

Trends in research and development toward carbon neutrality and a circular economy in the Japanese concrete industry

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Abstract

At present, Japan, similar to many other countries, is undertaking government-supported research and development aimed at transitioning the cement and concrete sectors toward carbon neutrality and a circular economy. This study introduces the approaches adopted by Japan's cement industry, which operates under unique geological conditions with limited domestic resources, as well as the initiatives pursued within the concrete sector. Because Japan has emphasized resource and energy efficiency since the oil crisis of the 1970s, background information on research and development originally conducted to reduce resource consumption during that period is also incorporated. Although carbon neutrality is a global challenge, each country faces distinct historical and contextual constraints, including geological and resource-related boundary conditions. Research and development efforts must therefore be tailored to national circumstances. In this respect, Japan's experience is presented here as an illustrative case.

Keywords: Carbon neutrality, Circular economy, Japanese concrete industry, CO₂ emission.

1 Introduction and research history in Japan

1.1 Background and objective

The objective of this manuscript is to describe the distinctive industrial structure and boundary conditions that have shaped technological development in Japan, with particular emphasis on recent advances and practical implementation in the cement and concrete sectors. A substantial portion of research and development in Japan has been published exclusively in Japanese and, as a result, has not been widely accessible to the international research community. This manuscript, therefore, aims to provide a comprehensive overview of the historical progression of these findings, including those reported only in Japanese, while also presenting recent developments and emerging trends in research, technology, and implementation.

In addition, this Introduction notes that, even before the current emphasis on carbon neutrality, Japan, facing the challenge of limited natural resources, had already pursued similar technological developments prior to 2000.

Understanding these earlier developments, as well as their similarities and potential synergies, helps clarify the priorities of recent research and how technological pathways have diverged over time. Therefore, we include an overview of relevant developments related to hydraulic cements, tracing back to the period before the widespread use of modern cement.

From this perspective, the Introduction first outlines the trajectory of technological development prior to the current strong emphasis on carbon neutrality and the circular economy.

1.2 Before Meiji restoration

Japan has a long tradition of wooden architecture, consequently, the utilization of limestone, a natural stone, for building applications has followed a trajectory distinct from that in Europe. One such application was shikkui, a lime-based plaster employed as a finishing material for buildings, while another was tataki, a flooring and hearth material that exhibits hydraulicity through a mechanism different from that

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of pozzolans. Shikkui is a wall-rendering material produced by mixing slaked lime with seaweed extracts and organic fibers such as straw, hemp, or paper. Tataki was produced by blending lime with weathered granite, adding water, kneading the mixture, and compacting it to form floors or stoves. Although tataki is similar to lime mortars, the mechanism responsible for its hydraulic behavior remains unclear. Notably, remnants of water-control structures constructed using tataki are still extant today.

1.3 Meiji restoration and industrialization

Following the Meiji Restoration, the term “lime concrete” came into use, and in 1886 it was described in *Zōka Hikkei*, a construction handbook authored by Josiah Conder [1], the first professor in the Department of Architecture at the University of Tokyo, as a mixture of lime powder with sand and gravel. Because Japanese limestone is highly pure and therefore does not impart hydraulicity after calcination, the addition of volcanic ash or ceramic powder as supplementary materials was recommended.

The first documented use of imported cement in Japan dates to 1861, when the Tokugawa shogunate employed it in the construction of the Nagasaki Ironworks. At that time, Japan depended on European imports for cement. One notable example is its use in early construction works at Yokohama Port, however, construction difficulties and cracking problems attracted public attention and were even debated in the national assembly. Japan’s first domestic cement plant was established in 1872, and domestically produced cement was shipped for the first time in 1875. Because cement was expensive at the time, research focused on cements incorporating volcanic ash, including studies on the relationship between silica content and strength development [2, 3]. From 1912 onward, cements were also produced by grinding mixtures of pozzolanic materials, such as diatomaceous earth, soluble clay, and calcined granite powder, together with gypsum. These products were used for a period but eventually fell out of common use.

Research on blast furnace cement in Japan began in 1910, and in 1913, a grinding mill was installed at the Yahata Steel Works, marking the commencement of its production. In its early stages, the clinker content was reported to be approximately 30–40%, and the cement was applied in structures such as dams. Between the 1910s and the Second World War, a range of technological developments was pursued to improve the effective utilization of materials. These efforts included studies on the incorporation of bentonite [4], calcined clay [5], shale [6], and even acid-dissolved rock powders of various origins [7] into cement.

1.4 Post World War II and modernization

After World War II, blast-furnace cement, fly-ash cement, silica cement, and related products were further developed. Throughout this period, the primary motivation was the efficient use of resources, particularly through the utilization of industrial by-products and waste materials as raw inputs for cement production.

Discussions on recycling and circularity in the concrete sector initially focused on the management of waste concrete. During the period of rapid economic growth, severe pollution problems emerged, followed by challenges related to solid waste management. Both issues were intrinsically linked to national land development and environmental contamination, reflecting challenges commonly encountered in developing regions worldwide.

The Waste Management and Public Cleansing Act was enacted in 1970, under which construction waste, primarily concrete debris, was formally designated as industrial waste, thereby obligating demolition contractors to ensure its proper treatment. This designation led to the emergence of intermediate treatment companies dedicated to processing construction waste. However, owing to limited processing technologies and insufficient operational experience, most of the material was reused only as landfill or road sub-base, effectively constituting disposal rather than true recycling. As landfill capacity became increasingly constrained, demand for the recovery and reuse of aggregates increased significantly.

The development of applications for demolished concrete as aggregates in new concrete began around 1975. In 1977, the Construction Industry Association of Japan established the Committee on Waste Construction Material Treatment and Reuse, which proposed the “Utilization Standards for Recycled Aggregates and Recycled Concrete.” This initiative marked the introduction of a policy promoting the use of recycled aggregates in low-strength concrete. In the same year, the Japan Road Association issued the “Quality Standards for Recovered Waste Concrete Aggregates for Road Base Materials,” which set out specific quality requirements.

In 1981, the Ministry of Construction initiated a comprehensive review of recycling technologies, including methods for producing recycled aggregates suitable for use in concrete. Two major national projects were subsequently implemented to establish technical standards: “Development of Technologies for Utilizing Waste in Construction Projects” (1981–1985) and “Development of Technologies for Reducing and Reusing Construction By-products” (1992–1996). In 1986, subcommittees within the building and civil engineering sectors proposed quality standards, usage criteria, and construction guidelines for recycled aggregates. These proposals included systems for removing adhered mortar in addition to crushing, as well as specifications for blending recycled aggregates with natural aggregates [8].

In 1994, the Ministry of Construction issued a notification entitled “Provisional Quality Standards for the Reuse of Concrete By-products by Application” [9]. Subsequently, the Japan Concrete Institute (JCI) advanced discussions toward standardization of recycled aggregates, culminating in the publication of Japan Industrial Standard (JIS) Technical Report TR A 0006, “Concrete Using Recycled Aggregates,” in 2000. However, despite these developments, recycled aggregates were still not permitted for use in structural concrete, and widespread adoption did not occur.

As the expansion of road infrastructure slowed, demand for recycled concrete base-course materials also declined, resulting in a surplus of waste concrete in some regions. Against this backdrop, the reuse of waste concrete as aggregate in new concrete has become increasingly necessary to promote efficient resource utilization and reduce the environmental burdens associated with waste disposal. This necessity ultimately drove the standardization of recycled concrete materials within the JIS framework. In addition, stock and flow analysis has been conducted on the Ca element [10], and the limited resource of limestone for the cement industry is clarified. In the narrowest case, about 80 years remain before the depletion of limestone in Japan. Therefore, the re-use of calcium is also an important research topic.

In 2005, recycled aggregate produced through advanced processing to achieve quality equivalent to that of natural aggregates was standardized under JIS A 5021. In 2006, JIS A 5023 was established for concrete made with Recycled Aggregate L, which was intended primarily for non-structural and simple concrete applications. Subsequently, in 2007, JIS A 5022 was completed for Recycled Aggregate M, which, although not produced through advanced treatment, could nevertheless be used for structural concrete.

During this period, global trends evolved significantly, and research and development progressed to address a wide range of international needs, developments that continue to influence the current direction of recycled concrete technologies.

2 Cement production

2.1 Background of the cement industry of Japan

The technological development of Japan's cement industry has been closely linked to the critical domestic challenge of limited landfill capacity, which arises from the country's geographically constrained land area. Japan faces major difficulties in expanding landfill capacity due to geographical, social, and regulatory constraints. The country has limited flat land, mountainous terrain, and frequent earthquakes and typhoons, making it difficult to secure safe disposal sites. In metropolitan areas, land use is already highly intensive, leaving little physical space for new facilities. Strong opposition from local residents over environmental concerns, such as odor, pests, noise, and landscape deterioration, further complicates development. In addition, strict environmental regulations require costly containment and wastewater treatment systems, while consensus-building and environmental assessment processes are often lengthy and difficult.

In response to this societal demand, technologies enabling the utilization of a wide range of wastes and by-products, such as waste tires, sewage sludge, and waste plastics, as alternative raw materials and fuels (ARF) have advanced since the 1980s. As a result, Japan's ARF utilization rate remains among the highest in the world [11].

Around 2015, the industry accepted up to 28 million tons of waste annually, equivalent to approximately 10% of the nation's total material circulation, thereby functioning as a "venous industry" that absorbs materials that are difficult to treat in other sectors. This role has positioned the cement industry as an integral component of Japan's social infrastructure [11, 12] (Table 1, Figure 1). The collapse of Japan's stock market bubble occurred around 1994, but the economy was still influenced by the IT bubble until around 2000. In addition, public investment, as part of post-bubble economic stimulus measures, supported construction demand until around 2000. However, due to the expansion of fiscal deficits, public works spending was later reduced. Although the working-age population peaked around 2008, cement consumption had already declined sharply earlier, partly due to reduced housing supply and lower construction demand in anticipation of a future population decline.

Within this historical context, the treatment of municipal solid waste incineration ash emerged as a critical societal issue. One solution developed to address this challenge was Eco-cement, which was standardized by JIS R 5214 in 2002 and focused on the effective utilization of the calcium oxide (CaO) in the ash [11]. This represented a groundbreaking technology in which municipal solid waste incineration ash served as a principal raw material for cement production.

However, the manufacturing process presented challenges in terms of energy efficiency, and reductions in CO₂ emissions were not necessarily achieved [11]. This outcome reflects the priorities of the Japanese cement industry at the time, when contributing to the establishment of a circular society was regarded as a more urgent objective than reducing CO₂ emissions.

2.2 Toward carbon neutrality of the cement industry in Japan

The Japanese government's declaration in 2020 of its commitment to achieving carbon neutrality by 2050 marked a turning point in this trajectory [13–15]. While the cement industry continues to be expected to play a major societal role in waste treatment, domestic technological development has accelerated toward the new objective of achieving net-zero CO₂ emissions.

The national strategy incorporates elements aligned with global trends, including CO₂ capture, utilization, and storage (CCUS), fuel switching, and the expanded use of blended cements (Figure 2).

On the other hand, the underlying philosophy and premises of technological development reveal characteristics unique to Japan. A distinctive aspect of Japan's approach is that technological innovation is directed not only toward achieving CO₂ reduction but also toward maintaining, and in some cases enhancing, the nation's capacity to process waste and by-products. This dual objective is directly reflected in concrete technological strategies [14, 15]. Figure 3 presents the Long-term Vision on Carbon Neutrality of the Cement Industry published by the Japan Cement Association [15]. The figure outlines how total CO₂ emissions from cement

Table 1. Amount of waste and by-products used for cement production (Unit: 1000 tonnes) [12].

Type	Used for	FY1990	FY2000	FY2010	FY2020	FY2021	FY2022	FY2023	FY2024
Coal ash	Raw materials, Admixture	2,031	5,145	6,631	7,286	7,450	6,893	6,294	6,188
Blast furnace slag	Raw materials, Admixture	12,213	12,162	7,408	6,981	6,939	6,519	5,420	5,110
Sludge	Raw materials	341	1,906	2,627	2,950	2,904	2,864	2,653	2,627
By-product gypsum	Raw materials(Additive)	2,300	2,643	2,037	2,032	2,098	2,000	1,764	1,740
Incineration ash(excluding coal ash), Soot, Dust	Raw materials	468	734	1,307	1,482	1,471	1,534	1,418	1,324
Waste soil from construction	Raw materials	-	-	1,934	1,241	1,159	946	963	826
Waste plastic	Heat energy	0	102	445	746	774	784	794	820
Non-ferrous slag	Raw materials	1,559	1,500	682	725	708	612	539	511
Steel slag	Raw materials	779	795	400	364	439	388	385	450
Woodchips	Heat energy	7	2	574	437	400	379	406	367
Foundry sand	Raw materials	169	477	517	336	379	365	351	336
Recycled oil	Heat energy	51	239	195	282	236	256	266	284
Waste oil	Heat energy	90	120	275	245	302	273	257	284
Waste white clay	Raw materials, Heat energy	40	106	238	260	267	272	291	269
Cullet	Raw materials	0	151	111	154	151	142	162	121
Meat and Bone meal	Raw materials, Heat energy	0	0	68	71	71	68	62	58
RDF RPF	Heat energy	0	27	48	46	34	39	51	53
Waste tire	Raw materials, Heat energy	101	323	89	69	68	80	62	52
Coal mining waste	Raw materials, Heat energy	1,600	675	0	0	0	0	0	0
Others	-	14	253	408	447	445	462	440	447
Total	-	21,763	27,359	25,995	26,155	26,294	24,878	22,579	21,867
Cement production		86,849	82,373	55,903	55,894	55,588	51,339	47,049	45,748
Consumption per ton of cement (kg/t)		251	332	465	468	473	485	480	478

Note 1) "Sludge" includes sewage from waste water treatment plants.

Note 2) "Coal ash" includes not only coal ash from power plants, but also coal ash from other industries.

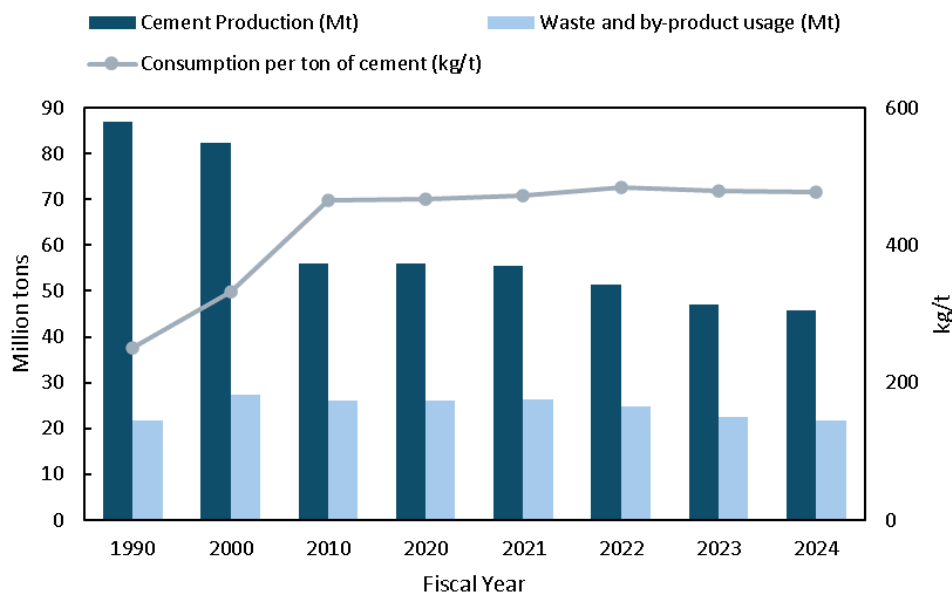
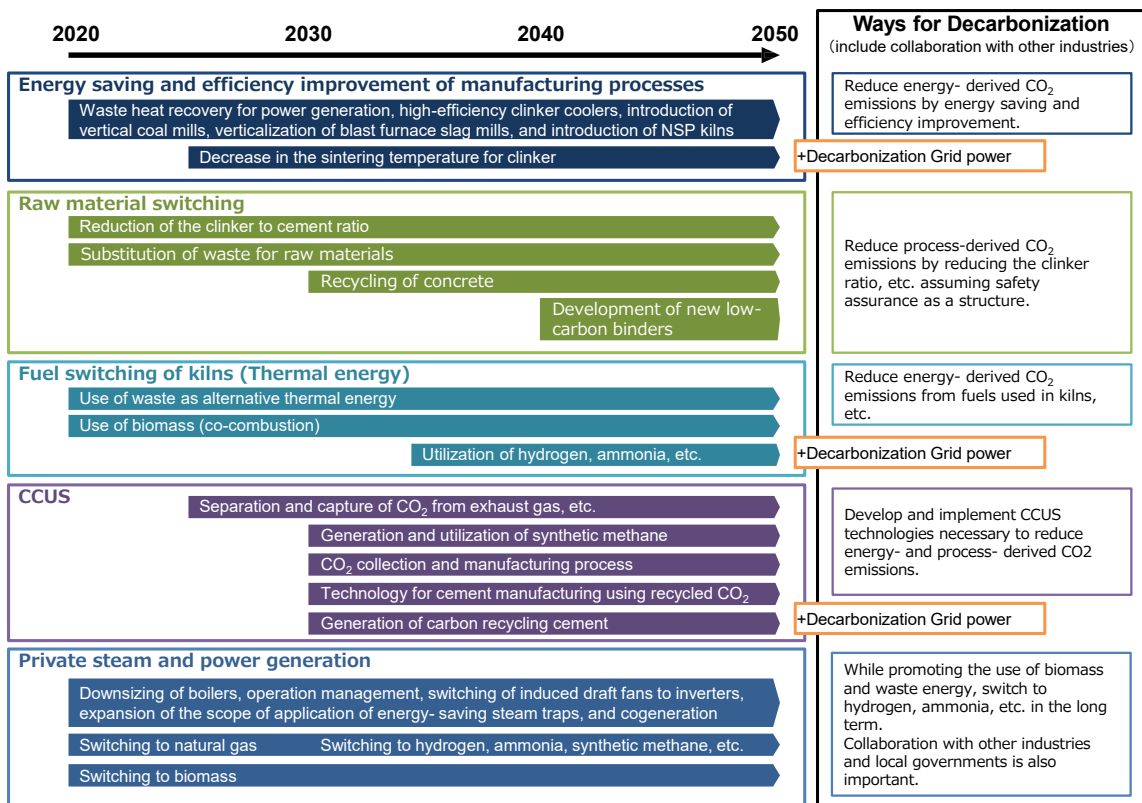


Figure 1. Transition in the quantity of wastes and by-products utilized in cement production [12].

production are expected to be addressed through various mitigation strategies.

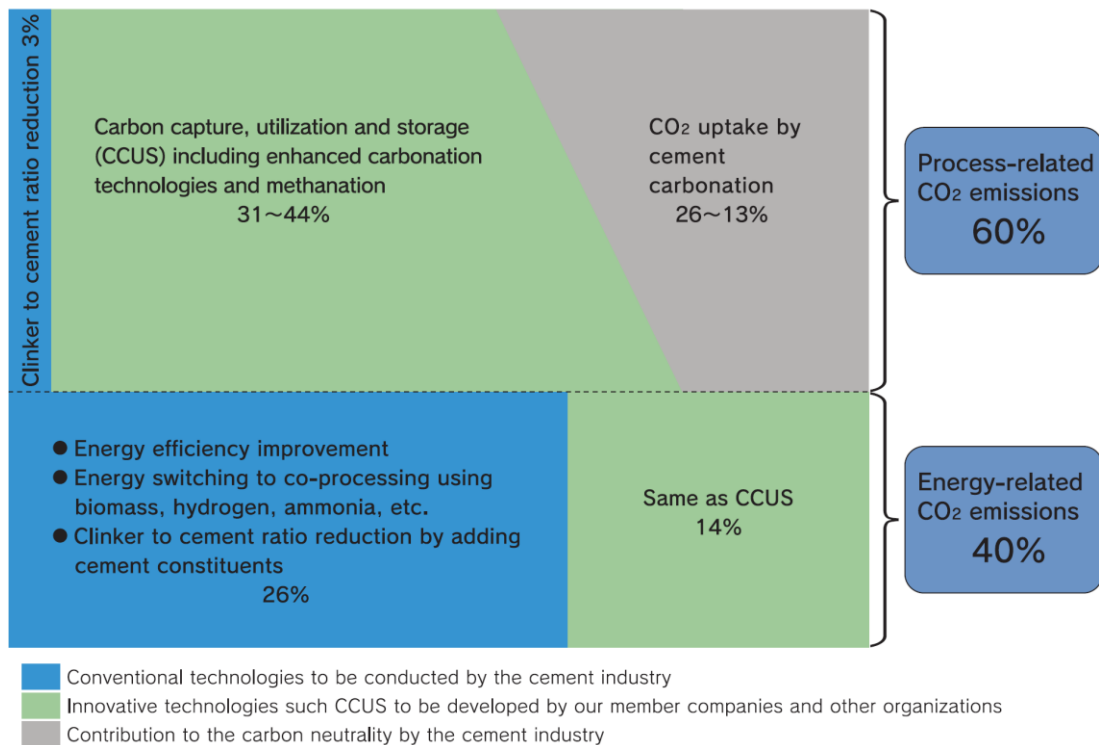
At present, CCUS technologies are considered capable of contributing roughly 51% of the total emission reduction potential, although a large portion of this relies on CCS involving underground storage. To further expand this

framework, national-scale initiatives are currently being promoted to increase the CO₂ reduction potential of cementitious materials. However, since underground storage technologies themselves are still under development, it is considered essential to broaden the overall capacity and diversity of available CO₂ mitigation options.



*In the cement industry, about 80% of energy consumption is heat energy.
 *Regarding fuel switching, it is assumed that conversion to waste and biomass will proceed underway, followed by switching to natural gas and other fuels. In the future, switching to hydrogen, ammonia, etc. using pipelines laid for natural gas, etc. is also possible.

Figure 2. Technological pathway for decarbonization in the cement industry [16].



Note: A reduction ratio of process-related CO₂ emissions using CCUS is corresponded to an amount of CO₂ uptake by the cement carbonation using each estimation model.

Figure 3. Long-term vision on the carbon neutrality of the cement industry [17].

2.2.1 Short-term initiatives: Revision of JIS standards and their rationale

As a short-term measure, the JIS standard (JIS R 5210) for ordinary Portland cement has now been revised, so that the allowable proportion of limestone powder blended into the cement can be increased from 5% to 10% [17]. This initiative reflects Japan's distinctive strategy of balancing CO₂ reduction with the sustained utilization of wastes and industrial by-products, following other countries, such as Australia AS 3972 (7.5%) [18], Europe EN 197-1(CEM II/A-L(LL), 20%) [19], USA ASTM C595 (15%) [20], that has already implemented such standards.

Specifically, to compensate for the potential reduction in strength associated with higher limestone contents, technologies that adjust the C₃A content in clinker are applied. This approach allows for increased use of blended materials without diminishing the conventional utilization of industrial by-products and wastes. Such technological adaptation builds upon knowledge accumulated over decades of managing diverse waste streams within the cement industry [20].

Another notable feature of this JIS revision is the possibility of using "synthetic calcium carbonate" produced via CO₂ capture and utilization (CCU) technologies with concrete waste, such as concrete slurry, returning concrete, and demolished concrete waste, as a minor constituent of cement [17]. This approach explicitly links CO₂ reduction with circular-economy development and exemplifies one of Japan's strategic characteristics.

2.2.2 Medium- to long-term initiatives: Development of transformative technologies

In the medium to long term, the development of innovative technologies is being actively promoted through programs such as the Green Innovation (GI) Fund [21]. As in the short term, Japan's distinctive industrial structure and societal constraints continue to shape the trajectory of technological development.

(1) Development of CCUS/CCU (carbon-recycling) technologies

To mitigate process emissions originating from limestone decarbonation, the development of CCUS technologies has intensified. Under the "Carbon Neutral Strategy 2050" [22], and with support from the New Energy and Industrial Technology Development Organization (NEDO), the development of a CO₂-capture-type cement production process, known as the C2SP kiln[®] (Figure 4), is being advanced [23, 24]. This technology enables the efficient separation and capture of CO₂ within the cement manufacturing process, targeting the recovery of more than 85% of the CO₂ emitted from the preheater, while achieving an energy efficiency over 20% higher than that of conventional amine-based absorption methods [24]. A demonstration trial commenced in April 2024 [25], and some outcomes are anticipated. In parallel, methanation technologies that convert captured CO₂ into fuel are under development. Newly generated fuel could

be used outside the cement industry, linking the carbon supply chain to the general market. At the same time, carbon-cycling processes that mineralize CO₂ using extracted CaO from concrete waste and other calcium-bearing waste and byproducts as a source of the cement production [26-29].

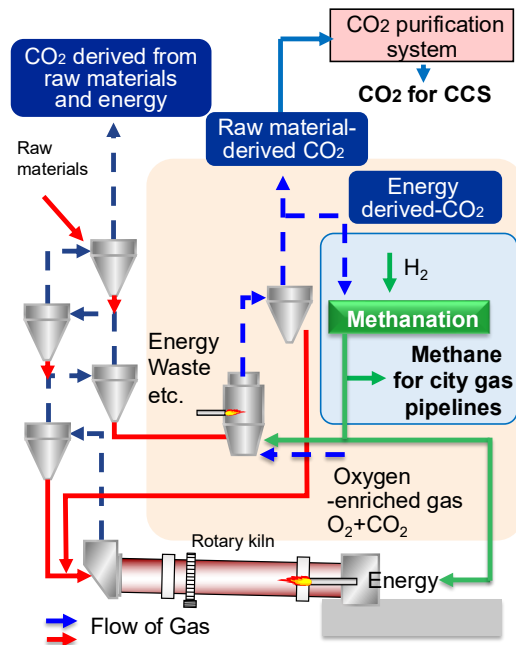


Figure 4. Cement manufacturing process incorporating the Carbon Capture Suspension Preheater (C2SP) kiln[®].

(2) Fuel switching

Demonstration projects, such as ammonia co-firing in commercial-scale kilns conducted by UBE Mitsubishi Cement, are currently underway [30]. In contrast to many overseas projects, which often optimize systems under the assumption of relatively homogeneous raw materials and fuels, Japan faces the challenge of continuously utilizing a highly diverse range of waste-derived alternative fuels containing variable impurities. Consequently, technological development in Japan must incorporate more sophisticated process-control systems to ensure stable kiln operation. This requirement characterizes Japan's distinctive approach to innovation in fuel-switching technologies.

(3) Collaboration with the construction industry

Efforts are also advancing, particularly within the domestic construction sector, to develop carbon-negative concretes capable of absorbing and permanently sequestering CO₂ with the enforced carbonation technology so that carbonation reaction is utilized for the strength development and the amount of sequestered CO₂ of the target material is more than that by natural carbon sink [31]. The information on this kind of concrete is introduced in Chapter 3. Such materials are expected to introduce new functionalities whereby built structures themselves function as carbon sinks. This approach represents an integrated perspective that conceptualizes cement manufacturing and concrete use as components of a unified carbon-cycling system (Figure 5).

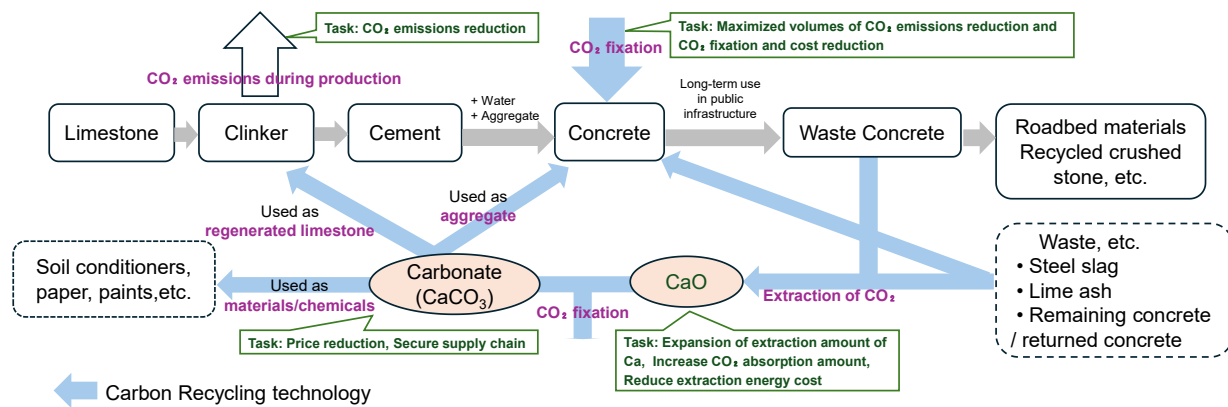


Figure 5. Concept of CO₂ utilization in cement and concrete production [21].

Japan's approach to achieving carbon neutrality in the cement industry integrates technological developments aligned with global trends while distinctly reflecting domestic conditions. Central to this approach is the premise that the industry must continue to fulfill its societal role as a "venous industry," responsible for the treatment of waste and industrial by-products, while simultaneously advancing circular-economy practices and carbon-neutrality objectives in a coordinated and integrated manner.

This approach, designed to address multiple challenges concurrently, defines the distinctiveness of Japan's strategy. By combining the incremental enhancement of existing technologies with the development of transformative innovations, Japan pursues a pathway that balances economic feasibility with substantial reductions in environmental impact. As such, this strategy offers a valuable reference for the global cement industry as it seeks sustainable and resilient transitions.

3 Concrete production

At present, a range of concrete technologies aimed at reducing, absorbing, and permanently fixing CO₂ are under development in Japan. Collectively, these materials and systems are often referred to as environmentally conscious concrete. They can generally be classified into three categories [32]:

- (I) technologies that reduce the clinker factor in cement,
- (II) technologies that fix CO₂ more than that naturally sequestered and utilize carbonation reaction within concrete, and
- (III) technologies that mineralize or fix CO₂ in aggregates or mineral powders.

Pioneering efforts toward the practical implementation of binders with reduced clinker factors have also been undertaken. In 2010, ECM[®] cement, characterized by a clinker ratio of less than 0.3 and corresponding to category (I) above, was developed [33], and its dissemination has since been jointly promoted by Takenaka Corporation and Kajima Corporation [34]. Meanwhile, Kajima Corporation and DENKA developed the CO₂-absorbing concrete "CO₂-SUICOM[®]" in

2008, corresponding to category (II) [35]. This SUICOM system is characterized by the use of γ -C₂S and the incorporation of other supplementary cementitious materials (SCMs), which significantly reduces the amount of Portland cement required. In addition, γ -C₂S is produced using by-product calcium hydroxide as a raw material, allowing it to be manufactured at lower temperatures than conventional cement, thereby greatly reducing CO₂ emissions during production. Another key feature of γ -C₂S is that, under accelerated carbonation at early ages, it decomposes into calcium carbonate and silica gel. The silica gel subsequently participates in a pozzolanic reaction to form C-S-H, while the formation of calcium carbonate refines pores, both of which enhance strength development and durability. At present, technological development is ongoing to establish various low-energy early-age carbonation curing methods. Under certain conditions, it has been reported that the system can achieve carbon neutrality even when energy consumption is accounted for [36]. By 2011, this material had been applied in actual construction projects (Figure 6), thereby accumulating a record of practical performance. More recently, since around 2020, technologies corresponding to category (III), namely, the mineralization and fixation of CO₂ in recycled fine aggregates, have been widely investigated [37]. While individual companies have pursued research, development, and implementation of these technologies, it has become evident that corporate-level efforts alone are insufficient to address challenges at the global scale.

Accordingly, Kajima Corporation, Takenaka Corporation, and DENKA assumed leadership roles as core members and established Carbon Utilized Concrete (CUCO), a consortium comprising 55 organizations. In alignment with the Japanese government's declaration to achieve a carbon-neutral society by 2050, the consortium submitted a proposal under the Green Innovation Fund program to develop concrete materials that maximize CO₂ reduction, uptake, and fixation. The proposal was accepted, and research and development activities have been underway since FY2021.

The CUCO consortium encompasses all stakeholders involved in the construction of concrete structures, including major contractors, precast concrete manufacturers, material

suppliers, ready-mixed concrete producers, as well as universities and research institutes. Its objective is the nationwide implementation of carbon-negative concrete, defined as concrete with net CO₂ emissions of zero or below. In GI project, the SUICOM system has undergone further advancement in the evaluation of CO₂ sequestration capacity, assessment of CO₂ emissions associated with each manufacturing process, and quality control of the final products. For example, it has been found that CO₂ can be fixed even in regions deeper than the phenolphthalein-colored zone, and that the amount of fixed CO₂ is spatially distributed within the carbonated region [38]. Accordingly, quality control methods that take these factors into account are now being implemented [39].

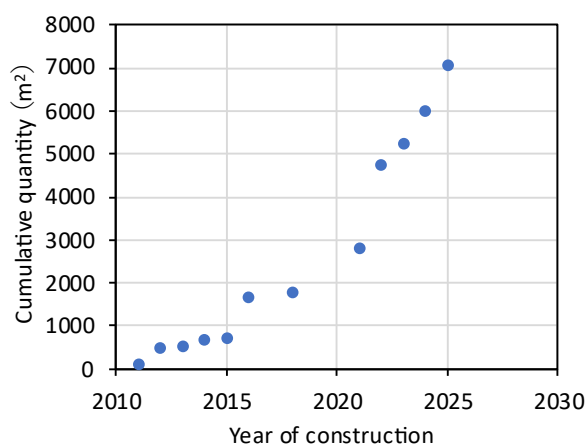


Figure 6. Application of SUICOM for constructions. The statistics are in m² because many of the applications are used as stay-in-place formworks.

Similarly, the Carbon Pool (CP) consortium, led by Hazama Ando Corporation as the secretariat, has also been established [40]. Research and development have been primarily focused on incorporating CO₂- or carbon-containing CCUS materials into concrete. Since cement hydrates in returned concrete are effective for CO₂ sequestration, one distinctive concept of CP concrete is to establish a regional resource circulation system by sequestering CO₂ in these materials and reusing them as concrete components. The objective is not simply to achieve carbon neutrality in terms of CO₂ balance alone. Rather, the concept is developed with consideration for the effective utilization of Japan's limited calcium and aggregate resources. At the same time, the approach aims to provide economic benefits to the concrete industry by reducing disposal costs for the ready-mixed concrete sector, which is financially burdened by waste generation such as returned concrete. Current research topics include the development of appropriate moisture-content control and moisture-history management methods to efficiently carbonate recycled aggregates and other cementitious materials throughout their interiors, as well as the development of continuous vibration-feeder-type plants designed to achieve homogeneous CO₂ fixation in large quantities of recycled aggregate powders and particles [41]. At present, government-supported research, development,

and demonstration activities are being advanced primarily through these two consortia. The corresponding topics for research, development, and practical implementation can be broadly categorized as follows.

3.1 Materials development

The first area focuses on materials development. Companies participating in the CUCO consortium are advancing technologies for the mass production of CO₂-reactive admixtures that harden through reaction with CO₂, technologies for manufacturing powders and aggregates in which CO₂ has been mineralized, and technologies that enhance CO₂ fixation within concrete. In addition, combinations of low-CO₂ cements or CO₂-curable cements with these materials are being investigated to further advance carbon-negative performance.

Currently, efforts are underway to further reduce the clinker factor of ECM cement and to optimize its composition, thereby producing an improved form of ECM cement (corresponding to category (1) mentioned earlier). In parallel, carbonation-curing technologies for structural precast components, employing carbonation-reactive admixtures that harden through CO₂ uptake (corresponding to category (3) above), are being integrated, enabling concrete to achieve net-negative carbon performance.

Further research includes the development of recycled cements [42], CO₂-curable cementitious systems, and CCU-based materials. Currently, many of the pilot projects and experiments have been conducted, while the Japan Industrial Standard is not as flexible as the EN standards. A representative CCUS product is light calcium carbonate manufactured by mineralizing CO₂, sourced from industrial flue gas, into calcium contained in highly alkaline waste liquids (concrete sludge) generated during concrete production. Incorporation of this CO₂-mineralized calcium carbonate into fresh concrete enables in-mix CCUS applications. The physicochemical properties, such as particle size, surface area and surface roughness, and dissolution rate, of the resulting calcium carbonate differ from those of natural calcite, and its incorporation introduces challenges related to concrete rheology. Partial substitution of the powder fraction with this lightweight calcium carbonate has been shown to affect shear stress and shear rate in mortars [43], indicating a strong influence on concrete flowability.

To ensure the effective deployment of these emerging materials, corresponding advances in chemical admixtures are required, and admixture manufacturers are jointly developing and optimizing such products. Moreover, the use of CCU-treated solid residues derived from concrete sludge as partial replacements for fine aggregates has been shown to improve concrete strength [44], demonstrating steady progress in CO₂-fixing aggregate technologies.

Beyond material development, CO₂-fixation methods are also being investigated for both precast concrete products and cast-in-place concrete. For example, in a trial dome structure (named as "CUCO- SUICOM DOME") constructed at the venue of the 2025 Expo 2025 Osaka, Kansai, Japan (Figure 7),

“ECM® concrete” and “CO₂-SUICOM®” were adapted for sprayed-concrete applications and used in combination, achieving an estimated 70% reduction in CO₂ emissions associated with construction materials for the entire concrete structure [45].

Efforts have also advanced toward optimizing the reuse of demolished concrete. In the 2000s, Takenaka Corporation developed a mechanical rubbing-process technology capable of removing adhered cement paste from demolished concrete, thereby producing high-quality recycled coarse aggregate [46]. However, the technology did not achieve widespread adoption at that time for two primary reasons. First, although high-quality recycled coarse aggregate—accounting for approximately 30% of the mass—could be recovered at a quality level comparable to natural aggregate, the recycled fine aggregate (approximately another 30%) retained a substantial amount of adhered cementitious material. As a result, the maximum achievable quality corresponded only to the “medium quality” classification specified in Annex A of JIS A 5022 for recycled-aggregate concrete M (oven-dry density ≥ 2.2 and < 2.5 g/cm³, water absorption $> 3.5\%$ and $\leq 7\%$), falling short of the quality of natural aggregate. Second, the recycled fines, accounting for approximately 40% of the material, generated during processing lacked suitable applications and consequently had to be disposed of, creating an economic burden.

Recognizing that adhered cement paste and recycled fines possess CO₂-mineralization potential, research was initiated to develop CO₂-fixation technologies (CCUS materials production technologies) in both dry and wet processing modes, integrated with recycled-aggregate production [46]. These technologies are now being extended to CCUS material applications in concrete and ground improvement (category (2) mentioned earlier).

In Japan’s urban areas, the acceptance of demolished concrete from construction sites has become increasingly limited. The CCUS-based strategy aims to convert such materials into valuable resources while simultaneously

promoting circularity (Figure 8). In 2023, wet-processed CCUS materials, comprising recycled fine aggregate and recycled fines, were applied to precast foundation elements (Figure 9) for the Messe Event Hall building at the Expo 2025 Osaka, Kansai, Japan. When combined with ECM cement, this approach achieved an 80% reduction in concrete-related CO₂ emissions [47].

Similar activities are underway within the CP consortium. Efforts are progressing toward the practical implementation of concretes in which CO₂ is mineralized into sludge, returned concrete, and concrete debris generated during demolition (Figure 10). Laboratory-scale CO₂-fixation studies have largely been completed [48], and the program has now entered the scale-up phase aimed at social deployment [49].

In FY2024, as shown in Figure 11 and 12, large-scale trial applications were conducted at sites such as LAGO Otsu and the “Future City” Pavilion at the Expo 2025 Osaka, Kansai, Japan, with the explicit objective of accelerating the future societal implementation of CP concrete [50].



Figure 7. “CUCO- SUICOM DOME” exhibited at the Expo 2025 Osaka, Kansai, Japan. (Original photograph).

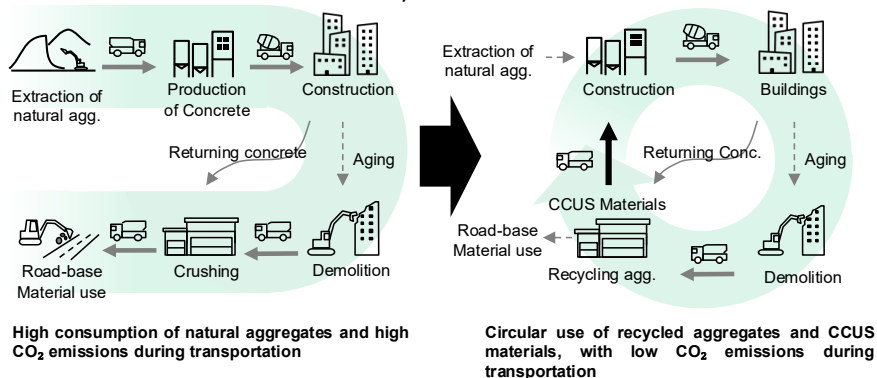


Figure 8. Schematic depicting the transformations in Japan’s concrete industry through the utilization of concrete waste and CO₂.



Figure 9. Application of CCUS pre-cast concrete elements at WASSE (the nickname for the event field), Expo 2025 Osaka, Kansai, Japan (Original photographs).

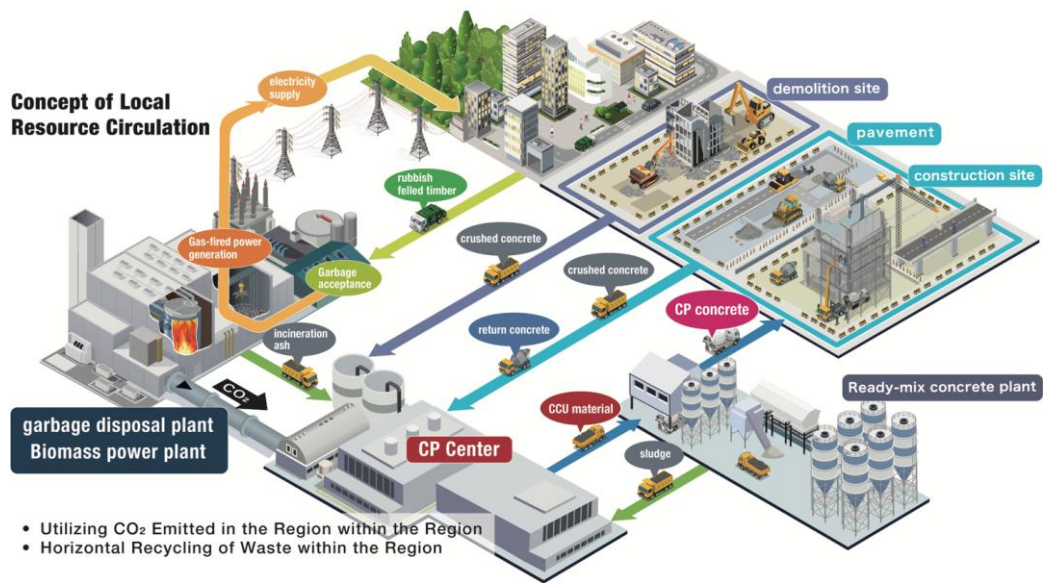


Figure 10. Example of a concrete industry supply chain incorporating concrete waste recycling and CO₂ utilization [48].



Figure 11. Snapshots of LAGO Otsu. (Original photographs).



Figure 12. Snapshots of the “Future City” Pavilion at the Expo 2025 Osaka, Kansai, Japan (Original photographs).

3.2 Development of manufacturing and construction technologies

The second area concerns manufacturing technologies. Efforts are being made to reduce energy consumption during concrete production while developing carbonation-curing technologies that sequester CO₂ into a wide range of precast concrete products and building components for civil engineering and architectural applications. Parallel development is also underway for technologies aimed at reducing or mineralizing CO₂ in cast-in-place concrete and in ground-improvement bodies.

Pilot-plant studies have examined multiple CO₂-fixation methods, including wet and dry processes [49], as well as repeated wet–dry cycling [48]. For example, within the CP consortium, efficient CO₂ fixation was achieved using flue gas containing slightly less than 20% CO₂ and applying three wet–dry cycles. However, when scaling this approach toward trial construction, targeting production of more than one metric ton per day, time constraints emerged as a critical limitation [51].

These processes also face challenges related to CO₂ unit cost and losses of efficiency caused by gas leakage during curing, which remain key development issues. Addressing these challenges will require supply-chain integration between ready-mixed concrete plants, intermediate treatment facilities handling returned and demolished concrete, construction contractors performing on-site curing, and both public and private clients. Additionally, cross-sector discussions are emerging regarding the efficient utilization of flue gas and waste heat [52, 53].

3.3 Development of supply chain considering LCCO₂

In both consortia, it is well recognized that the CO₂ gas supply chain and moderate heat treatment have a significant impact on the LCCO₂ of production. One of the major advantages of CO₂ sequestration using cementitious materials, compared with other industrial technologies, is that effective CO₂ fixation can be achieved without necessarily requiring high

CO₂ concentrations or pure 100% CO₂. Although many industrial plants emit CO₂-containing exhaust gases, there is not yet an established supply chain capable of collecting and utilizing these gases at low cost and with minimal additional CO₂ emissions. Similarly, pre-drying processes for removing moisture from materials, as well as curing at moderately elevated temperatures below 100°C to accelerate reactions, can enhance efficiency by promoting moisture evaporation and increasing reaction rates. While waste heat at temperatures below 100°C is also widely discharged from various industrial facilities, there is currently no well-established supply chain for effectively utilizing this heat. From this perspective, it is important to develop urban and district-scale designs, as well as infrastructure systems such as pipeline networks and integrated supply chains, that can effectively utilize CO₂ emissions and waste heat that have traditionally been discarded.

As mentioned in the history of recycled aggregate, the stock of waste concrete, as well as recycled aggregate, is one of the main market problems for the realization of CCUS-recycled aggregate. The location of the recycled aggregate stockyard also needs to be integrated into the supply chain system. If this location is far from the ready-mixed concrete factory or the site of a building's deconstruction, it results in high CO₂ emissions.

3.4 Quality assessment and quality control

The third area focuses on technologies for assessing the amount of CO₂ fixed in concrete and for evaluating concrete performance. Robust analytical methods capable of quantifying mineralized CO₂ within concrete are essential. In this context, the University of Tokyo is coordinating the development of measurement methodologies, disseminating research on multiple techniques for quantifying CO₂ fixation, and supporting their incorporation into JIS and ISO standards. From the perspective of concrete producers, technologies for monitoring and controlling CO₂ during the manufacturing process are also under development.

Performance evaluation of hardened concrete is equally indispensable for structural design and long-term

maintenance. Accordingly, technologies are being developed to assess durability-related properties—such as mass transport characteristics and surface-layer quality—as well as steel reinforcement corrosion behavior. By considering multiple combinations of technological elements in categories (II) and (III), including materials, manufacturing methods, and construction approaches, ongoing studies are examining effective geometries and utilization strategies. Additionally, structural tests on reinforced concrete members [52], strength development monitoring to ensure no-strength-degradation in the future, fire-resistance experiments because of the rich calcite that decomposed dramatically at the temperature range between 700 and 800°C, and element-level evaluations, such as reinforcement bond behavior [54-57], bond-splitting resistance, and creep characteristics, are being conducted.

In the field of ground improvement, the utilization of CCU materials derived from demolished concrete is being actively investigated. At the Expo 2025 Osaka, Kansai, Japan, surface-mixing soil stabilization incorporating CCU materials was implemented in practice. Furthermore, efforts are underway to establish deep-mixing ground-improvement technologies that combine ECM cements with improved ECM formulations.

4 Development and standardization of methods for evaluating sequestered CO₂ in cementitious materials.

To date, carbonation has primarily been regarded as a deterioration process that promotes steel corrosion. Accordingly, most studies have focused on reductions in pore-solution pH, the chemical environment governing iron-ion diffusion around reinforcing steel, and changes in pore structure that influence ionic transport pathways, whereas comparatively little attention has been given to the amount of CO₂ sequestered. Although the validity of the reaction processes assumed in accelerated carbonation tests has been widely debated [58-65], no clear consensus has yet been established. In particular, the controlling factors governing carbonation rates, degrees of carbonation, associated changes in pore structure and phase assemblage, and mass transport within the material remain insufficiently understood, and agreement on the underlying mechanisms has yet to be achieved. Nevertheless, these issues are critically important not only from a scientific perspective but also for accelerating production rates and ensuring quality control in materials in which CO₂ is fixed into concrete waste. As introduced in Section 3, technologies that incorporate CO₂ into concrete, when regarded as CO₂ offset technologies, require rigorous evaluation of both fixation mechanisms and quantification methods, both during the development phase and aftermarket deployment. In recognition of this need, a national research project has been launched, with the University of Tokyo acting as the principal contractor in a public and neutral capacity, the project is currently ongoing.

Within this project, the following key technological developments have been identified as essential research themes:

- (a) the development of methods to measure the amount of CO₂ fixed in concrete components and in concrete as a whole, through the application and extension of existing analytical techniques, together with the development of new CO₂ sequestration methods [59],
- (b) the development of technologies to accurately predict and monitor the amount of CO₂ sequestered in novel materials over their service life.

4.1 Evaluation of sequestered CO₂

Existing methods for quantifying carbon or CO₂ content reported in the literature were reviewed and summarized in Table 1 of Ref. [59]. These methods were subsequently applied to individual concrete constituents [60] and to carbonated cement paste [61]. The results confirmed that, depending on the combination of target material and measurement technique, the amount of CO₂ sequestered may be either overestimated or underestimated.

For example, during acid dissolution of calcium carbonate, carbonated cement paste may retain calcium carbonate within silica gel, necessitating careful adjustment of particle size, acid concentration, and the powder-to-solution ratio. In the case of fly ash, unburned carbon can interfere with measurements, whereas in aggregates, pre-existing calcite may be misclassified as newly sequestered CO₂. When organic materials are present, attempts to quantify calcium carbonate by thermal decomposition may also induce decomposition of organic matter, the resulting CO₂ can react in situ with CaO to form calcium carbonate, which subsequently decomposes at higher temperatures and is erroneously quantified as CO₂ derived from inorganic carbonates [62]. Under such conditions, acid dissolution methods provide a more appropriate approach for evaluating CO₂ sequestration [66].

In thermogravimetric analysis (TGA), which is commonly employed, carbonated cement paste may begin to release CO₂ at a temperature as low as approximately 200°C. Because this temperature range overlaps with the dehydration of hydration products, accurate quantification of sequestered CO₂ becomes difficult. This behavior has been attributed to mineral-formation reactions associated with the Hedvall effect, whereby heating induces the formation of new phases, such as wollastonite precursors, through interactions between silica gel and calcium carbonate [63]. Furthermore, concrete is inherently heterogeneous at the scale relevant to chemical analysis owing to the presence of aggregates. Although pulverization and representative subsampling are therefore essential, these processes are time-consuming. In particular, preparing a chemically representative material, on the order of several tens of milligrams, from a standard cylindrical specimen (e.g., $\Phi 10 \times 20$ cm) is technically challenging. From this perspective, we developed a prototype apparatus that directly heats concrete cylinders and measures the amount of CO₂ released in the decomposition

gas, and its high reproducibility was confirmed [67, 68]. However, if the used aggregate in concrete contains organic and/or inorganic carbon, one-time measurement cannot quantify the captured CO₂ in concrete, especially, fossil-derived CO₂. Measurements for two samples, one is a pristine concrete and the other is CO₂-treated concrete, are necessary. Measurement principles can be found in the coming Japan Industrial Standards, JIS A 1016-1: Determination of mass of carbon dioxide sequestered in concrete and concrete constituents - Part 1: General principles, JIS A 1016-2: Part 2: Acid decomposition and back titration method, JIS A 1016-6: Thermogravimetry, are scheduled to be published in June 2026. From the standpoint of industrial application, however, further improvements, such as reductions in analysis time, remain necessary for the practical evaluation of CO₂ sequestration in concrete.

4.2 Prediction of CO₂ sequestration in concrete during service life

From this perspective, as already described in EN 16757 [49], it is essential to evaluate both the degree of carbonation and the carbonation depth under specific environmental conditions. Accordingly, we are constructing a database of carbonation degrees representative of Japanese environmental conditions (e.g., [57]). In parallel, we are developing a framework for the time-dependent evaluation of carbonation depth [56, 59].

Through this work, we have clarified that many existing accelerated carbonation tests (here, CO₂ concentration is more than 1%), particularly those strongly influenced by drying conditions and by the distribution of moisture within and outside the aggregated structure of C–S–H, primarily reflect moisture transport rates rather than carbonation behavior representative of natural environments [57]. As a result, such tests do not adequately capture carbonation processes occurring under actual service conditions. Currently, we are developing methods to predict carbonation rates under natural exposure by incorporating data from diverse temperature–humidity environments, evaluating the effects of surface coatings on structures, assessing the influence of cracks around aggregates on carbonation rates, and introducing new preconditioning approaches that enable reliable estimation of CO₂ sequestration under realistic environmental conditions [70].

4.3 Verification of CO₂ sequestration from ambient air

Because carbonates can also occur naturally in aggregates employed in concrete, it is necessary to demonstrate that the concrete constituents, or the concrete itself, have sequestered CO₂ from ambient air or flue gas, thereby verifying that the applied measures are valid as CO₂ offset strategies. From this perspective, we have demonstrated that sequestration through direct air capture can be verified by quantifying the amount of carbon-14 (¹⁴C) fixed in the material [64]. This method has been applied to reinforced concrete structures with service lives exceeding 50 years, and it has been shown that the amount of sequestered carbon can

be quantified even when aggregates contain carbonate phases such as limestone [64]. Current studies are extending this approach to cases in which CO₂ is derived from various combustion flue gases [71].

5 Summary

In Japan, there are concerns that reducing the clinker factor may give rise to secondary impacts, owing to limited domestic resources, especially high-quality limestone, and the cement industry's close integration with local communities and other industrial sectors. Consequently, approaches distinct from those adopted in Europe and the United States need to be considered. One such approach involves sequestering large amounts of CO₂ while maintaining concrete performance and ensuring that the design and use of concrete do not compromise long-term durability.

At present, various strategies aligned with this direction are being explored, namely, the developments of 1) CCUS materials that capture the CO₂ and used as the concrete components, 2) Manufacturing and construction technologies, 3) Supply chain considering LCCO₂, 4) Methods for the quality control of the products, 5) Standards for evaluating the sequestered CO₂ in concrete and concrete components. The realization of these approaches will require the establishment of new supply chains and broader societal transformations, particularly the development of appropriate networks for supplying CO₂-containing exhaust gases and waste heat to material production lines. The Japanese government is currently supporting a wide range of research and development activities as strategic investments for the future. Should further novel outcomes emerge, they will be reported in due course

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Authorship statement (CRediT)

Ippei Maruyama: Conceptualization; Investigation; Visualization; Writing – Original Draft. **Masaro Kojima:** Conceptualization; Investigation; Visualization; Writing – Original Draft. **Goro Sakai:** Conceptualization; Validation; Writing – Original Draft. **Yoshiyuki Suzuki:** Investigation; Validation; Formal Analysis; Writing – Original Draft; Writing – Review & Editing. **Hikotsugu Hyodo:** Investigation; Writing – Original Draft; Writing – Review & Editing.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI use

The authors used ChatGPT and Grammarly to enhance manuscript readability and employed a native English-

speaking language service to assess the quality of the manuscript's language.

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