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Pathways of Carbon Reduction in Concrete-Related Industries as a Methodology toward Carbon Neutrality

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Abstract: Carbon neutrality is a great challenge for humankind. However, as most industries depend on fossil fuels and use various natural resources, it is not so simple to change the technologies and systems. Concrete, which has a history of more than 200 years, is a typical example of such technology and has played a significant role in the construction of infrastructures and buildings. CO_2 emissions resulting from cement production and construction operation have posed a new challenge to the industries. All industries need to conduct an appropriate "transition design" for carbon reduction and neutrality using effective tools. This paper describes the pathways of carbon reduction in concrete-related industries as a methodology, so that the other industries can take appropriate action toward carbon neutrality depending on each BAT (best available technologies) situation.

Key words: Best available technologies, carbon neutrality, carbon reduction, concrete-related industries, transition design.

1. Introduction

Carbon neutrality is a great challenge for humankind. However, as most industries depend on fossil fuels and use various natural resources, it is not so simple to change the technologies and systems. Concrete, which has a history of more than 200 years, is a typical example of such technology and has played a significant role in the construction of infrastructures and buildings. CO_2 emissions resulting from cement production and construction operation have posed a new challenge to the industries. Concrete has become an essential material for human activities along with steel. Therefore, specifications and standards for design and construction have been stipulated for their use. As the fundamental importance of structures is the mechanical aspect such as safety and serviceability, the technologies have been remarkably developed. However, it is becoming important that the construction industry also needs to consider environmental issues related to material production and construction activities because the extension of human economic activities causes resources and energy constraints and CO_2 emissions from fossil fuels have contributed to global warming. In response to these societal changes, Koji Sakai et al. have proposed the concept of sustainability design of concrete structures [1, 2], which includes social aspects like safety, environmental and economic aspects.

A broad consensus has emerged that all industries must aim for CN (carbon neutrality) in order to mitigate global warming. The essence of CN is moving away from fossil fuels. Fuels will transition to renewable energy sources, such as hydrogen and ammonia, which do not emit CO_2 during use. Regarding CO_2 originating from the raw materials, the capture, use, and/or storage of CO2 will be required. It will also be possible to absorb CO_2 in plants/trees and oceans. Our problems can thus be conceptualized more simply.

However, some confusion has arisen risks obscuring the true essence of CN [3]. Typical examples include the assumptions that CO_2 can be absorbed into concrete through carbonation and that the large scale substitution of cement with SCMs (supplementary cementitious

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materials) is feasible without sufficient examination of their practicality. The objective that the cement/concrete and construction sectors should pursue is a realistic “transition design” toward CN achieved by gradually implementing CR (carbon reduction) through the use of best available technologies (BAT) over time. All industries need to conduct an appropriate “transition design” for carbon reduction and neutrality using effective tools.

This paper describes the pathways of carbon reduction in concrete-related industries as a methodology toward carbon neutrality, so that other industries can take appropriate action depending on the progress of its BAT (best available technologies). The paper provides a nautical chart toward carbon neutrality for all industries.

2. Research Significance

Although we have had a broad consensus in which all industries must aim for carbon neutrality to mitigate global warming, there is a turmoil on how to realize it. We need to move away from the turmoil with a clear and rational concept. The main point of this paper is to clarify quantitatively the feasibility of potential carbon reduction scenarios in concrete-related industries as an example toward carbon neutrality in order to promote rational directions in each industry.

3. Gemlike Value of Concrete: Long-Term Durability

Concrete, which is made from abundantly available materials on Earth, generally has a service life of approximately 50 to 100 years. This long-term durability gives concrete a gemlike value. The history of modern cement concrete is only a few hundred years. This fact indicates that concrete cannot be discussed independently of the knowledge accumulated over history.

The book *The Long-Term Durability of Concrete—Lessons from the Otaru-Port Hundred-Year Durability Tests* [4] reported that the tensile strength of mortar briquettes subjected to various environmental actions including carbonation over a hundred years began to decline several decades to a half century after production.

The strength degradation was attributed to the combined effects of several mechanisms: the decline or cessation of cement hydration and volcanic-ash pozzolanic reaction; coarsening of hardened paste systems due to the leaching of hydrates and/or calcium ions; the formation of microcracks resulting from the generation of ettringite; and the embrittlement of C-S-H structures due to various chemical actions.

In addition to the above-mentioned book, some other studies [5, 6] have reported the negative aspects of concrete carbonation. Based on these findings, it should be noted that the carbonation of concrete adversely affects not only the corrosion of reinforcing steel but also the performance of the concrete itself. Generally speaking, the performance requirements of materials used should be clearly defined. However, to date, such knowledge has not been sufficiently established.

Concrete is an essential material used in enormous quantities. Therefore, no new performance requirements should be prioritized over safety and long-term durability. In order to promote CR/CN, such a fact should be clearly recognized. Otherwise, humanity will be unable to fully benefit from the gemlike value of concrete.

4. CO_2 Emissions from Cement/Concrete and Construction-Related Industries

4.1 Cement and Production

The world cement production in 2024 was 4.004 billion tonnes [7]. China and India account for 58.7% of world cement production.

Although the amount of CO_2 emitted per tonne of cement produced varies by country and manufacturer, in this paper cement-related emissions are discussed based on the emission intensity of cement used in Japan, namely, 820.4 kg-CO_2/1 tonne of cement [8]. Therefore, the global CO_2 emissions from cement production are estimated to be 3.28 billion tonnes, accounting for approximately 8.7% of the total CO_2 emissions from fossil fuel sources (37.79 billion tonnes) [9] (Fig. 1).

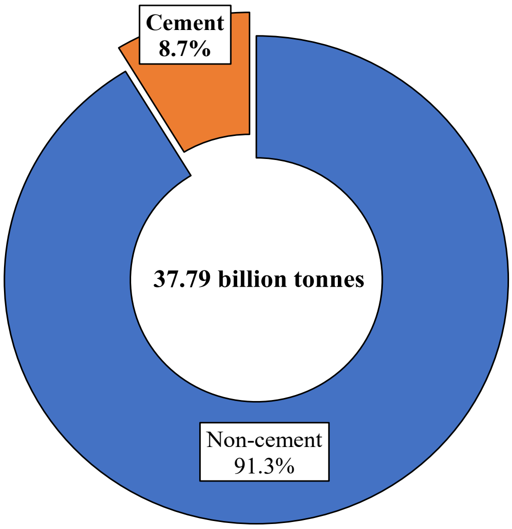

Fig. 1 Proportion of global CO_2 emissions from cement production.

Of the total CO_2 emissions from cement production, 41.8% are derived from fossil fuels, and 58.2% come from limestone, the main raw material [8]. Although alternative fuels, materials, and electric power are used in practice, they are not discussed in this paper.

4.2 Concrete- and Construction-Related Machines and Equipment

The main machinery and equipment related to concrete consist of those for ready-mixed concrete and precast concrete. The former includes mixing machines and vehicles for mixing and pumping, while the latter includes facilities for concrete production and curing. The electricity used for curing facilities is usually derived from fossil fuels.

In general, the use of precast concrete is limited compared with ready-mixed concrete. In Japan, 71% of cement is used for ready-mixed concrete [10]. Although the proportions vary by country and region, CO_2 emissions from concrete- and construction-related machinery and equipment appear to be relatively small compared with those from cement production.

If desired, the CR/CN could be relatively easily achieved by transitioning the power supply to renewable energy. To this end, societal systems as a whole must shift away from reliance on fossil fuels. Although cost remains an issue until these technologies mature, the overall direction toward the target is quite clear.

5. CO_2 Reduction Tools in Cement Manufacturing

5.1 Replacement of Fuel with Hydrogen

The essence of CN is a transition away from fossil fuels. One option is the replacement of coal with hydrogen. Hydrogen can be categorized into three types: "grey hydrogen" produced from fossil fuels; "blue hydrogen" produced like grey hydrogen but with CO_2 being captured/utilized/stored; and "green hydrogen" produced using renewable energy. The use of green hydrogen is a key prerequisite for achieving CN. Recently, naturally occurring hydrogen has also attracted attention.

Although CO_2 emissions originating from fuel combustion account for 41.8% of total emissions in cement production, replacing coal with green hydrogen would reduce fuel-related emissions to zero. As a result, the CO_2 emission intensity of cement can be reduced from 820.4 kg-CO_2/tonne to 477.5 kg-CO_2/tonne and global CO_2 emissions from cement production can be reduced from 3.28 billion tonnes to 1.91 billion tonnes. The calcination of limestone using hydrogen may require some additional measures in order to provide the performance necessary for cement. On the other hand, the use of ammonia as an alternative to hydrogen is also possible. However, it has been pointed out that the use of ammonia may lead to the generation of N_2O and NOx which are other GHGs (greenhouse gases), depending on the combustion conditions [11]. Therefore, appropriate conditions would be required when using ammonia.

The transition from coal to hydrogen as a fuel involves significant cost barriers. The estimate power generation costs using hydrogen, ammonia and coal are 97.3 yen/kWh, 23.5 yen/kWh and 12.5 yen/kWh, respectively [12, 13]. However, as the use of hydrogen expands, costs are expected to decrease due to economics of scale, and domestic hydrogen production could further reduce the transportation costs. It may also be argued that energy costs to date have been artificially low. In fact, cement prices in Japan have already doubled due to rising resource prices. Such cost increases may be acceptable depending on the level of carbon taxation. Thus, although various challenges remain at present, technologies supporting the transition toward energy transformation are expected to develop steadily, because the essence of CN lies in the use of renewable energy.

5.2 Partial Replacement of Cement with SCMs

5.2.1 Production Volume of Blast Furnace Slag and Possible Cement Replacement

Approximately 0.307 tonne of blast furnace slag is produced per tonne of pig iron [14]. Fig. 2 shows the production volume of pig iron by country. In 2023, global pig iron production amounted to 1.311 billion tonnes [15], corresponding to approximately 0.4 billion tonnes of blast furnace slag (1.311×0.307). In Japan, blast furnace slag production was 19.52 million tonnes [14]. Blast-furnace slag is classified into air-cooled slag and granulated slag, which are used for different purposes in different volumes for cement production.

The global production volume of blast-furnace slag available as a SCM was estimated based on the situation in Japan shown in Table 1 [14-18]. As a result, it was calculated to be approximately 0.33 billion tonnes. Given that global cement production is 4.004 billion tonnes, the potential cement replacement ratio is estimated to be about 8.2%.

A report [19] indicates that the global availability of blast furnace slag is estimated to range from 0.3 to 0.36 billion tonnes per year. Therefore, the above estimation seems to be reasonable. On the other hand, future steel production is expected to shift from blast furnaces to electric furnaces that utilize recycled steel. As a result, the production volume of blast furnace slag will decrease. Taking this societal change into consideration, it can be said that blast furnace slag cannot be regarded as a sustainable long-term tool for achieving CR.

5.2.2 Production Volume of Fly Ash and Its Possible Cement Replacement

Several reports have addressed the global production of fly ash, with the references [19-25] indicating that approximately 0.7 to 1.1 billion tonnes of fly ash are available annually. However, it is difficult to determine the quantity precisely. Using data presented in the previous references [21, 22, 26] and data published by government agencies [27-35], the global production fly ash was estimated to be approximately 1.05 billion tonnes as shown in Fig. 3.

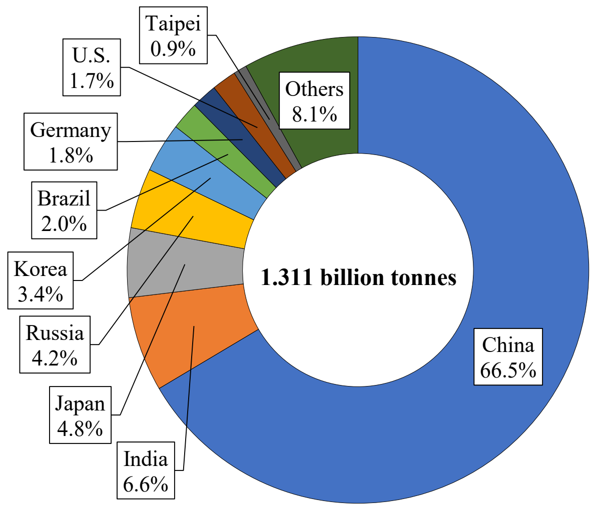

Fig. 2 Pig iron production by country.

Table 1 Production volume of various slag types.

	(1)	(2)	(3)	(4)	(5)
	Blast furnace slag	Air-cooled slag	Granulated slag	Air-cooled slag used in cement	Granulated slag used in cement
		(1)×12.9%	(1)×87.1%	(2)×2.6%	(3)×94.7%
World	0.4 billion tonnes	0.052 billion tonnes	0.348 billion tonnes	1.35 million tonnes	0.33 billion tonnes
Japan	19.52 million tonnes	2.519 million tonnes	1.7002 million tonnes	0.065 million tonnes	16.097 million tonnes

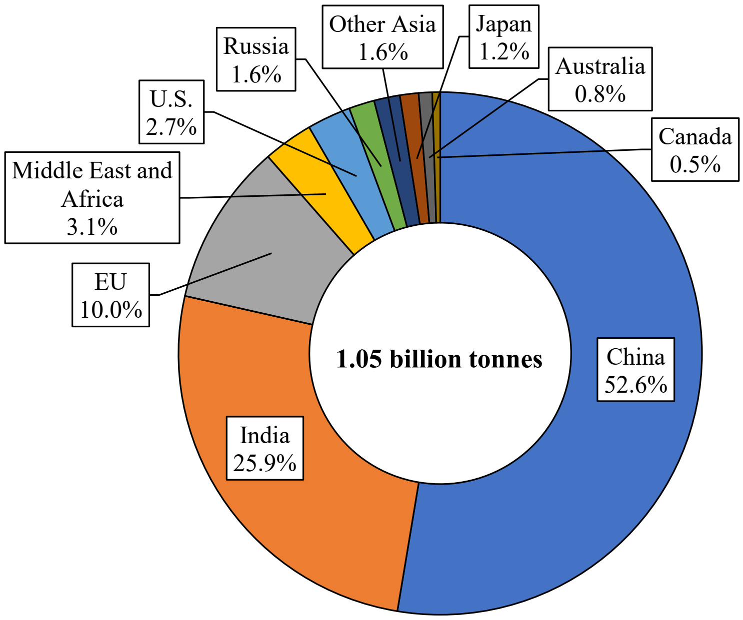

Fig. 3 Amount of fly ash generated.

Table 2 Amount of fly ash used in SCM.

Country	Amount of fly ash generated (billion tonnes)	SCM	
		Utilization ratio (%)	Amount of use (billion tonnes)
China	0.55	35.0 (※)	0.193
India	0.27	17.8	0.048
EU	0.10	24.5	0.026
U.S.	0.03	49.9 (※)	0.014
Japan	0.01	2.0	0.0002
Australia	0.01	27.0 (※)	0.002
Total of 6 regions	0.97	29.0	0.283
World	1.05		0.305

However, not all fly ash produced is actually utilized. The mean value of the utilization ratio in China, India, US, Japan, and Australia as a SCM is estimated to be approximately 29% as shown in Table 2. Accordingly, the global availability of fly ash as a SCM is calculated to be 0.305 billion tonnes. From this estimation, as the world cement production volume is 4.004 billion tonnes, the corresponding potential cement replacement ratio is 7.6%.

In September 2024, the first coal-fired power plant in the UK ceased operation 140 years after its foundation in 1882. The UK is the birthplace of the Industrial Revolution, and this event symbolizes the beginning of the end of fossil fuel use. Considering this societal transition, it can be concluded that fly ash will not be a viable tool for achieving CR in the future.

5.2.3 CO_2 Emission Intensity for the Production of Blast Furnace Slag and Fly Ash

The CO_2 emission intensities for blast furnace slag and fly ash in Japan are taken as 35.6 and 29.0 kg-CO_2/tonne [36]. The former is calculated by multiplying the energy consumption associated with the crushing, transportation, mixing and drying processes in Germany (104.9 kWh/t) by the CO_2 emission intensity of electricity in Japan at that time (0.339 kg-CO_2/kWh) [37]. The latter is the sum of the CO_2 emissions of JIS fly ash (23.0kg-CO_2/tonne) and the emissions associated with the classification process [38].

It is obvious that the CO_2 emission intensities of blast furnace slag and fly ash are quite small compared with the emissions from cement production. From this perspective, if the objective is to reduce CO_2 emissions, it would appear sufficient to substitute cement with large amounts of blast furnace slag or fly ash. However, there are some problems. Namely, the large amounts of blast furnace slag and fly ash are not available. In addition, as these materials are produced simultaneously with steel and electricity, strictly speaking they should be considered as bearing CO_2 emissions of energy origin necessary for their production. In other words, it is not appropriate to simply dismiss CO_2 emissions by assuming that the use of industrial byproducts entails no CO_2 emissions. The authors have already discussed the details of this issue elsewhere [39]. The calculation of CO_2 emission intensities cannot be conducted under arbitrarily convenient conditions. Common rules for environmental burden assessment like ISO standards are therefore necessary.

Japan developed the ISO13315 series on environmental management for concrete and concrete structures. Its 2nd part presents system boundaries and basic rules of inventory data, in which the CO_2 emissions generated during the production stage of byproducts are not included within the system boundaries. Thus, the large-scale substitution of cement with byproducts may have been justified. Nevertheless, this would require a substantial change in the way emission intensities for byproducts are defined, and, more importantly, the long-term durability of concrete incorporating large amounts of such additions is by no means guaranteed. That said, the replacement of cement with SCMs can be regarded as the simplest approach to CR.

5.3 CCUS Approaches

CO_2 originating from raw materials during cement production is emitted even if the fuel is replaced with hydrogen. The only way to handle this CO_2 is through carbon capture, utilization, and/or storage (CCUS). The utilization of captured CO_2 does not have any constraint. The IPCC (Intergovernmental Panel on Climate Change) [40] has suggested that depleted oil and gas fields have a potential CO_2 storage capacity of 900 billion tonnes, deep underground brine layers (aquifers) 10 trillion tonnes, and unmined coal seams 200 billion tonnes. In total, this amounts to 11.1 trillion tonnes. It means that if CO_2 were captured from the current annual global emissions of 38 billion tonnes, the storage capacity would cover 292 years.

On the other hand, one study [41] estimates that the ultimate CO_2 storage capacity of aquifers could be as high as 26 trillion tonnes. It may therefore be possible to sequester CO_2 underground for the foreseeable future. However, in practice, there will be limits to CCS (Carbon Capture and Storage) due to challenges including capture efficiency, transportation to suitable locations, its cost etc.

The CO_2 storage necessary for the scenario in the premise assuming net-zero emissions by 2050 is estimated to be 3.8 to 7.6 billion tonnes per year [42, 43]. The Global CCS Institute and IEA (International Energy Agency) project an annual CO_2 storage capacity of 5.6 billion tonnes by 2050 [44, 45]. Assuming 8.7% of anthropogenic CO_2 emissions are attributable to cement production, and allocating this share to the cement sector, the volume would be 0.487 (56×8.7%) billion tonnes. With the application of CCS, CO_2 emissions from the cement sector will become 2.79 billion tonnes. It means that the CO_2 emission intensity of cement manufacturing is reduced to 697.8 kg-CO_2/tonne.

The Heidelberg Materials has already begun operating CCS in the cement industry at Norway in 2025. In order to enable CO_2 storage, there are many technological barriers and legal problems. Therefore, it will be necessary to develop technologies for CO_2 utilization. For example, there is a plan to capture CO_2 from cement production processes, react it with hydrogen to produce methane, and use that methane as an energy source. From these points, green hydrogen is essential.

5.4 Absorption into Trees and Oceans

Trees and oceans serve as natural CO_2 sinks. According to the Global Carbon Budget 2024 [46], the CO_2 uptake in 2023 was estimated at 8.44 billion tonnes for trees and 10.56 billion tonnes for the oceans. Trees and oceans are essentially common resources. Assuming that 8.7% of anthropogenic CO_2 emissions are attributable to the cement sector, the absorption of 1.65 billion tonnes ((8.44+10.56) × 8.7%) is expected in trees and oceans. It means that the CO_2 emissions from cement production would become 1.63 billion tonnes. The CO_2 emission intensity of cement production would thus be reduced to 407.7kg-CO_2/tonne.

It should be noted that the CO_2 uptake by trees exhibits considerable variability ranging from 0.84 to 15.04 billion tonnes. The reason for this variability is due to a complex interplay of multiple factors including forest fires. A large-scale fire can release up to 2.37 billion tonnes of CO_2 according to one report [47]. On the other hand, another report [48] suggests that trees may have a 1.72 times greater CO_2 uptake than the usual calculation basis. Thus, although uncertainties remain, proper forest management could potentially increase CO_2 sequestration. By promoting such measures, it may be possible to tolerate a certain portion of the inevitable raw material-origin CO_2 from steel and cement production. Going forward, an objective analysis and discussion will be required.

5.5 Absorption into Concrete

The amount of CO_2 uptake due to carbonation of cement-concrete has been estimated by Cao et al. [49], Zi Huang et al. [50, 51], and Xi et al. [52] to be 0.61 (2014), 0.876 (2020), and 0.916 (2013) billion tonnes, respectively.

However, it should be emphasized that all absorption volumes are less than 1 billion tonnes, corresponding to less than 2.6% of total global CO_2 emissions of 38 billion tonnes. The value of CO_2 sink is substantially smaller than that of trees and the oceans, and carbonation due to concrete demolition would require a very long time to become effective. In other words, technologies based on the concept of cement and concrete as CO_2 sinks do not warrant enthusiastic promotion at the expense of the extensive body of knowledge accumulated over many decades.

In addition, there are no available data on the long-term performance of carbonated concrete, and it is meaningless to define carbonation itself as a performance requirement of concrete. Accordingly, the most rational approach to addressing CO_2 emissions from cement production is the transition of fuel sources and the capture of emitted CO_2.

5.6 Comprehensive Evaluation of Individual Tools

The replacement of fuel with hydrogen can directly reduce the CO_2 emission intensity of cement production. In contrast, SCM substitution does not reduce the CO_2 emission intensity of cement production itself but is equivalent to reducing the amount of cement produced by the substituted fraction. However, the availability of SCMs is extremely limited, and increased replacement leads to performance degradation of concrete.

CCS removes CO_2 emitted during the manufacturing process and thus can be regarded as reducing the CO_2 emission intensity in proportion to the amount of CO_2 captured. However, CCS is not exclusive to the cement industry, and since CO_2 emissions from cement production account for only 7.9% of total emissions, deploying CCS at a corresponding scale should be considered feasible.

Of course, the increase in manufacturing costs would be substantial, and environmental issues associated with CO_2 storage may be unavoidable. If CCU is possible, CCS would be conducted depending on the amount of possible CO_2 emissions, but it is not discussed here. Although trees and oceans are also effective tools for CO_2 sequestration, there are significant uncertainties in their sequestration capacities. As with CCS, it will be possible to propose allocating 8.7% of these natural sinks to the cement industry. However, the deployment of CCS and the use of trees and oceans will require a

Table 3 Comprehensive evaluation of each tool.

Tools		Cement production (billion tonnes/year)	CO_2 emission intensity for cement production (kg-CO_2/tonne)	CO_2 emissions (billion tonnes)
Current state		4.004	820.4	3.28
Hydrogen fuel		4.004	477.5 (820.4×58.2%)	1.91
SCM	Slag	3.674 (4.004-0.330)	820.4	3.01
	Fly ash	3.699 (4.004-0.305)	820.4	3.03
CCS (8.7% utilization)		4.004	697.8 (2.79/3.28×820.4)	2.79 3.28-(5.6×8.7%)
Trees and oceans (8.7% utilization)		4.004	407.7 (1.63/3.28×820.4)	1.63 3.28-(8.44+10.56)×8.7%

broad social consensus and appropriate legal frameworks. In contrast, CO_2 fixation in concrete lacks rationality both in terms of its limited sequestration potential and its adverse implications for performance of resulting concrete. Table 3 indicates the comprehensive evaluation of each tool.

Based on the above results, CR can be achieved by each individual tool, but no single approach can realize CN on its own. The effect of SCM utilization is extremely limited, and the amount of CO_2 reduction achievable through CCS is also constrained. While CCUS has significant potential, further progress in technologies for utilizing captured CO_2 is needed. Fuel substitution with hydrogen should be an important target of the cement industry as it can be implemented independently. In addition, CCUS should be considered as a complementary option. Through an appropriate combination of these measures, the realization of CN becomes possible. Therefore, a rational transition design that accounts for these factors will be needed in the future.

6. Conclusions

(1) Transitioning the fuel used in cement production from coal to green hydrogen can reduce the fuel-origin CO_2 emissions by 41.8%. Although cost will be a major challenge during the transition period, this issue is expected to be resolved by the advance of technology.

(2) The possible replacement ratio of cement with SCMs is just 8.2% for blast furnace slag and 7.6% for fly ash, which means that excessive expectations should not be placed on SCMs. The CO_2 emission intensities of SCMs should be evaluated appropriately according to their utilization value.

(3) Although large underground storage spaces exist for sequestering CO_2, it is necessary to establish technologies that enable economically reasonable capture and transport of raw-material-origin CO_2. Excessive reliance on CCS should be avoided, and CO_2 utilization should be actively pursued.

(4) CO_2 sequestration by trees and oceans has the potential to reduce about 60% of the raw-material-origin CO_2 emissions from cement production. However, it is important to recognize the uncertainties in current evaluations of CO_2 uptake capacity. Nevertheless, these sinks remain worth utilizing under societal consensus.

(5) By integrating scenarios involving hydrogen utilization and CO_2 sequestration by natural sinks, substantial CR is possible, and CN can be realized through the appropriate application of CCUS technologies.

(6) Concrete and steel are two of the most important materials invented by humankind, and their manufacturing technologies have been refined over long periods accompanied by the development of highly advanced utilization systems. Therefore, technologies which risk undermining accumulated knowledge cannot be regarded as true innovations.

(7) This paper examined quantitatively the options necessary for the transition design towards CN. It is expected that a rational transition design will be

developed in the future by improving data accuracy and incorporating technological progress.

(8) Based on these results, it is not realistic to consider concrete itself as a tool for CR/CN from the viewpoint of both its quantitative potential and the accumulated body of concrete technology and knowledge.

(9) CO_2 emissions from cement production consist of those derived from fossil fuels and raw materials. The former should be replaced with hydrogen while the latter should be addressed through CO_2 capture. Other measures should be regarded as part of a transition process until technological and cost barriers are overcome.

(10) The process indicated in an article on the CR/CN of concrete-related industries can be applied to other industries depending on their BAT situation without unnecessary turmoil.

Biography

ACI honorary member Koji Sakai is the Representative of the Japan Sustainability Institute, Sapporo, Japan. He is a member of ACI Committee 130, Sustainability of Concrete. He was the founder of ISO/TC 71/SC 8. He was the Chair of fib previous Commission 3 from 2002 to 2010, and the Japan Concrete Institute Committee on Sustainability from 2010 to 2021. Sakai was also the founder of ACI Concrete Sustainability Forum.

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