GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

DOI: **10.5937/greenb26039T**
Review paper

CO_2 CARBONATION OF FLY ASH AND THE FORMATION OF GRANULATED CARBONATED PRODUCTS FOR CONCRETE APPLICATIONS

Gordana Topličić Ćurčić[1], Nenad Ristić[2], Dušan Grdić[3], Zoran Grdić[4]

Abstract

Mineral carbonation of fly ash is a controlled physicochemical route in which reactive Ca- and Mg-bearing phases bind CO_2 as stable carbonates. This critical review evaluates reaction mechanisms, carbonation-assisted granulation and the use of carbonated fly ash in concrete, with particular attention to high-calcium and fluidized-bed-combustion ashes. Recent studies confirm that performance is strongly feedstock- and process-specific: reported results range from approximately 94 kg CO_2/t for wet-carbonated high-calcium fly ash to carbonation efficiencies of 78–95% in selected aqueous systems, while fly-ash-rich artificial aggregates have achieved pellet strengths close to 10 MPa after combined air and CO_2 curing. Carbonation can reduce residual free CaO, improve volume stability and modify porosity, but excessive surface precipitation, soluble salts, high absorption and non-uniform core conversion remain important limitations. Carbonated pellets are therefore treated as multiphase artificial aggregates rather than pure $CaCO_3$ granules. The most defensible near-term applications are controlled precast and non-reinforced products; reinforced-concrete use additionally requires verification of alkalinity, cover carbonation, chloride transport and corrosion protection. The review concludes that CO_2 uptake must be reported together with mineralogical conversion, pellet properties, concrete performance and a transparent net-CO_2 balance.

Key words: *fly ash, mineral carbonation, CO_2 utilization, granulation, concrete*

[1] PhD, Full Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, gordana.toplicic.curcic@gaf.ni.ac.rs, ORCid 0000-0001-5967-4964
[2] PhD, Full Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, nenad.ristic@gaf.ni.ac.rs, ORCid 0000-0002-8201-892X
[3] PhD, Associate Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, dusan.grdic@gaf.ni.ac.rs, ORCid 0000-0002-2651-7388
[4] PhD, Full Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, zoran.grdic@gaf.ni.ac.rs, ORCid 0000-0002-0653-210X

1. INTRODUCTION

Fly ash is a fine particulate residue generated during the combustion of coal, lignite, biomass and other solid fuels. Its established use in construction is mainly associated with pozzolanic or latent hydraulic activity, filler effects and the partial replacement of Portland cement. However, not all fly ashes comply with the chemical, mineralogical and environmental requirements for use as a conventional supplementary cementitious material. Their properties vary with fuel type, combustion technology, flue-gas treatment, collection point and storage history [1,2]. This variability has stimulated research into alternative valorisation pathways in which fly ash is treated as a reactive mineral feedstock rather than used directly as an unmodified cement replacement.

Mineral carbonation is one such pathway. Calcium- and magnesium-bearing phases react with CO_2 and are converted, wholly or partly, into carbonate phases that are stable over long time scales [3–5]. In reinforced concrete, natural carbonation of hardened cement paste is generally a durability concern because it lowers pore-solution pH and may depassivate embedded steel. Controlled pre-carbonation of fly ash has a different purpose: recent high-calcium-fly-ash studies show that it can consume residual free CaO, increase volume stability and store measurable CO_2 before the material is incorporated into a cementitious product [6]. The distinction between pre-carbonation of the ash and carbonation of the cover concrete is therefore fundamental.

The aim of the paper is to critically systematize current knowledge on the carbonation of fly ash with CO_2, explain the governing chemical and transport mechanisms, evaluate carbonation-assisted granulation, and define the conditions under which the resulting material may be used in concrete. The paper is a critical narrative review and does not present original experimental results. Its contribution is the integration of reaction chemistry, processing parameters, environmental safety, aggregate performance, concrete durability and net CO_2 accounting into a single decision framework for subsequent laboratory and pilot-scale research.

2. REVIEW METHODOLOGY AND SCIENTIFIC SCOPE

A structured critical narrative review was conducted using peer-reviewed literature available through ScienceDirect, SpringerLink, Google Scholar and Crossref. The search covered publications from 2000 to August 2026, with recent experimental evidence from 2022–2026 used to establish the current state of the art and earlier studies retained where they define reaction mechanisms or durability concepts. Search combinations linked “fly ash” with “mineral carbonation”, “CO_2 uptake”, “accelerated carbonation”, “high-calcium fly ash”, “fluidized-bed combustion ash”, “artificial aggregate”, “pelletization”, “granulation”, “carbonation curing”, “leaching”, “durability” and “concrete”.

Studies were included when the investigated ash or residue was clearly identified and when carbonation conditions and/or quantitative or phase-based evidence relevant to CO_2 binding, free-CaO stabilization, granule properties, environmental

behaviour or concrete performance were reported. Studies without sufficient material identification or without evidence transferable to fly-ash carbonation and concrete applications were excluded. Search results were screened against these criteria, and 20 unique sources were retained for the final critical synthesis.

Critical comparison was performed at four linked levels: feedstock chemistry and mineralogy; carbonation conditions and measured CO_2 uptake; granule or aggregate physical-mechanical performance; and concrete or environmental response. Because the studies differ in ash origin, free-CaO content, liquid-to-solid ratio, CO_2 concentration, temperature, pressure, particle size and reactor configuration, reported optima are interpreted as study-specific rather than universal. Quantitative values are therefore compared together with their experimental context and used to define screening ranges rather than general design limits.

3. FLY ASH AS A REACTIVE CARBONATION FEEDSTOCK

3.1. Chemical and mineralogical variability

Low-calcium coal fly ash is commonly dominated by aluminosilicate glass, quartz and mullite, whereas high-calcium ash may additionally contain free CaO, portlandite, calcium silicates, aluminates and sulfates. Fluidized-bed-combustion ash frequently contains higher proportions of free lime and anhydrite because of lower combustion temperature and in-furnace desulfurization [1,2,7]. Theoretical carbonation capacity increases with reactive Ca and Mg content; practical capacity is lower because not all Ca and Mg are accessible or reactive within the selected process time.

A reliable feedstock assessment should combine X-ray fluorescence (XRF), X-ray diffraction (XRD), thermogravimetry and derivative thermogravimetry (TG/DTG), scanning electron microscopy with energy-dispersive spectroscopy (SEM/EDS), particle-size distribution, specific surface area, loss on ignition, moisture, free CaO, pH and electrical conductivity. XRF alone cannot determine carbonation capacity because it does not distinguish reactive free lime from calcium bound in relatively inert silicate or sulfate phases. XRD identifies crystalline phases, whereas TG/DTG supports quantification of portlandite and carbonate decomposition. Quantitative XRD with an internal standard or Rietveld analysis is preferable when the amorphous fraction must be estimated.

3.2. Environmental compatibility and volume stability

Fly ash may contain trace elements such as As, Cr, Pb, Zn, Cu, Ni, Mo and Se, and their mobility can change as carbonation lowers alkalinity. For fluidized-bed-combustion fly ashes containing 1.7–6.8% free CaO, a reported CO_2-binding potential of 9.7–15.7% was accompanied by a pH decrease from about 12 to about 9 and reduced leachability of several contaminants, including Zn, Cu, Pb, Ni, As, Hg, Cd and Cr; sulfate behaviour was ash-dependent and did not show a uniform reduction [7]. Because industrial residues differ markedly in phase composition and contaminant inventory, these environmental effects cannot be generalized across ash sources [8].

Environmental compatibility should therefore be verified by standardized leaching tests on the raw ash, carbonated powder or granule and, where relevant, the crushed final concrete product.

Free CaO and reactive MgO govern both carbonation potential and dimensional stability. Delayed hydration may cause expansion, while a dense carbonate rim may leave an unreacted core. Verification should therefore include residual free lime, expansion or soundness, cross-sectional microscopy and sulfate control.

4. CHEMICAL AND TRANSPORT MECHANISMS OF CO_2 CARBONATION

Carbonation requires the simultaneous availability of gaseous or dissolved CO_2, water and reactive alkaline-earth phases. CO_2 first diffuses through the gas-filled pore space and dissolves in a thin water film. Depending on pH, dissolved inorganic carbon is present mainly as $CO_2(aq)$, HCO_3^- and CO_3^{2-}. At the same time, dissolution or hydration of CaO, $Ca(OH)_2$ and other Ca-bearing phases supplies Ca^{2+} to the pore solution. Once supersaturation is reached, $CaCO_3$ nucleates and precipitates [3,4]. The simplified reactions are:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s) \quad (3)$$

These equations describe the global stoichiometry but not the rate-controlling steps. Under very dry conditions, dissolution and ionic transport are insufficient. Under water-saturated conditions, gas diffusion is strongly restricted. The fastest reaction is therefore commonly observed at an intermediate moisture content, although the optimum depends on particle size, pore structure, mixing intensity and reactor design [3,4]. Pre-hydration may increase the availability of portlandite but can also cause agglomeration and reduce gas permeability.

Calcite, aragonite and vaterite may form, with calcite being thermodynamically stable and vaterite metastable. Polymorph, crystal morphology and spatial distribution influence porosity, pellet strength, water absorption and interfacial behaviour; total carbonate content alone is insufficient.

A dense carbonate shell may make the reaction diffusion-controlled and conceal an unreacted core. Cross-sectional SEM/EDS, phase analysis after controlled grinding and residual free-CaO measurement are therefore needed to demonstrate uniform conversion.

5. CARBONATION-ASSISTED GRANULATION

5.1. Process routes

Four principal process routes can be distinguished: carbonation of loose ash prior to granulation; simultaneous wetting, pelletization and carbonation; pelletization followed by carbonation curing; and repeated wetting-carbonation cycles. For producing artificial

aggregate, pelletization followed by controlled carbonation is technically attractive because pellet geometry and gas exposure can be regulated separately. Simultaneous carbonation may accelerate early stiffening, but premature surface precipitation can restrict further growth or cause non-uniform pellets.

Disc pelletizers and rotating drums produce cold-bonded agglomerates by nucleation, coalescence and layering. Liquid content has a narrow optimum: too little water produces dusty weak pellets, while excess water causes sticking, deformation and poor gas transport. Any supplementary binder must be included in the carbon balance.

5.2. CO_2 source and curing conditions

Pure CO_2 supports controlled laboratory work, whereas conditioned process gas is more industrially relevant. Because flue gas may contain water vapour, SOx, NOx, oxygen and particulates, results obtained with pure CO_2 cannot be transferred directly; gas composition, flow, pressure, humidity and temperature must be reported.

Higher CO_2 concentration can accelerate early reaction, but final conversion may be limited by reactant depletion or surface passivation. Temperature and curing time must be optimized against CO_2 uptake, residual free CaO, pellet strength, absorption, leaching and energy demand.

Recent experiments show that carbonation performance cannot be ranked by a single uptake value without considering feedstock and reactor conditions. Ding et al. obtained 94.8% carbonation efficiency from low-CaO fly ash (7.272 wt% CaO) in seawater at ambient temperature and pressure using 99% CO_2; the high efficiency was associated with a pH window of 8.2–10.4 that favoured Ca release and carbonate precipitation [9]. Miao et al. reported a maximum uptake of 0.128 g CO_2/g circulating-fluidized-bed fly ash and 78.17% efficiency in direct aqueous carbonation [10]. For high-calcium Class C fly ash, Ge et al. measured 94 kg CO_2/t and 57.21% efficiency after wet carbonation; the treatment significantly reduced free CaO and improved volume stability, while cement paste containing carbonated fly ash showed 98.97% and 113.41% higher compressive strength than the corresponding untreated-fly-ash paste at 1 and 3 d, respectively [6]. At aggregate scale, Zhang et al. used 70% fly ash, 15% Portland cement and 15% slag; after 3 d air curing plus 12 h carbonation curing, pellet strength reached 9.98 MPa, water absorption 10.35% and CO_2 content 4.33%, and concrete containing the aggregate reached 37.94 MPa compressive strength [11]. Using cold-bonded fly-ash lightweight aggregate, Yao et al. reported that 4 h carbonation with simulated coal-fired flue gas containing 15% CO_2 and 1000 ppm SO_2 increased CO_2 uptake by 25.8% and reduced porosity and water absorption; however, the effect of SO_2 on leaching was element-dependent and requires separate environmental verification [12]. The comparison demonstrates that ash chemistry, liquid phase, gas concentration, curing sequence and the performance metric must be reported together; a high carbonation efficiency does not by itself establish a suitable concrete aggregate.

6. CHARACTERIZATION AND PERFORMANCE VERIFICATION

Successful carbonation must be demonstrated by complementary methods. XRD identifies the appearance or increase of carbonate peaks and the reduction of portlandite or other crystalline reactants. TG/DTG is commonly used to estimate carbonate-bound CO_2 from mass loss in the de-carbonation range, but overlapping decomposition of different carbonate, hydrate and sulfate phases can bias the result. Baseline correction using untreated ash and confirmation by total inorganic carbon analysis improve reliability. SEM/EDS provides morphological and spatial evidence but is semi-quantitative and should not be used alone to calculate bulk conversion.

For granulated products, chemical evidence must be linked to engineering performance. Minimum characterization should include particle-size distribution, loose and compacted bulk density, apparent particle density, water absorption, open porosity, resistance to crushing, abrasion or attrition, fines generation and dimensional stability. Water absorption is particularly important because highly porous pellets may remove mixing water, reduce workability and change the effective water-to-binder ratio. Pre-wetting may control this effect, but it introduces additional water and must be standardized.

Standard selection also requires care. Carbonated pellets are commonly lightweight and porous, so methods developed for normal-weight natural aggregate are not automatically interchangeable. EN 1097-6:2022 explicitly provides reference methods for particle density and water absorption of both normal-weight and lightweight aggregates [13], whereas EN 13055:2016 provides the product framework for lightweight aggregates, including manufactured aggregates from industrial by-products and end-use-dependent performance requirements [14]. Fragmentation or abrasion methods developed for dense natural aggregate may still provide comparative information for sufficiently robust fractions, but their results should be interpreted together with particle density, friability and the intended application.

The ITZ requires direct study because a rough carbonate-rich surface may enhance mechanical interlocking, while a porous shell or high absorption may create a locally weak zone. Backscattered-electron imaging, elemental mapping and fracture analysis can distinguish pellet failure from ITZ debonding.

7. POTENTIAL USE IN CONCRETE

7.1. Microfiller and partial binder replacement

Finely ground carbonated ash can act as a microfiller by improving particle packing and providing nucleation surfaces. Calcium carbonate can also modify aluminate reactions in Portland-cement systems and promote carbonate-bearing hydrate assemblages [15]. However, pre-carbonation may consume phases that would otherwise contribute to pozzolanic or hydraulic reactions. The net result is therefore a balance among filler and nucleation effects, dilution, residual reactivity and changes in

water demand; a fixed replacement level cannot be recommended independently of ash chemistry and fineness.

Replacement levels such as 5%, 10% and 20% may be used for screening, but they are not general application limits. Strength at several ages must be interpreted with calorimetry, phase assemblage, porosity and durability because similar 28-day strength does not prove equivalent service performance.

7.2. Artificial aggregate and precast products

Carbonated pellets may partially replace natural fine or lightweight aggregate. Their suitability depends on grading, density, crushing and abrasion resistance, water absorption, freeze–thaw stability and compatibility with the intended concrete. Low-density porous pellets may reduce unit weight but commonly increase absorption and may reduce elastic modulus. Conversely, internal water stored in pre-wetted pellets can contribute to internal curing, provided that desorption kinetics and the effective mixture water are quantified.

Controlled precast and non-reinforced products are the most realistic near-term applications. Structural reinforced concrete requires additional evidence on cover carbonation and chloride transport [16–18], together with electrical resistivity and corrosion-related electrochemical indicators where reinforcement is present.

8. CRITICAL DISCUSSION AND RESEARCH GAPS

The principal value of fly-ash carbonation is the possibility of combining waste valorisation with CO_2 utilization, but laboratory efficiency cannot be equated directly with industrial performance. Process configuration is particularly important: recent seawater-carbonation work showed that, under otherwise comparable ambient conditions, carbonation efficiency decreased from 94.8% in an open system to 26.5% in a sealed system as elevated CO_2 partial pressure altered dissolution and precipitation behaviour. This illustrates the risk of transferring optimum laboratory conditions directly to dust-contained or gas-recycling industrial reactors [19]. Likewise, gross carbonate formation may be offset by electricity for grinding and pelletization, heat for drying, CO_2 conditioning, transport and additional binder, while service-life effects also influence the environmental balance. A carbon-negative claim therefore requires a transparent system boundary and inventory rather than uptake data alone [5,8,20].

Compositional variability is a major barrier to standardization. Industrial implementation requires feedstock acceptance limits, rapid incoming control and batch-to-batch statistics; blending may reduce variability but can dilute the reactive fraction.

Research must couple CO_2 uptake with service-life performance. Increased compressive strength may coexist with greater shrinkage, lower modulus, higher absorption or deeper cover carbonation; a balanced performance matrix is therefore essential.

Terminology must reflect demonstrated material identity. “Carbonated fly ash”, “artificial aggregate” and “$CaCO_3$ granule” are not interchangeable, and claims of $CaCO_3$

production require quantitative phase evidence and disclosure of the residual non-carbonate fraction.

Five priorities emerge for future research: standardized feedstock classification based on reactive rather than total Ca/Mg; coupled carbonation–granulation kinetics; quantitative links between carbonation degree, pellet pore structure and concrete performance; long-term durability, leaching and reinforcement protection; and net CO_2 benefit under realistic industrial boundaries. These gaps define the logic of the validation programme proposed in Section 9.

9. PROPOSED LABORATORY VALIDATION PROGRAMME

Based on the identified evidence gaps, a six-stage validation framework is proposed as an authors' synthesis of established characterization and performance methods. Stage 1 characterizes the feedstock by XRF, quantitative XRD, TG/DTG, SEM/EDS, particle size, specific surface area, loss on ignition, free CaO, moisture, pH, conductivity, soluble salts and leaching. Stage 2 screens moisture content, CO_2 concentration, temperature and time, with gas consumption/outlet concentration for mass balance and TG/DTG or total inorganic carbon for bound CO_2.

Stages 3 and 4 comprise granulation and carbonation curing. Disc angle, speed, feed rate, liquid addition, residence time and target grading should be reported. Green-pellet yield and strength are followed by residual free CaO, carbonate content, cross-sectional conversion, density, absorption, crushing, attrition and leaching tests.

Stage 5 evaluates reference concrete, powder additions and at least two pellet replacement levels. Fresh-state tests include consistency, density and air content; hardened-state tests include strength, modulus, shrinkage, absorption, water penetration, resistivity, chloride transport, freeze–thaw resistance and carbonation depth. Reinforced-concrete use additionally requires corrosion indicators.

Stage 6 quantifies net CO_2 benefit from measured uptake and process inventory, with sensitivity to electricity mix, CO_2 source, transport, drying, pellet yield and service life. Pilot production is justified only after chemical, mechanical, durability and environmental criteria are met.

10. CONCLUSIONS

Controlled carbonation of fly ash can convert reactive Ca- and Mg-bearing phases into stable carbonates while modifying particle surfaces and, for suitable high-calcium ashes, reducing residual free CaO. High-calcium and fluidized-bed-combustion ashes generally offer the greatest direct carbonation potential, whereas low-calcium Class F ash may require activation or an external Ca source. Carbonation-assisted granulation can produce multiphase pellets for investigation as artificial aggregate, but these products should not be described as pure $CaCO_3$ unless phase composition and purity are quantitatively demonstrated.

Potential applications include microfiller use, partial binder replacement and partial aggregate substitution. Controlled precast or non-reinforced products remain the most

defensible initial route; reinforced concrete additionally requires evidence on alkalinity, cover carbonation, chloride resistance, dimensional stability and corrosion protection. Environmental value should be reported as net rather than gross CO_2 benefit, combining measured uptake with process energy, material and transport inputs and verified service performance.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Agreement No. 451-03-34/2026-03/200095 (05/02/2026).

Sustainable Development Goals: Industry, Innovation and Infrastructure

LITERATURE

[1] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*, *36*(3), 327–363. https://doi.org/10.1016/j.pecs.2009.11.003

[2] Hemalatha, T., & Ramaswamy, A. (2017). A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete. *Journal of Cleaner Production*, *147*, 546–559. https://doi.org/10.1016/j.jclepro.2017.01.114

[3] Fernández Bertos, M., Simons, S. J. R., Hills, C. D., & Carey, P. J. (2004). A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO_2. *Journal of Hazardous Materials*, *112*(3), 193–205. https://doi.org/10.1016/j.jhazmat.2004.04.019

[4] Montes-Hernandez, G., Pérez-López, R., Renard, F., Nieto, J. M., & Charlet, L. (2009). Mineral sequestration of CO_2 by aqueous carbonation of coal combustion fly-ash. *Journal of Hazardous Materials*, *161*(2–3), 1347–1354. https://doi.org/10.1016/j.jhazmat.2008.04.104

[5] Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., & Maroto-Valer, M. M. (2014). A review of mineral carbonation technologies to sequester CO_2. *Chemical Society Reviews*, *43*(23), 8049–8080. https://doi.org/10.1039/C4CS00035H

[6] Ge, Z., Xue, X., Fang, H., Shao, Y., Sun, K., Zhang, H., & Šavija, B. (2025). Preparation and characterization of carbonated high-calcium fly ash as supplementary cementitious material. *Construction and Building Materials*, *466*, 140285. https://doi.org/10.1016/j.conbuildmat.2025.140285

[7] Uliasz-Bocheńczyk, A., & Mokrzycki, E. (2020). The potential of FBC fly ashes to reduce CO_2 emissions. *Scientific Reports*, *10*(1), 9469. https://doi.org/10.1038/s41598-020-66297-y

[8] Baena-Moreno, F. M., Leventaki, E., Riddell, A., Wojtasz-Mucha, J., & Bernin, D. (2023). Effluents and residues from industrial sites for carbon dioxide capture: A review. *Environmental Chemistry Letters*, *21*(1), 319–337. https://doi.org/10.1007/s10311-022-01513-x

[9] Ding, Z., Zhang, X., Cheng, T., Shen, Y., Cai, W.-J., Chen, C.-T. A., Yang, Z., Liu, T., Xiao, J., Xia, M., Chen, Y., & Pan, Y. (2023). Unlocking high carbonation efficiency: Direct CO_2 mineralization with fly ash and seawater. *Chemical Engineering Science*, *282*, 119349. https://doi.org/10.1016/j.ces.2023.119349

[10] Miao, E., Du, Y., Zheng, X., Zhang, X., Xiong, Z., Zhao, Y., & Zhang, J. (2023). Kinetic analysis on CO_2 sequestration from flue gas through direct aqueous mineral carbonation of circulating fluidized bed combustion fly ash. *Fuel*, *342*, 127851. https://doi.org/10.1016/j.fuel.2023.127851

[11] Zhang, Z., Lyu, J., Liu, S., Ma, S., Zhang, Z., Niu, X., Wang, C., Zhou, C., Song, L., Ma, K., Yin, X., & Yue, H. (2025). Preparation of artificial aggregates with high fly ash content through air curing and carbonation curing. *Construction and Building Materials*, *461*, 139874. https://doi.org/10.1016/j.conbuildmat.2025.139874

[12] Yao, X., Song, B., Huan, Q., Hu, Y., & Song, M. (2024). Ambient pressure carbonation curing of cold-bonded fly ash lightweight aggregate using coal-fired flue gas for properties enhancement and CO_2 sequestration. *Journal of Environmental Chemical Engineering*, *12*(6), 114208. https://doi.org/10.1016/j.jece.2024.114208

[13] European Committee for Standardization. (2022). *Tests for mechanical and physical properties of aggregates—Part 6: Determination of particle density and water absorption* (EN 1097-6:2022).

[14] European Committee for Standardization. (2016). *Lightweight aggregates* (EN 13055:2016).

[15] Lothenbach, B., Le Saout, G., Gallucci, E., & Scrivener, K. (2008). Influence of limestone on the hydration of Portland cements. *Cement and Concrete Research*, *38*(6), 848–860. https://doi.org/10.1016/j.cemconres.2008.01.002

[16] Atiş, C. D. (2003). Accelerated carbonation and testing of concrete made with fly ash. *Construction and Building Materials*, *17*(3), 147–152. https://doi.org/10.1016/S0950-0618(02)00116-2

[17] Khunthongkeaw, J., Tangtermsirikul, S., & Leelawat, T. (2006). A study on carbonation depth prediction for fly ash concrete. *Construction and Building Materials*, *20*(9), 744–753. https://doi.org/10.1016/j.conbuildmat.2005.01.052

[18] Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. *Cement and Concrete Research*, *30*(2), 291–299. https://doi.org/10.1016/S0008-8846(99)00249-5

[19] Cheng, T., Ding, Z., Zhang, X., Chai, J., Shen, Y., Cai, L., Bao, R., Chen, Y., & Pan, Y. (2025). Cyclic aqueous carbonation of fly ash in seawater: Enhancing carbonation efficiency and CO_2 removal rate. *Chemical Engineering and Processing - Process Intensification*, *216*, 110428. https://doi.org/10.1016/j.cep.2025.110428

[20] Meng, D., Unluer, C., Yang, E.-H., & Qian, S. (2022). Carbon sequestration and utilization in cement-based materials and potential impacts on durability of structural concrete. *Construction and Building Materials*, *361*, 129610. https://doi.org/10.1016/j.conbuildmat.2022.129610