



Water-Cement Ratio Effects on LC³ Concrete Properties and Carbonation

Efeitos da Relação Água/Cimento nas Propriedades e Carbonatação de Concretos com LC³

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ABSTRACT

Limestone Calcined Clay Cements (LC³) incorporate calcined clays and limestone filler in cements becoming an alternative for decarbonizing the cement industry. Despite refining the pore structure and improving resistance to aggressive ion diffusion, the lower portlandite content may increase carbonation susceptibility, especially in concretes with high water-to-cement (w/c) ratios. This study evaluated the carbonation performance and service life of LC³-50 concretes with w/c ratios specified by ABNT NBR 6118 for the four environmental exposure classes. Raw materials were characterized by X-ray fluorescence, X-ray diffraction, while mechanical and accelerated carbonation tests were performed on the hardened state. The results showed that portlandite availability influences CO₂ ingress resistance and w/c ratios affect both mechanical strength and durability. Carbonation depth decreased approximately 30% as the w/c ratio was reduced from 0.65 to 0.45. Service-life predictions indicated that the concrete cover thicknesses prescribed by ABNT NBR 6118 are adequate, with a 3 cm carbonation front expected only after 80 years for concretes produced with a w/c ratio of 0.65. Overall, the results demonstrate that LC³ concretes can achieve satisfactory long-term durability.

keywords calcined clays, durability, concrete structures, carbon dioxide

RESUMO

Os cimentos do tipo LC³ (Limestone Calcined Clay Cements) incorporam argilas calcinadas e filer calcário tornando-se uma alternativa para a descarbonização do setor cimenteiro. Apesar do refinamento da porosidade e aumento da resistência à difusão de íons agressivos, a menor disponibilidade de portlandita pode aumentar a suscetibilidade à carbonatação, especialmente em concretos com elevada relação água/cimento (a/c). Este estudo avaliou a carbonatação e a vida útil de concretos produzidos com LC³-50, e relações água/cimento (a/c) definidas na ABNT NBR 6118 para as quatro classes de agressividade ambiental. As matérias-primas foram caracterizadas utilizando espectroscopia de fluorescência e difração de raios X, e no estado endurecido propriedades mecânicas e carbonatação foram avaliadas. Os resultados indicaram que a disponibilidade de portlandita influencia na resistência à penetração de CO₂, e que a relação a/c influencia não apenas a resistência mecânica, mas também a durabilidade. A profundidade de carbonatação reduziu cerca de 30% quando a relação a/c foi reduzida de 0,65 para 0,45. As previsões de vida útil indicaram que os cobrimentos de armadura recomendados pela ABNT NBR 6118 são adequados, com uma profundidade de carbonatação de 3 cm esperada somente após 80 anos para concretos produzidos com relação a/c de 0,65. Em geral, os resultados demonstraram que concretos com LC³ podem atender às expectativas de durabilidade a longo prazo.

palavras-chave argilas calcinadas, durabilidade, estruturas de concreto, dióxido de carbono

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Introduction

The significant carbon dioxide (CO₂) emissions associated with Portland cement production stem mostly from the calcination of calcium carbonate (CaCO₃) during clinker formation. This process has encouraged the development of cements with a lower climate impact, since the cement industry is responsible for approximately 5–10% of global CO₂ emissions, reaching about 1.65 billion tons per year (Friedlingstein et al., 2023). According to Mañosa et al. (2024), for the sector to achieve carbon neutrality by 2050, a minimum annual reduction in direct emissions of 3% is required. Among the mitigation strategies, the use of supplementary cementitious materials (SCMs), such as blast furnace slag, silica fume, fly ash, and agricultural waste ashes, stands out, with pozzolanic and/or hydraulic functions complementary to cement, thereby maximizing the amount of C-S-H in concrete and contributing to improved mechanical performance and durability (Avet & Scrivener, 2020; Balestra et al., 2023; Ferreiro et al., 2019).

Although slag and fly ash are widely used commercially, their global availability limits large-scale adoption to meet future demand. In this context, the use of ternary cements consisting of Portland clinker, calcined clays, limestone filler, and gypsum, known as Limestone Calcined Clay Cements (LC³), has gained prominence (Matos et al., 2023; Silvestro et al., 2024; Yu et al., 2021; Zhang et al., 2020). The typical formulation of LC³, in mass percentage, consists of 50% Portland clinker, 30% calcined kaolinitic clay (metakaolin), 15% limestone filler, and 5% gypsum (defined as LC³-50, where the numerical value refers to the clinker content), and can reduce CO₂ emissions by up to 40% and production costs by about 30% compared to ordinary Portland cement (Sánchez Berriel et al., 2016). The viability of this technology stems from the wide availability of limestone and kaolinitic clays in the Earth's crust, as well as its compatibility with current production lines (Danner et al., 2018; Schmid & Plank, 2021). From an environmental perspective, the calcination of clays requires temperatures between 600 °C and 850 °C, lower than those needed for clinker production, reducing energy consumption and eliminating emissions from decarbonation, since the decomposition of CaCO₃ does not occur in this process (Krishnan & Bishnoi, 2020; Nair et al., 2020; Scrivener et al., 2019; Yu et al., 2021). Furthermore, clays with relatively low kaolinite contents (approximately 40%) can exhibit adequate reactivity for use as a supplementary cementitious material (SCM) after calcination, broadening the global potential for the technology's application. Scrivener et al. (2019) demonstrate that kaolinite content directly influences the rheology and mechanical strength of LC³ systems, while sulfate and alkali amounts must be adjusted to maximize performance. From a durability standpoint, LC³ mixtures exhibit lower permeability, greater resistance to chloride penetration, and greater mitigation of expansive reactions, such as the alkali-silica reaction. However, these mixtures tend to exhibit deeper carbonation fronts compared to ordinary concretes, reinforcing the need for efficient curing and stricter criteria for structural use.

Ghazy et al. (2025) presented a comprehensive review of Limestone Calcined Clay Cement (LC³), integrating environmental, mechanical, and microstructural perspectives to provide a unified understanding of its performance, benefits, and challenges. The authors emphasize that, from a sustainability standpoint, LC³ has the potential to reduce carbon emissions by up to 40% compared to ordinary Portland cement (OPC), driving the intensification of research in this field. The methodology states that LC³ is a ternary blend produced by calcining kaolinitic clays at optimal temperatures between 600 °C and 850 °C to ensure pozzolanic reactivity. Regarding carbonation behavior, the authors indicate that the carbonation rate in LC³ concrete is higher than in Portland-cement-only concretes due to a lower alkaline reserve, resulting in greater carbonation depths; however, low limestone-to-calcined-clay ratios (≈ 10 –15%) do not significantly impact carbonation fronts. Furthermore, the carbonation of limestone promotes the conversion of hemicarboaluminate into monocarboaluminate, acting as a carbonation sink.

Hosen and Chen (2025), after analyzing 177 publications, identify carbonation resistance as the main gap in the structural application of LC³ concretes. As observed in Bahman-Zadeh et al. (2022) and Balestra et al. (2023), the low availability of portlandite (Ca(OH)₂) in these systems is a determining factor, since this compound acts as a buffer phase in the reaction with CO₂. Carbonation, although contributing to carbon sequestration and potentially being employed as an accelerated curing technique (Cheng et al., 2026; Jan et al., 2024), reduces the pH of the concrete's pore solution, depassivating and leading to the corrosion of the reinforcement, negatively impacting the microstructure with the progressive formation of cracks that increase permeability and compromise the mechanical performance of the concrete (Bahman-Zadeh et al., 2022; Compeľová et al., 2026; Jan et al., 2024).

Accelerated carbonation assessment is generally performed by exposing specimens to high concentrations of CO₂ under controlled temperature and humidity, followed by the application of a 1% phenolphthalein solution, which acts as a pH indicator. Prediction models for the progression of carbonation are frequently based on Fick's First Law ($x = K_c \cdot \sqrt{t}$), where x represents the carbonation depth, t is the time, and K_c is a coefficient dependent on the concrete's properties (Cheng et al., 2026). Jan et al. (2024) highlight that, although phenolphthalein presents carcinogenic potential, the use of thymolphthalein did not prove suitable for LC³ systems. The authors verified that LC³-50 mortars exhibit low resistance to carbonation due to reduced clinker content and the consumption of portlandite during the pozzolanic reaction, and they recommend using LC³-70 for durability. Compel'ová et al. (2026) corroborate this behavior by observing, under supercritical conditions (conditions observed in geothermal power plant wells, for example), high carbonation of ettringite and C-(A)-S-H, with a predominance of aragonite and amorphous carbonates.

According to Wang et al. (2025), comparing the carbonation performance of ordinary Portland cement (OPC) and LC³ concretes at 28 days can lead to erroneous conclusions, as LC³ concretes may exhibit insufficient performance. This does not reflect reality due to the temporal evolution of pozzolanic reactions. Furthermore, higher atmospheric CO₂ emissions have led to severe climate change impacts. Thus, the authors proposed a method for optimizing LC³-50 concretes using a genetic algorithm in MATLAB, considering aspects of carbonation durability and the impacts of climate change across eight different cities under three scenarios (1– no carbonation resistance; 2– an environment with a CO₂ concentration of 0.04%; 3– an environment with a CO₂ concentration of 0.05%). The experimental and modeling results demonstrated that the carbonation front is highly dependent on relative humidity; cities such as New Delhi and Beijing exceeded the 25 mm threshold due to their local relative humidity, requiring an increase in binder content to mitigate CO₂ penetration. Additionally, the authors reinforce that reducing the water-to-binder ratio (reaching 0.33–0.36 in critical regions) is an effective tool to refine the pore structure and, consequently, reduce the CO₂ diffusion coefficient.

Sabtiwu et al. (2025) evaluated the impact of carbonation on concretes produced with binary and ternary cements containing blast furnace slag and/or limestone filler, with 50% of the Portland cement binder replaced (CEM I 52.5 N). The main objective was to verify how carbonation modifies the long-term durability of low-clinker systems. Accelerated carbonation tests were performed on cylindrical concrete specimens with a binder content of 320.3 kg/m³ and a water-to-cement ratio of 0.50. The specimens were exposed in a carbonation chamber for 7, 28, 70, and 100 days under a CO₂ concentration of 3%, relative humidity of 57%, and a temperature of 20 °C. Conversely, under natural conditions, the exposure period to atmospheric CO₂ was 365 days, with a concentration near 400 ppm. In the methodology, four concrete mixtures were used: a reference mix with CEM I 52.5N (designated as N), a binary mix with 50% ground granulated blast-furnace slag (designated as NS), a ternary mix with blast furnace slag (40%) and limestone filler (10%) (designated as NSL), and another mix with blast furnace slag and limestone filler contents of 30% and 20%, respectively (designated as NS2L). The authors also proposed a correlation coefficient between the accelerated (K_{acc}) and natural tests (K_{nat}), asserting that the conditions adopted in the accelerated test and their coefficients can be used to estimate CO₂ penetration under natural conditions ($K_{nat} = 0.115K_{acc}$). Furthermore, the results showed that the carbonation fronts in the slag-containing concretes (NS, NSL, and NS2L) were significantly higher than those of the reference concrete (N) due to the reduction in the alkaline reserve and portlandite content within the concretes. However, adding up to 20% limestone filler had no notable effect on carbonation resistance, indicating that partial replacement of slag with limestone filler is viable.

Bahman-Zadeh et al. (2022), evaluating LC³-70 with clays of varying kaolinite content, observed that increasing kaolinite content reduces the carbonation depth due to microstructural refinement and decreased permeability. Even so, carbonation was consistently higher than in Portland cement, consistent with a portlandite content of less than half. Furthermore, the authors evaluated the chloride-binding capacity in carbonated LC³ pastes. In this study, four different types of calcined clays with kaolinite contents ranging from 19.2% to 66% were utilized in the production of the LC³ pastes, and their results were compared with binary mixtures of ordinary Portland cement (OPC) blended with silica fume, calcined clays, or limestone filler. Accelerated carbonation tests were conducted in a chamber with 5% CO₂ for up to 84 days, revealing that OPC pastes exhibited the lowest carbonation front due to their higher portlandite (CH) content. In contrast, the LC³ pastes showed significantly lower carbonation depth progression rates than OPC between

14 and 84 days. Moreover, the increase in kaolinite content within the LC³ mixtures resulted in shallower carbonation depths due to the greater refinement of pore connectivity, despite the consumption of the alkaline reserve by the pozzolanic reaction.

Although other authors highlight microstructure refinement, the lower carbonation fronts observed contrast with those reported in other studies. Cheng et al. (2026) observed carbonation coefficients three times higher for LC³ than for Portland cement, attributing this to the scarcity of portlandite and the rapid drop in pH resulting from a lower Ca/(Si+Al) ratio. Similar results were reported by Khan et al. (2020) when evaluating the behavior of LC³ concretes subjected to natural and accelerated carbonation. To this end, the authors utilized two concretes with a compressive strength of approximately 36 MPa and Portland cement replacement rates of 30% and 45% by a blend of calcined clay and limestone filler (mass ratio of 2:1). For the natural carbonation tests, specimens were maintained under laboratory conditions at a temperature of 23 °C and a relative humidity of 55%. Conversely, for accelerated carbonation, specimens were placed in a carbonation chamber under the same temperature and humidity conditions, but in an environment with a 1% CO₂ concentration. In both cases, a phenolphthalein solution was used to measure the carbonation fronts. The results indicate that the carbonation fronts in LC³ concretes are generally higher than in concretes made solely with Portland cement due to the lower alkaline reserve. In this regard, the authors emphasize that, in the absence of portlandite, owing to its consumption in pozzolanic reactions, carbonation also proceeds in other phases, such as C-S-H and ettringite, thereby increasing porosity at high carbonation rates.

Liu et al. (2025) present another perspective on the effects of CO₂ on LC³, considering the adoption of supplementary cementitious materials (SCMs) and enforced carbonation (EC) techniques. The authors state that, while the carbonation phenomenon is well understood in the literature, their study focuses on a comprehensive approach to enforced carbonation techniques, considering their mechanisms, operational parameters, and the impacts of various precursors on carbon capture and the performance of the resulting cementitious materials. To this end, the methodology considers three Levels of Action (LOAs): the first level addresses enforced carbonation in raw materials (LOA-I), the second deals with the application of EC in the fresh state (LOA-II), and the third focuses on EC as a secondary curing strategy to achieve higher early-age strength. The authors note that carbonation alters the porosity and microstructure of the cementitious material, leading to the formation of calcium carbonate polymorphs (calcite, vaterite, and aragonite). These polymorphs fill capillary pores and densify the interfacial transition zones (ITZ) between the aggregates and the cementitious matrix, thereby reducing water absorption. However, the authors warn of over-carbonation, where excessive exposure to CO₂ during enforced carbonation degrades the densified internal structure, leading to a reverse effect that increases both overall porosity and pore size, posing potential risks to concrete durability. Furthermore, over-carbonation can induce adverse effects, such as the retardation of hydration due to the formation of carbonate films around clinker grains, or a drastic reduction in pH, compromising reinforcement passivation.

Regarding the application of LC³ in different concrete types, such as cellular concrete, Huang et al. (2023) observed shallower carbonation depths (< 5 mm) in ultra-lightweight composites treated with LC³, which they attributed to the extremely dense microstructure resulting from high binder consumption. In contrast, Zhou et al. (2025) evaluated the natural carbonation of cellular concretes using a blend of calcined clay, limestone, and gypsum (mass ratio of 6:3:1), designated LC² in their study, ranging from 30% to 70% replacement of Portland cement. For this purpose, cubic specimens with 100 mm sides were produced and, after 28 days of curing, were exposed to natural conditions for one year, with carbonation fronts evaluated using a phenolphthalein solution. The authors found no direct correlation between carbonation fronts and the mechanical strength of the cellular concretes; however, correlations were observed between carbonation and both porosity and the water-to-binder ratio. Specifically, a linear correlation was observed between the natural carbonation coefficient and porosity, with the mixture containing 50% LC² at a water-to-binder ratio of 0.3 exhibiting the shallowest carbonation depth (7.50 mm after 14 months) and the lowest coefficient (6.94 mm/year^{0.5}). Conversely, while maintaining the 50% replacement rate and increasing the water-to-binder ratio to 0.4, a higher carbonation coefficient (15.13 mm/year^{0.5}) was observed, comparable to that of the mixture with a 70% replacement rate (13.19 mm/year^{0.5}). Comparing mixtures with LC² Portland cement replacement at 50%–70% across distinct water-to-binder ratios, it becomes evident that the consumption of the alkaline reserve, combined with interconnected porosity, accelerates the carbonation front.

This literature review indicates that the carbonation performance of low-carbon cements is strongly influenced by portlandite consumption, a key factor in the greater carbonation depths observed. However, the literature also indicates that incorporating supplementary cementitious materials (SCMs) into these cements promotes microstructural refinement, thereby enhancing the durability and service life of the concretes. In this context, one of the main approaches to controlling concrete porosity is specifying the water-to-cement ratio (w/c) based on the exposure conditions to which concrete structures are subjected. In this context, this study investigates the carbonation of LC³-50 concretes produced with materials available in Brazil, following the recommendations of ABNT NBR 6118 (Associação Brasileira de Normas Técnicas [ABNT], 2023) for water/cement (w/c) ratios for the different environmental aggressiveness classes, focusing on the structural viability of concretes using low-carbon-emission cements.

Material and methods

Experimental program

The experimental program evaluated four different concrete mixtures with LC³-50 that met the environmental aggressiveness classes prescribed by the ABNT NBR 6118 standard (ABNT, 2023). In this case, the respective standard defines four environmental aggressiveness classes (I–IV), establishing cover layer thicknesses and limiting the water-to-cement (w/c) ratio for reinforced concrete structures in each class, as shown in Table 1.

Table 1 - Mixture identification and durability parameters presented in the NBR 6118 building code.

Mixture identification	Environmental aggressiveness class	Aggressiveness	w/c ratio	Minimum cover depth (mm)
S1	I	Weak	≤ 0.65	20–30
S2	II	Moderate	≤ 0.60	25–35
S3	III	Strong	≤ 0.55	35–45
S4	IV	Very strong	≤ 0.45	45–55

From ABNT NBR 6118: *Projeto de estruturas de concreto – Procedimento*. Associação Brasileira de Normas Técnicas (2023).

The materials required for producing 1 m³ of concrete are presented in Table 2. The proportion of dry materials was 1: 2.24: 2.07: 0.70 (CP V-ARI Portland Cement: Quartz Sand: Basaltic gravel No. 0: Basaltic gravel No. 1).

Table 2 - Materials proportions for the production of 1 cubic meter of concrete (kg).

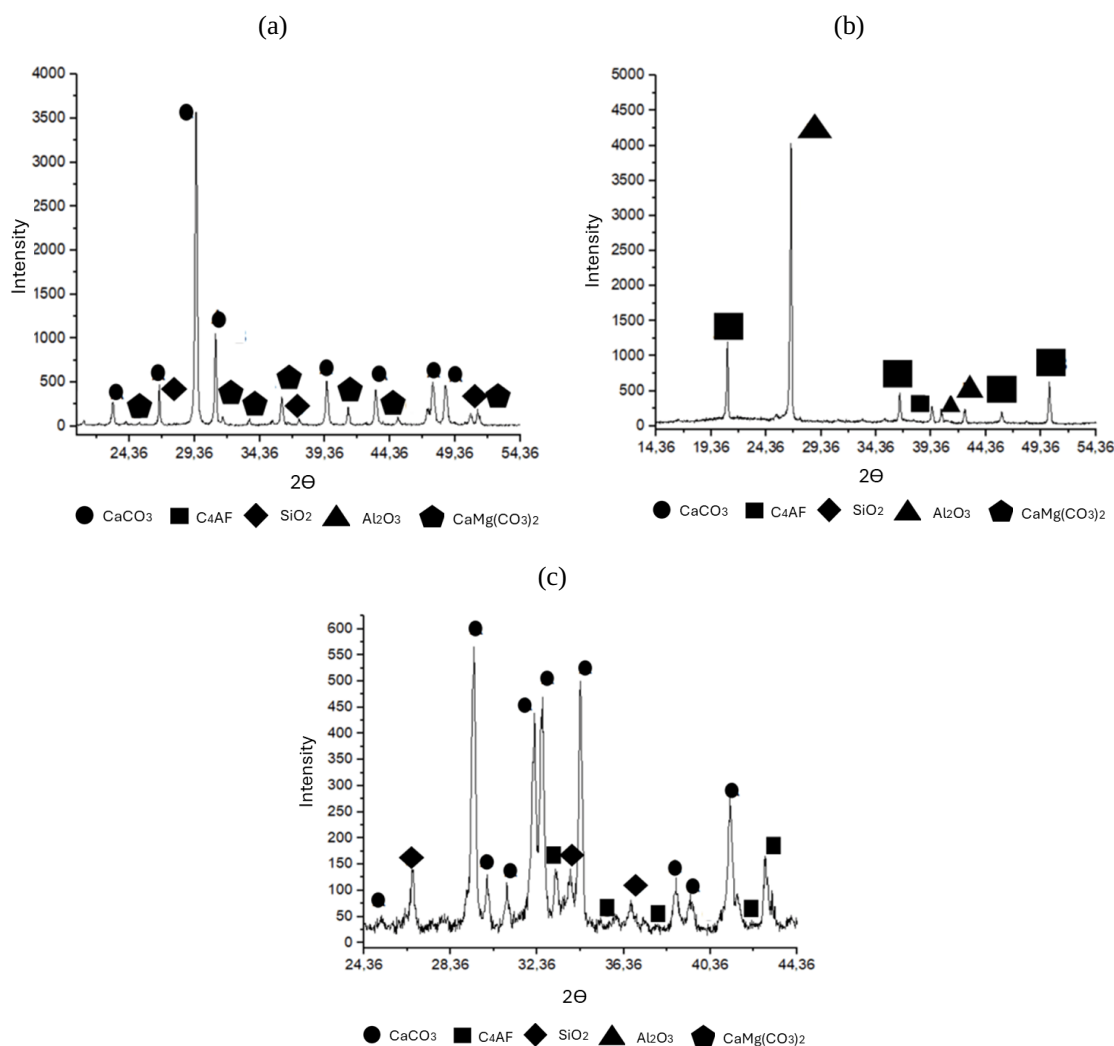
Mixture identification	LC ³	Sand	Coarse aggregate 1	Coarse aggregate 2	Water
S1	355.40	796.08	735.67	245.22	231.01
S2	361.82	810.49	748.98	249.66	217.09
S3	368.49	825.42	762.78	254.26	202.67
S4	382.59	857.00	791.96	263.99	172.17

The LC³ cement consumption ranged from 355.4 to 382.59 kg/m³, as shown in Table 2. This variation was necessary to maintain constant aggregate proportions while varying the w/c ratio across the mixtures.

For the production of the LC³ cement, the proportion (by mass) and the materials used were: 55% CP V-ARI cement; 30% calcined clay with a kaolinite content of 60%, and 15% limestone filler composed of 99.7% calcium carbonate. The calcined clay was sourced from an industrial facility 50 km from the city of São Paulo and produced by thermal treatment at 800 °C for 2.5 h. The resulting material exhibited particle sizes below 0.045 mm. The adoption of CP V-ARI cement is justified by the difficulties in obtaining Portland clinker directly from cement plants and by its commercial status, which allows it to be used without the addition of supplementary cementitious materials such as fly ash and blast furnace slag. For the research, this adoption assumes a clinker content of 95% and 5% gypsum in the LC³, after considering the filler and gypsum from the original CPV-ARI content (9% filler and 7% gypsum, according to the manufacturer) to adjust the LC³ proportions. This assumption is also found in the literature in the works of Khan et al. (2018), Balestra et al. (2023), and Huang et al. (2023).

The elemental composition and crystalline structures of the raw materials used for the production of LC³ were obtained through X-ray Fluorescence and X-ray Diffraction (XRF and XRD, respectively) tests (diffractograms are shown in Figure 1). At the same time, the physical properties determined were their bulk density and particle size distribution, as presented in Table 3, where the percentile values D₁₀, D₅₀, and D₉₀ indicate the size below which 10%, 50%, and 90% of all particles are found, respectively. The XRF tests were performed in an X-ray fluorescence spectrophotometer with a rhodium tube (50 kV and 100 μ A), Si(Li) detector, and a measuring range from ¹¹Na to ⁹²U, using powder samples passed through a No. 200 sieve (0.075 mm), with a diameter of 300 mm and a height of 150 mm. In the XRD test, a Shimadzu XRD-7000 was used, equipped with a copper tube ($K\alpha = 0.1542$ nm), an acceleration voltage of 30 kV, and a current of 30 mA, in continuous angular scanning from 10° to 80° with a step of 0.05°. For the analysis of the results, the peaks were indexed using the JCPDS-ICDD (Joint Committee on Powder Diffraction Standards - International Centre for Diffraction Data) crystallographic database.

Figure 1 - Diffractograms of the raw materials: (a) Filler, (b) Calcined Clay, and (c) CP V-ARI Portland Cement.



The specific mass of the materials was determined according to the ABNT NBR 16605 (ABNT, 2017a), and the laser granulometry was conducted in a BETTERSIZER/S3 Plus Laser Diffraction DLOIOS laser granulometer with an analysis range of 0.01 to 3500 μm and a liquid dispersion system according to the ISO 13320 standard (International Organization for Standardization [ISO], 2020). It is also worth noting that the pozzolanic activity of the calcined clay was evaluated through the modified Chapelle test according to the ABNT NBR 15895 (ABNT, 2010), in which a pozzolanic activity index equal to 760 mg CaO/g of sample was obtained, certifying its high pozzolanic activity (330 mg CaO/g of sample is considered the minimum standardized value).

Table 3 - Physicochemical properties of the raw materials used to produce LC³.

Property		CP V-ARI	Calcined Clay	Filler
Chemical composition (%)	SiO ₂	27.1	56.75	2.86
	Al ₂ O ₃	9.26	27.16	0.08
	CaO	55.25	0.92	45.4
	Fe ₂ O ₃	–	0.19	0.07
	TiO ₂	–	0.33	0.02
	K ₂ O	0.75	7.39	0.01
	SO ₃	8.12	7.24	< 0.01
	MgO	< 6.5	–	10.6
Specific mass (g/cm ³)		3.07	2.68	2.60
Particle size distribution (μm)	D ₁₀	1.99	2.79	4.99
	D ₅₀	8.88	17.18	23.90
	D ₉₀	27.97	338.93	123.63

Table 4 presents the aggregates (river sand and crushed basaltic rock – obtained in the western region of the state of Paraná) used in the production of the concretes, their physical characterization, and granulometric parameters.

Table 4 - Physical properties of sand and coarse aggregates.

Property	Sand	Coarse aggregate n° 0	Coarse aggregate n° 1
Specific mass (g/cm ³)	2.55	2.76	2.86
Fineness modulus	1.75	–	–
Maximum characteristic dimension (mm)	1.18	12.5	19.0
Water absorption (%)	–	3.16	2.27
Particle size distribution (μm)	D ₁₀	8.46	–
	D ₅₀	150.15	–
	D ₉₀	1,024.97	–

Superplasticizer admixtures become necessary in concretes with LC³ due to the rheological behavior of mixtures containing calcined clays (Balestra et al., 2024; Silvestro et al., 2024). Thus, a polycarboxylate ether-based superplasticizer admixture was used, with a maximum dosage of 0.5% relative to the cement mass. This value was defined based on both the manufacturer's guidelines, which limit its use to 1.0%, and the saturation point reported in the Marshall Cone test by Balestra et al. (2024), which prescribes a maximum dosage of 0.6% for LC³ mixtures. Regarding its physical characteristics, the superplasticizer used has a density of 1.060–1.100 g/cm³ and a pH of 4.5–6.5, according to the manufacturer.

Concrete mixtures were produced in a drum mixer with a 240-liter capacity. First, the coarse aggregates were added to the mixer with half the water, and the materials were mixed for 1 minute. Subsequently, the cementitious materials and the fine aggregate were added and mixed for 5 minutes. Finally, the remaining water with the superplasticizer admixture was added and mixed for another 5 minutes to ensure a homogeneous mixture. At this point, the superplasticizer dosage was adjusted directly in the mixture in 0.1% increments to avoid concrete bleeding or segregation. Rheological tests could not be performed due to the lack of appropriate equipment. In this regard, rheological studies on LC³ and the effects of superplasticizer addition are reported in Balestra et al. (2024).

After mixing, the concrete's workability was evaluated by the slump cone test – ABNT NBR 16889 (ABNT, 2020), and, subsequently, prismatic (10 × 10 × 40 cm) and cylindrical (10 × 20 cm) specimens were molded as prescribed by ABNT NBR 5738 (ABNT, 2015). These specimens were demolded after 24 hours and cured submerged in water at a controlled temperature (23 ± 2 °C) until the dates of the physical, mechanical, and durability tests in the hardened state.

The axial compressive strength test was performed as prescribed by the ABNT NBR 5739 standard (ABNT, 2018) at 28 and 90 days of age, in which the specimens, after capping the top and bottom, were subjected to a constant increment load (0.45 ± 0.15 MPa/s) until failure.

The elastic modulus test was performed using cylindrical specimens, as prescribed by the ABNT NBR 8522 standard (ABNT, 2017b). In this case, the specimens are subjected to limited loading cycles equal to 0.5 MPa (for 60 seconds), followed by 30% of the ultimate load (for 60 seconds), applying a loading rate equal to 0.45 ± 0.15 MPa/s, where the strains are measured by a digital extensometer, which is then removed for the last loading cycle that leads the specimen to failure. The ABNT NBR 7222 standard (ABNT, 2011) prescribes the splitting tensile strength test through the application of a diametrical load along the height of the cylindrical specimens, with a loading rate equal to 0.05 ± 0.02 MPa/s applied until the failure of the specimens.

The water absorption by immersion test followed the prescriptions of ABNT NBR 9778 (ABNT, 2009), which is based on the gravimetric variation of the specimens after drying, saturation, and boiling procedures. The specimens were dried in an oven at 105 ± 5 °C until a constant mass was reached, corresponding to a variation of less than 0.1 g between successive measurements, and the dry mass was recorded. After cooling, the specimens were immersed in water at 23 ± 2 °C for 72 hours. In this case, the normative procedure prescribes that the immersion must be done in cycles that consider capillary rise, that is: during the first four hours, 1/3 of the height of the specimen remained immersed in water; subsequently, 2/3 of the height of the specimen; and finally, the specimen was completely submerged for the remaining 64 hours, with the mass of the specimens recorded after the immersion period. Once the immersion cycle was completed, the specimens were placed in boiling water at 110 °C for 5 hours, with their mass recorded after this period. Based on the percentage difference in mass of the specimens after boiling and oven-drying, the water absorption and void ratio can be determined.

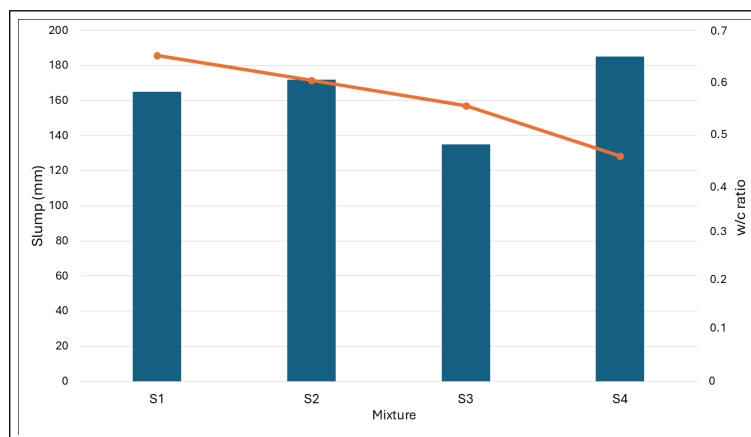
The ISO 1920-12 standard (ISO, 2015) prescribes the accelerated carbonation test, which was performed using the prismatic specimens. In this case, after 28 days submerged in water for curing, the specimens were preconditioned in a container at room temperature for 20 days to achieve a degree of saturation between 50% and 70%. After this period, these specimens were placed in an accelerated carbonation chamber where they remained for 63 days under a temperature of 27 ± 2 °C, relative humidity equal to $65 \pm 5\%$, pressure of 1 atm, and carbon dioxide (CO₂) concentration equal to $3.0 \pm 0.5\%$ to promote the ingress of CO₂ through the concrete's microstructure. Accelerated carbonation tests were conducted to evaluate CO₂ ingress and estimate the durability performance of concrete structures. In this context, due to the lack of LC³-based structures available for long-term assessment, the durability analysis was conducted through accelerated laboratory testing. Nevertheless, despite the higher CO₂ concentration used in the carbonation chamber compared with natural environmental conditions, the exposure period adopted in accordance with Item 7 of ISO 1920-12 enables the accelerated test to provide a reliable estimation of the service life and carbonation resistance of concrete structures under natural exposure conditions.

After the carbonation period in the chamber, the specimens were removed and subjected to a three-point bending test, with a 1% phenolphthalein solution sprayed onto the freshly fractured concrete surface, allowing verification of the concrete's alkalinity from the coloration. In this case, if a pink/carmine red coloration is observed, it indicates a pH greater than 9.0 and, therefore, uncarbonated concrete; however, if it is colorless, this corresponds to the concrete's carbonation front, since it indicates a pH below 9.0.

Results and Discussion

Concrete properties in the fresh state

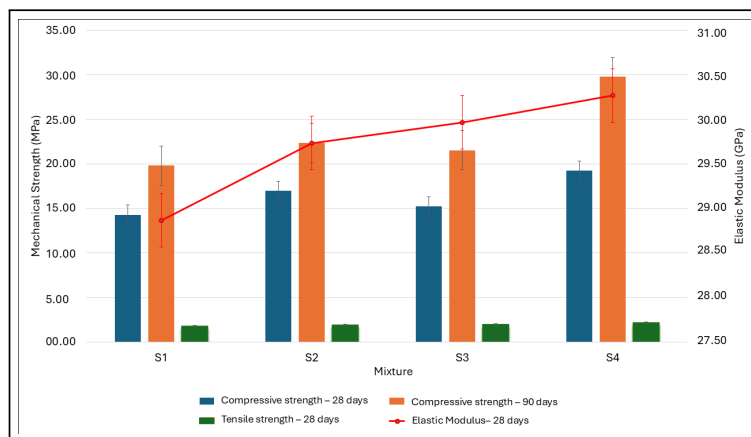
Figure 2 presents the slump test results obtained for the concretes. In this case, except for concrete S3, all mixtures fall within the S160 class of ABNT NBR 16889 (ABNT, 2020), which is suitable for typical applications in structural elements and can be pumped and cast. During concrete mixing, the aim was to maintain similar workability among the mixtures. For this purpose, adjustments were made using a polycarboxylate ether superplasticizer (SP). Mixture S1 was used as a reference, as it had the highest w/c ratio and, without superplasticizer, resulted in a slump of 165 mm. For mixtures S2, S3, and S4, superplasticizer dosages of 0.1%, 0.2%, and 0.5% of the cement mass were applied, respectively. However, for mixture S3, the SP dosage was limited to 0.2%, even though its slump was lower than that of S1, because the concrete seemed to be bleeding. This behavior was unexpected for that mixture and is reflected in its reduced mechanical properties compared to those of the others, as shown below.

Figure 2 - Slump test results for mixtures with different water/cement ratios.

The results also demonstrate that, in addition to the use of a superplasticizer when calcined clays are present, there is an inverse relationship between the w/c ratio and the demand for superplasticizer admixtures. Such behavior was expected and is corroborated by the literature, which indicates that, to impart fluidity to concrete, superplasticizer admixture dosages are required (Balestra et al., 2024; Nair et al., 2020; Silvestro et al., 2024).

Mechanical properties of concrete in the hardened state

The results obtained in the axial compression tests (at 28 and 90 days), splitting tensile strength, and elastic modulus (both at 28 days) are presented in Figure 3.

Figure 3 - Axial compressive strength, split tensile strength, and elastic modulus of the evaluated concrete mixtures.

It is possible to observe, an increase in compressive strength from 28 to 90 days for all mixtures, especially as the w/c ratio decreases. Such behavior was expected given the evolution of pozzolanic activity, as evidenced by the 49% increase in strength in group S4, along with improvements in the concrete microstructure resulting from the reduced w/c factor.

Furthermore, there is a tendency for the tensile strength to be 10% of the compressive strength, just as occurs in concretes with ordinary Portland cement. Regarding the concrete's elastic modulus, similar values are noted for all mixtures – close to 30 GPa – showing only a slight increase between the S1-S4 formulations. These values corroborate those observed in the literature (Agarwal et al., 2020; Dhandapani et al., 2018; Ghazy et al., 2025; Hosen & Chen, 2025), which highlight that the elastic modulus values obtained for concretes with LC³ are similar to those observed for concretes with Portland cement.

In the Analysis of Variance (ANOVA) of the axial compressive strength results for the ages of 28 and 90 days, the p-value was below 0.05, indicating significant differences in the means of the analyzed groups.

The Tukey-Kramer test was performed to compare the means. A statistically significant difference was then observed between groups S1, S2, and S4, while the means of group S3 were similar to those of groups S1 and S2 at both evaluated ages. The limitation of the use of the superplasticizer admixture during the production of concrete S3 influenced the mechanical properties of this mixture. On the other hand, in the analysis of variance for elastic modulus and splitting tensile strength, the group differences were not statistically significant ($p > 0.05$).

Immersion absorption, void ratio, and carbonation results of the concretes

The physical parameters of the produced concretes (water absorption by immersion and void ratio) are presented in Table 5. It can be observed that as the water/cement ratio increases, the absorption rate and the void ratio increase, corroborating the strength parameters presented in previous section as a function of the increased porosity of the concrete microstructure. In this case, it can be observed that for classes S1–S3, the values observed for both water absorption by immersion and the void ratio are similar, despite the variation in the water/cement ratio from 0.65 to 0.55. On the other hand, with a water/cement ratio of 0.45, a considerable improvement in the concrete microstructure is observed, resulting in a significant reduction in these parameters.

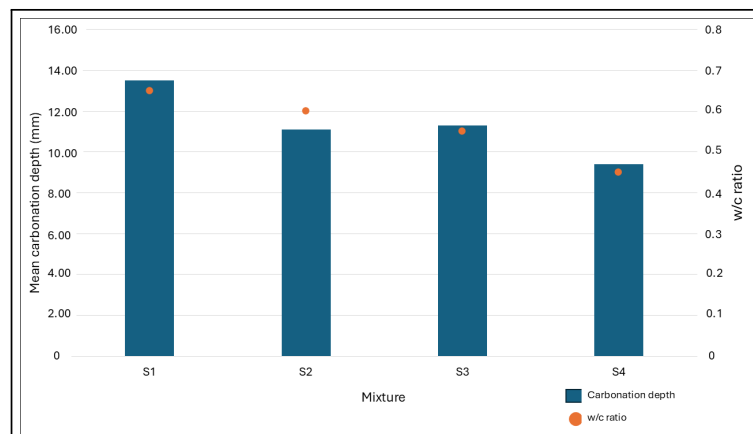
Table 5 - Water absorption and void ratio of tested mixtures.

Property	Mixture			
	S1	S2	S3	S4
Water absorption (%)	9.7 ± 0.15	9.1 ± 0.10	9.3 ± 0.23	4.4 ± 0.15
Void ratio (%)	21.6 ± 0.26	20.2 ± 0.16	21.1 ± 0.08	10.2 ± 0.36

Considering in this context that the use of superplasticizers produces cohesive and pumpable concretes (Figure 2) and that there is an increase of compressive strength between 28 and 90 days due to pozzolanic reactions (Figure 3), it is possible to state that limiting the water/cement ratio of concretes with LC³ to values below 0.55 can be an effective strategy in the production of structural concretes with greater durability, given that water/cement ratios above 0.55 already make the LC³ concrete microstructure more porous and, consequently, more prone to exhibiting lower mechanical strength and durability.

Figure 4 presents the average carbonation depths measured after spraying the phenolphthalein solution. It is noted that although the literature points out that the absence of portlandite (Calcium Hydroxide – Ca(OH)₂) in the cementitious matrix due to its consumption in pozzolanic reactions makes it difficult to obtain durable concretes with LC³ (Balestra et al., 2023; Ghazy et al., 2025; Hosen & Chen, 2025), the results obtained showed carbonation fronts lower than the cover layer thickness stipulated by ABNT NBR 6118 (ABNT, 2023) for the four analyzed aggressiveness classes.

Figure 4 - Mean values of carbonation depth and correlation with w/c ratio.



At this point, such behavior may be related to an atmospheric pressure of 1 atm. Although the test parameters were maintained as prescribed by the ISO 1920-12 standard (ISO, 2015), CO₂ concentration, test time, relative humidity, and temperature, this pressure does not force the ingress of CO₂ into the concrete's microstructure, allowing the formation of calcium carbonate and reducing the size and interconnections of the pore network. Consequently, this behavior suggests a limitation in CO₂ penetration, even with continuous exposure for 63 days during the test.

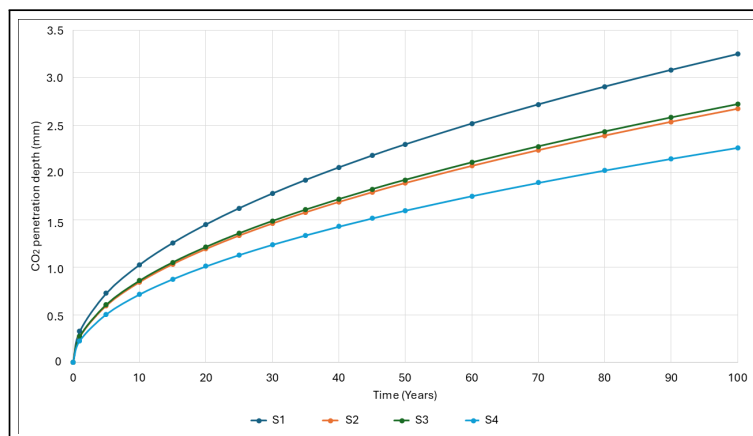
Regarding the evaluation of the carbonation fronts (Figure 4), the Analysis of Variance (ANOVA) of the carbonation depth between the groups resulted in a p-value of less than 0.05, demonstrating that there is a significant difference between the analyzed concrete groups, but allowing the analysis of the means of the carbonation fronts. Comparing the means using the Tukey-Kramer test, a statistically significant reduction in the carbonated depth is observed across the 3 treatment groups (S1, S2–S3, and S4), with the average depths of S2 and S3 statistically equal.

In this perspective, precautions can be established regarding the use of LC³ to achieve durable concretes. Environments that hinder CO₂ dissipation, such as in confined underground garage environments with poor ventilation, or environments with high concentration and/or pressure, as in the case of geothermal power plants, can be unfavorable for the use of concretes with LC³ considering the cover layer thickness for reinforced concrete structures foreseen in ABNT NBR 6118 (ABNT, 2023), even considering an aggressiveness class IV (Group S4 in this work). Thus, for design purposes, it is recommended that larger cover layer thicknesses, combined with w/c ratios limited to 0.45, be used to guide design guidelines aimed at the durability of concretes with LC³.

Comparing the results obtained from the observed carbonation fronts with the w/c ratios established in the different aggressiveness classes (Figure 4), it is observed that, as the w/c ratio increases, the carbonation fronts become larger. This fact corroborates the results of the immersion absorption tests and the void ratio, indicating a more porous concrete microstructure as the void ratio increases. These results also corroborate the study by Câmara (2020), which observed carbonation fronts between 12 and 13 mm in mortars with a w/c ratio of 0.5 subjected to accelerated carbonation, as specified in ISO 1920-12 (ISO, 2015).

Based on the presented data, a model-based approach can be proposed to predict the durability of real reinforced concrete structures. At this point, Neves et al. (2013) and Marani and Panesar (2025) evaluated the carbonation of concretes under accelerated and natural exposure conditions. The authors point out that, considering the model based on the solution of Fick's First Law, there is a relationship between the coefficients K_c for concretes subjected to accelerated tests ($K_{c(ac)}$) and under natural carbonation ($K_{c(nat)}$) in the order of 8 to 17 times, depending on the characteristics of the concrete. At this point, taking into account a value equal to 10, for demonstration purposes, and the carbonation results obtained in this work, Figure 5 presents the evolution of the carbonation fronts up to 100 years, considering the solution of Fick's First Law, together with the minimum cover values established for each environmental aggressiveness class defined in ABNT NBR 6118 (ABNT, 2023).

Figure 5 - Carbonation front modeling based on the solution of Fick's First Law.



The results demonstrate that, initially, the cover values foreseen in ABNT NBR 6118 (ABNT, 2023) are suitable for application in concrete with LC³, since only in class I (defined as group S1 in this work) did the carbonation fronts reach a cover depth of 3 cm after 80 years of exposure, allowing us to state that abrupt changes in the normative parameters are not necessary. However, it is emphasized that designers must consider the specific characteristics of their projects, for example, pressure, CO₂ concentration, and confinement, and the scarcity of portlandite due to pozzolanic reactions, to determine the most appropriate cover layer thickness in their reinforced concrete structure designs.

Conclusions

This work presented an analysis of the durability of concretes with LC³ using accelerated carbonation tests in accordance with ISO 1920-12 (ISO, 2015). Concretes were produced in accordance with the different environmental aggressiveness classes (I–IV) presented in the ABNT NBR 6118 standard (ABNT, 2023), in which restrictions regarding w/c factors for reinforced concrete structural elements are prescribed. Furthermore, chemical, physical, and mechanical tests on the constituent materials and concretes were also part of the scope of this work, which led to the following main conclusions:

- Due to the high specific surface area and water demand of calcined clays, all LC³ concretes required the incorporation of superplasticizer admixtures to ensure adequate pumpability. Furthermore, lower w/c ratios increased admixture demand, indicating the need for controlled addition at pre-established stages, limited to 0.1% of the binder mass, to prevent segregation.
- Reducing the w/c ratio significantly enhanced compressive strength at all curing ages, demonstrating the suitability of LC³ for the production of structural concretes with adequate mechanical performance. This behavior is associated with pore-structure refinement driven by the pozzolanic reactions of calcined clays. In contrast, variations in the w/c ratio had little effect on the elastic modulus, which remained between 29 and 30 GPa for all mixtures, with values comparable to those reported for conventional Portland cement concretes. The physical characterization further confirmed the strong influence of the w/c ratio on the concrete microstructure, as higher w/c ratios increased water absorption and void ratio, indicating greater porosity and, consequently, facilitating CO₂ ingress. These findings are consistent with the observed reductions in compressive strength and increases in carbonation depth.
- The carbonation results demonstrated that the w/c ratio was the primary parameter controlling CO₂ penetration in LC³ concretes. Although higher w/c ratios led to deeper carbonation fronts, even the most porous mixtures showed carbonation depths below the minimum concrete cover specified by ABNT NBR 6118 after 63 days of accelerated exposure. Unlike part of the literature, which reports increased carbonation susceptibility in LC³ systems due to portlandite consumption during pozzolanic reactions, the present results suggest that the low CO₂ pressure adopted in the accelerated test favored calcium carbonate precipitation within the pore network, partially refining the microstructure and reducing further CO₂ ingress. In addition, service-life predictions based on Fick's First Law indicated that carbonation depths of approximately 30 mm would be reached in the concrete with the highest w/c ratio after approximately 80 years of exposure. Overall, the results demonstrate that adequate control of the w/c ratio, combined with proper curing conditions, enables LC³ concretes to achieve satisfactory carbonation resistance.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

D. C. Brandalize: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Visualization, Writing – original draft. **G. Savaris:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft. **C. E. T. Balestra:** Conceptualization, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft. **F. Freire:** Validation, Visualization, Writing – review and editing. **S. C. Maestrelli:** Validation, Visualization, Writing – review and editing. **L. Silvestro:** Validation, Visualization, Writing – review and editing.

References

- Agarwal, S. K., Palla, S., Chaturvedi, S. K., Mohapatra, B. N., Bishnoi, S., & Maity, S. (2020). Investigation on limestone calcined clay cement system. In S. Bishnoi (Ed.), *Calcined clays for sustainable concrete* (RILEM Bookseries, Vol. 25, pp. 443–454). Springer. https://doi.org/10.1007/978-981-15-2806-4_52
- Associação Brasileira de Normas Técnicas. (2009). *ABNT NBR 9778: Argamassa e concreto endurecidos – Determinação da absorção de água, índice de vazios e massa específica*.
- Associação Brasileira de Normas Técnicas. (2010). *ABNT NBR 15895: Materiais pozolânicos – Determinação do teor de hidróxido de cálcio fixado – Método Chapelle modificado*.
- Associação Brasileira de Normas Técnicas. (2011). *ABNT NBR 7222: Concreto e argamassa – Determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos*.
- Associação Brasileira de Normas Técnicas. (2015). *ABNT NBR 5738: Concreto – Procedimento para moldagem e cura de corpos de prova*.
- Associação Brasileira de Normas Técnicas. (2017a). *ABNT NBR 16605: Cimento Portland e outros materiais em pó – Determinação da massa específica*.
- Associação Brasileira de Normas Técnicas. (2017b). *ABNT NBR 8522: Concreto endurecido – Determinação dos módulos estáticos de elasticidade e de deformação à compressão*.
- Associação Brasileira de Normas Técnicas. (2018). *ABNT NBR 5739: Concreto – Ensaio de compressão de corpos de prova cilíndricos*.
- Associação Brasileira de Normas Técnicas. (2020). *ABNT NBR 16889: Concreto fresco – Determinação da consistência pelo abatimento do tronco de cone*.
- Associação Brasileira de Normas Técnicas. (2023). *ABNT NBR 6118: Projeto de estruturas de concreto – Procedimento*.
- Avet, F., & Scrivener, K. (2020). Influence of pH on the chloride binding capacity of Limestone Calcined Clay Cements (LC³). *Cement and Concrete Research*, 131, 106031. <https://doi.org/10.1016/j.cemconres.2020.106031>
- Bahman-Zadeh, F., Ramezani-pour, A., & Zolfagharnasab, A. (2022). Effect of carbonation on chloride binding capacity of limestone calcined clay cement (LC³) and binary pastes. *Journal of Building Engineering*, 52, 104447. <https://doi.org/10.1016/j.job.2022.104447>
- Balestra, C. E. T., Dragunski, D. C., Neckel, R. M., Silvestro, L., Savaris, G., & Schneider, R. (2024). Fresh properties of low-carbon cement pastes incorporating industrial by-products. *Journal of Materials in Civil Engineering*, 37(1). <https://doi.org/10.1061/JMCEE7.MTENG-18157>
- Balestra, C. E. T., Garcez, L. R., Silva, L. C., Veit, M. T., Jubanski, E., Nakano, A. Y., Pietrobelli, M. H., Schneider, R., & Gil, M. A. R. (2023). Contribution to low-carbon cement studies: Effects of silica fume, fly ash, sugarcane bagasse ash and acai stone ash incorporation in quaternary blended

- limestone-calcined clay cement concretes. *Environmental Development*, 45, 1–15. <https://doi.org/10.1016/j.envdev.2022.100792>
- Câmara, M. Y. F. (2020). *Estudo da durabilidade de concreto com utilização do cimento LC³* [Dissertação de Mestrado]. Universidade de Brasília. https://repositorio.unb.br/bitstream/10482/40750/1/2020_MyrelleYasminedeFreitasC%c3%a2mara.pdf
- Cheng, L., Kurihara, R., Yang, Z., Ohkubo, T., Kitagaki, R., Teramoto, A., Suda, Y., & Maruyama, I. (2026). Accelerated carbonation fronts in cement pastes: Mechanistic insights and simplified modeling. *Cement and Concrete Research*, 199, 1–21. <https://doi.org/10.1016/j.cemconres.2025.108050>
- Compeľová, K., Másilko, J., Švorec, J., Peciar, P., & Kuzielová, E. (2026). Comparison of LC³ and traditional SCM-blended cement pastes under supercritical CO₂ exposure. *The Journal of Supercritical Fluids*, 229, 1–13. <https://doi.org/10.1016/j.supflu.2025.106832>
- Danner, T., Norden, G., & Justnes, H. (2018). Characterization of calcined raw clays suitable as supplementary cementitious materials. *Applied Clay Science*, 162, 391–402. <https://doi.org/10.1016/j.clay.2018.06.030>
- Dhandapani, Y., Sakthivel, T., Santhanam, M., Gettu, R., & Pillai, R. G. (2018). Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cements (LC³). *Cement and Concrete Research*, 107, 136–151. <https://doi.org/10.1016/j.cemconres.2018.02.005>
- Ferreiro, S., Canut, M. M. C., Lund, J., & Herfort, D. (2019). Influence of fineness of raw clay and calcination temperature on the performance of calcined clay limestone blended cements. *Applied Clay Science*, 169, 81–90. <https://doi.org/10.1016/j.clay.2018.12.021>
- Friedlingstein, P., O’Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., ... Zheng, B. (2023). Global carbon budget 2023. *Earth System Science Data*, 15(12), 5301–5369. <https://doi.org/10.5194/essd-15-5301-2023>
- Ghazy, M. F., Maaty, E. S. A., Elaty, M. A., & Alrwashdeh, A. A. (2025). A comprehensive review of limestone calcined clay cement (LC³): Environmental and properties benefits, challenges, opportunities, and future directions. *Results in Engineering*, 28, 1–18. <https://doi.org/10.1016/j.rineng.2025.108319>
- Hosen, K., & Chen, B. (2025). Limestone calcined clay cement (LC³): A review of materials, properties, production and environmental impact. *Journal of Building Engineering*, 112, 1–23. <https://doi.org/10.1016/j.job.2025.113672>
- Huang, Z., Liang, T., & Chen, L. (2023). Experimental studies on durability performances of ultra-lightweight low-carbon LC³ cement composites against chloride ingress and carbonation. *Construction and Building Materials*, 395, 1–16. <https://doi.org/10.1016/j.conbuildmat.2023.132340>
- International Organization for Standardization. (2015). *ISO 1920-12: Testing of concrete – Part 12: Determination of the carbonation resistance of concrete – Accelerated carbonation method*.
- International Organization for Standardization. (2020). *ISO 13320: Particle size analysis – Laser diffraction methods – Part 1: General principles*.
- Jan, A., Ferrari, L., Mikanovic, N., Ben-Haha, M., & Franzoni, E. (2024). Chloride ingress and carbonation assessment of mortars prepared with recycled sand and calcined clay-based cement. *Construction and Building Materials*, 456, 1–14. <https://doi.org/10.1016/j.conbuildmat.2024.139337>
- Khan, M. S. H., Nguyen, Q. D., & Castel, A. (2018). Carbonation of limestone calcined clay cement concrete. In F. Martirena, A. Favier, & K. Scrivener (Eds.), *Calcined clays for sustainable concrete* (RILEM Bookseries, Vol. 16, pp. 238–243, Vol. 16). Springer. https://doi.org/10.1007/978-94-024-1207-9_38

- Khan, M. S. H., Nguyen, Q. D., & Castel, A. (2020). Performance of limestone calcined clay blended cement-based concrete against carbonation. *Advances in Cement Research*, 32(11), 481–491. <https://doi.org/10.1680/jadcr.18.00172>
- Krishnan, S., & Bishnoi, S. (2020). A numerical approach for designing composite cements with calcined clay and limestone. *Cement and Concrete Research*, 138, 1–9. <https://doi.org/10.1016/j.cemconres.2020.106232>
- Liu, J., Liu, Y., Zeng, J., & Zhuge, Y. (2025). A comprehensive review of mechanisms, techniques, and precursors in enforced carbonation for low-carbon concrete. *Journal of Building Engineering*, 112, 1–29. <https://doi.org/10.1016/j.jobbe.2025.113685>
- Mañosa, J., Calderón, A., Salgado-Pizarro, R., Maldonado-Alameda, A., & Chimenos, J. M. (2024). Research evolution of limestone calcined clay cement (LC³), a promising low-carbon binder: A comprehensive overview. *Heliyon*, 10(3), 1–14. <https://doi.org/10.1016/j.heliyon.2024.e25117>
- Marani, A., & Panesar, D. K. (2025). Unraveling the correlation between natural and accelerated carbonation of low-carbon concrete using machine learning. *Sustainable Materials and Technologies*, 45, 1–20. <https://doi.org/10.1016/j.susmat.2025.e01561>
- Matos, P. R., Zat, T., Lima, M. M., Andrade Neto, J. S., Souza, M. T., & Rodríguez, E. D. (2023). Effect of the superplasticizer addition time on the fresh properties of 3D printed limestone calcined clay cement (LC³) concrete. *Case Studies in Construction Materials*, 19, 1–10. <https://doi.org/10.1016/j.cscm.2023.e02419>
- Nair, N., Haneefa, K. M., Santhanam, M., & Gettu, R. (2020). A study on fresh properties of limestone calcined clay blended cementitious systems. *Construction and Building Materials*, 254, 1–12. <https://doi.org/10.1016/j.conbuildmat.2020.119326>
- Neves, R., Branco, F., & de Brito, J. (2013). Field assessment of the relationship between natural and accelerated concrete carbonation resistance. *Cement and Concrete Composites*, 41, 9–15. <https://doi.org/10.1016/j.cemconcomp.2013.04.006>
- Sabtiwu, M., Dhandapani, Y., Drewniok, M., Adu-Amankwah, S., & Bernal, S. A. (2025). Carbonation-induced changes in the mechanical performance, water, and chloride permeability of Portland cement-slag-limestone ternary cement concretes. *Cement and Concrete Composites*, 163, 1–15. <https://doi.org/10.1016/j.cemconcomp.2025.106222>
- Sánchez Berriel, S., Favier, A., Rosa Domínguez, E., Sánchez Machado, I. R., Heierli, U., Scrivener, K., Martirena Hernández, F., & Habert, G. (2016). Assessing the environmental and economic potential of limestone calcined clay cement in Cuba. *Journal of Cleaner Production*, 124, 361–369. <https://doi.org/10.1016/j.jclepro.2016.02.125>
- Schmid, M., & Plank, J. (2021). Interaction of individual meta clays with polycarboxylate (PCE) superplasticizers in cement investigated via dispersion, zeta potential, and sorption measurements. *Applied Clay Science*, 207, 1–12. <https://doi.org/10.1016/j.clay.2021.106092>
- Scrivener, K., Avet, F., Maraghechi, H., Zunino, F., Ston, J., Hanpongpan, W., & Favier, A. (2019). Impacting factors and properties of limestone calcined clay cements (LC³). *Green Materials*, 7(1), 3–14. <https://doi.org/10.1680/jgrma.18.00029>
- Silvestro, L., Ruviano, A. S., Lima, G., Tambara, J., L. U. D., Feys, D., & Kirchheim, A. P. (2024). Rotational rheometry test of Portland cement-based materials: A systematic literature review. *Construction and Building Materials*, 432, 1–14. <https://doi.org/10.1016/j.conbuildmat.2024.136667>
- Wang, K., Kwon, S., & Wang, X. (2025). Optimal mixture design method for low-CO₂ limestone-calcined clay cement (LC³) concrete considering climate change and carbonation durability: A case study of

eight countries. *Sustainable Chemistry and Pharmacy*, 46, 1–16. <https://doi.org/10.1016/j.scp.2025.102108>

- Yu, J., Wu, H. L., Mishra, D. K., Li, G., & Leung, C. K. Y. (2021). Compressive strength and environmental impact of sustainable blended cement with high-dosage limestone and calcined clay (LC2). *Journal of Cleaner Production*, 278, 1–11. <https://doi.org/10.1016/j.jclepro.2020.123616>
- Zhang, D., Jaworska, B., Zhu, H., Dahlquist, K., & Li, V. C. (2020). Engineered cementitious composites (ECC) with limestone calcined clay cement (LC³). *Cement and Concrete Composites*, 114, 1–14. <https://doi.org/10.1016/j.cemconcomp.2020.103766>
- Zhou, G., Zhu, Y., Chen, L., & Su, R. (2025). Low-carbon and durable limestone calcined clay cement foam concrete reinforced by BFRP bars. *Journal of Building Engineering*, 115, 1–21. <https://doi.org/10.1016/j.job.2025.114547>