carbonation process produces the calcium carbonate that occupies the capillary pores, thereby reducing the pore connectivity and overall water transport (Ravikumar et al. 2021; Tang et al. 2024). This microstructural densification contributes to a reduction in shrinkage.

Park and Choi quantified the relationship between the CO<sub>2</sub> concentration and shrinkage (Park and Choi 2020). They reported that at CO<sub>2</sub> concentrations of approximately 10-15 %, carbonation-induced pore filling by CaCO<sub>3</sub> improves the microstructure, reduces the capillary porosity, and can lead to a shrinkage reduction of 22-29 %. (Ravikumar et al. 2021) and (Zhang et al. 2015) similarly quantified the shrinkage-mitigating effect of CO<sub>2</sub> curing. They reported up to a 20-30 % reduction in shrinkage compared with the air-cured specimens. In addition, the carbonation-induced improvement of the ITZ contributes to a more uniform stress distribution, thereby further reducing shrinkage-induced cracking. These effects are consistent with the higher compressive strength observed in the specimens cured in a CO<sub>2</sub> chamber (Kravanja and Knez 2025; Li et al. 2019).

The effectiveness of carbonation is further dependent on the relative humidity during exposure. Optimal pore refinement and improvement of the mechanical properties are typically achieved at intermediate relative humidity levels (approximately 40-70 %), as the CO<sub>2</sub> diffusion is limited at a very high RH. At the same time, insufficient moisture for the reaction is available at a very low RH (Xian et al. 2022).

## 4 CONCLUSION

The aim of this experiment was to demonstrate that it was possible to reduce the carbon footprint of concrete structures, which could be split into two directions. As to the first topic, we can bind CO<sub>2</sub> into the material during the manufacturing process, thereby reducing the amount of CO<sub>2</sub> that would otherwise be released into the atmosphere. The other direction is to leverage improved structural properties by providing higher compressive strength, which could lead to slimmer structures, and help us save precious resources and reduce transport costs and the amount of work needed for production. To meet Net Zero criteria, this research has shown that curing significantly affects the mechanical properties of concrete and can significantly reduce the CO<sub>2</sub> footprint of OPC-based building materials; however, further investigation is needed. Concrete CO<sub>2</sub> curing technology can be used on an industrial scale for elements with reinforcement not prone to corrosion, e.g., glass fibres, PP fibres, carbon fibres, etc. For further research, other chemical-mechanical properties need to be evaluated using Differential Thermogravimetric Analysis (DTG), Fourier transform infrared spectroscopy (FTIR), X-ray fluorescence analysis (XRF), and mercury intrusion porosimetry (MIP), which will allow for a deeper

understanding of the processes underlying the development of the strength. The effect of changes in pH on the steel reinforcement should also be investigated, which could help us understand the role of β-C<sub>2</sub>S and CaCO<sub>3</sub> in the process of the development of strength.

## Acknowledgments

AI tools were used for language editing/grammar improvement; the authors retain full responsibility for the content.

This study was financially supported by the Slovak Research and Development Agency under Contract Nos. APVV-23-0383 and APVV-19-0490, the Slovak Grant Agency VEGA under Contract No. 2/0080/24, the European project Interreg CENTRAL EUROPE 2021-2027 under Contract No. CE0100390, and the Grant Programme for SAS PhD students under the APP0569 Contract.

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