Takafumi Noguchi*
Ryoma Kitagaki
Masato Tsujino

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Minimizing environmental impact and maximizing performance in concrete recycling

The sheer amount of concrete in use and in stock compared with other building materials throws up environmental issues such as the huge amount of CO_2 emitted when cement and concrete are produced and transported and the enormous amount of waste generated when concrete is disposed of. In addition, we are beginning to deplete aggregate resources at a fast rate. Concrete has conventionally been regarded as being difficult to recycle. The construction industry has addressed these problems and carried out research and development regarding the recycling of concrete since the 1970s. Recycling technology has been shifting from simple crushing into scrubbing with some preparations to produce high-quality recycled aggregate for structural concrete, and recycling of concrete in a completely closed loop has now become technically feasible. This paper reviews the development history of recycling technologies in Japan from the viewpoint of the properties of recycled aggregate and recycled aggregate concrete as well as the environmental impact such as CO_2 emissions and waste generation in recycling. The paper also presents the outline of completely recyclable concrete, with which closed-loop circulation of component materials is realized.

Keywords: Waste, Recycled aggregate, Absorption, Density, CO_2 emission, Standard, Microwave, Heating, Scrubbing, Crushing

1 Introduction

The development of civilization and industrialization since the Industrial Revolution has caused various environmental problems on a global scale, such as global warming, ecosystem disruption, resources depletion and waste accumulation.

According to the White Paper on the Environment in Japan [1], the total material input in Japan has reached approx. 2.0 billion tonnes annually in recent years, of which around 1.0 billion tonnes (50 %) are accumulated every year in the form of buildings and civil engineering structures as shown in Fig. 1. This indicates the enormous consumption of resources by the construction industry compared with other industries. The production of concrete, a primary construction material for forming the infrastructure of modern nations, amounted to approx. 500 million tonnes (217.4 million m^3 volume) in Japan, accounting for nearly 50 % of the annual resources consumption of the construction industry (see Fig. 1) [2]. In other words, concrete accounts for nearly 25 % of Japan's total materials input. Incidentally, the construction industry's consumption of steel and timber, two other primary construction materials, amounted to 32.5 million and 17 000 tonnes (4 170 000 and 34 000 m^3 volume) respectively, both far less than concrete consumption. On the other hand, the amount of waste in Japan totalled approx. 458 million tonnes in 2000 (general waste: 52 million tonnes; industrial waste: 406 million tonnes) as shown in Fig. 2 [3]. Waste from construction accounted for approx. 20 % (79 million tonnes) of total industrial waste. Moreover, construction waste accounted for nearly 30 % (12.8 million tonnes) of the 45 million tonnes of industrial waste destined for final disposal sites and approx. 60 % (241 000 tonnes) of the 400 000 tonnes of illegally dumped industrial waste. As demolished concrete waste accounts for approx. 42 % (35 million tonnes) of total construction waste (see Fig. 2), approx. 8 % of total waste in Japan therefore consists of demolished concrete waste. As stated above, concrete accounts for large percentages of both resources input and waste streams. Promoting the re-

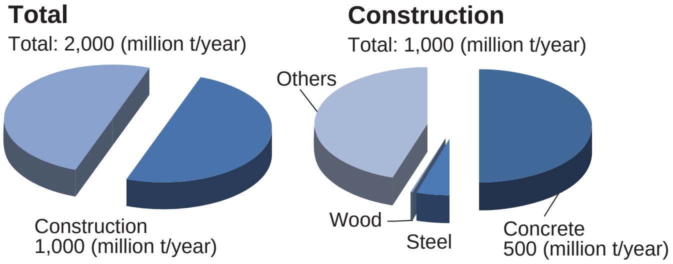

Fig. 1. Resources input into construction industries

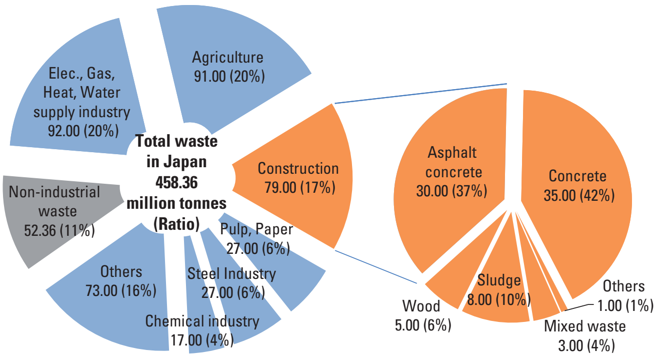

Fig. 2. Waste output from construction industries

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* Corresponding author: noguchi@bme.arch.t.u-tokyo.ac.jp

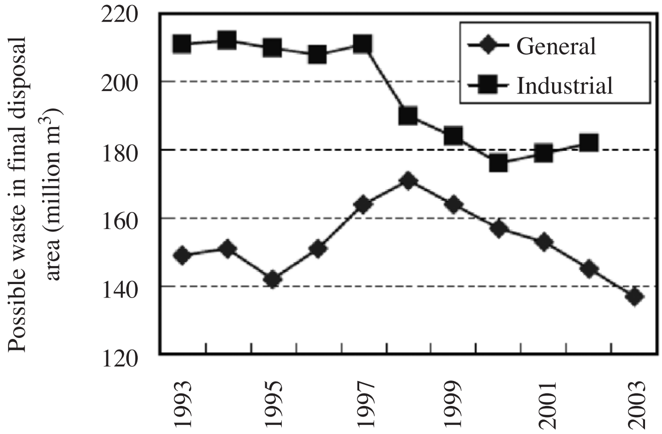


Fig. 3. Waste disposal area

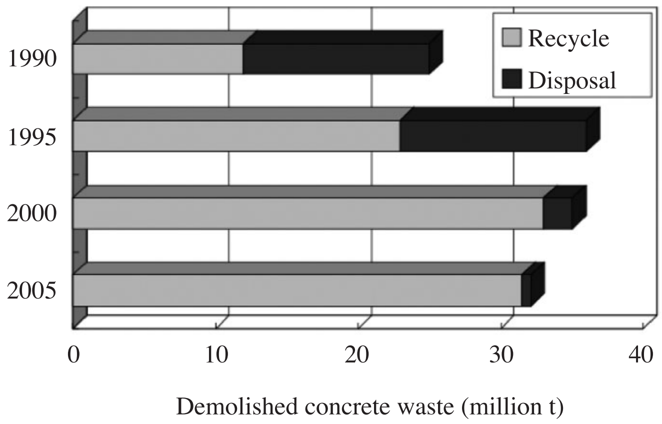


Fig. 5. Recycling of concrete rubble

cycling of demolished concrete has therefore been a pressing social issue in Japan where the remaining capacity of landfill sites for industrial waste has been diminishing every year as shown in Fig. 3 [4]. The shortage of landfill space in Japan, especially in urban areas, is really serious.

Since the adoption of the Kyoto Protocol, the reduction in CO_2 emissions to curb global warming has been a crucial task for all industries. Urgent measures are required, particularly for construction-related industries, whose CO_2 emissions account for 40 % of the total as shown in Fig. 4 [5]. The production of 1 m^3 of concrete requires approx. 330 kg of Portland cement. As Portland cement, which is made from limestone, is decarbonized during incineration, the production of 1 t of Portland cement generates approx. 0.75 t of CO_2, which is caused by decarbonation of limestone (60 %) and fossil fuel combustion (30 %) in the process of clinker production. Therefore, manufacturing 1 m^3 of concrete generates approx. 0.25 t of CO_2 from cement production and a further 0.1–0.2 t of CO_2 from aggregate production, transportation of materials and concrete production. Some 10 billion tonnes of concrete are produced annually worldwide and therefore concrete-related industries emit approx. 7–10 % of global, man-made CO_2.

Consequently, concrete accounts for large percentages of both resources input and CO_2 emissions. Considering natural resources conservation and prevention of global warming, resources recycling systems that do not generate additional CO_2 emissions must be urgently established in concrete-related industries.

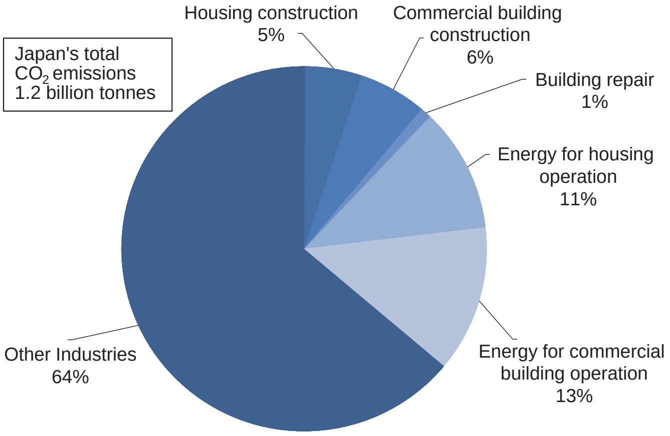


Fig. 4. CO_2 emissions in Japan

2 History of recycling measures

2.1 Political measures

With the aim of solving the construction waste problem, the Japanese Ministry of Land, Infrastructure & Transport (MLIT, formerly the Ministry of Construction) formulated an "Action Plan for Construction By-products" in 1994, which called for halving the amount of final disposal of construction waste by 2000, and a "Promotion Plan for Construction Waste Recycling" in 1997. Thanks to such active and continuing policies, construction waste streams began to decrease, with the recycling ratio of concrete rubble exceeding 95 % in 2000 as shown in Fig. 5. In view of the recycling ratios for waste timber, construction sludge and mixed waste generated by construction, which are all still low, the MLIT then enforced a "Basic Law for Establishing a Recycling-based Society", a "Construction Materials Recycling Act" and a "Law on Promoting Green Purchasing."

However, concrete rubble, which boasted a high recycling ratio, was entirely destined for pavement sub-bases and grading adjusters for arterial high-standard highways, urban expressways and general roads as designated by the MLIT's Road Bureau. The quality of recycling was therefore completely different from that of asphalt concrete rubble, for which level-cycling was accomplished. It was expected that an enormous amount of demolished concrete rubble would be generated in the future from the mass of concrete structures built during Japan's period of rapid economic growth, which were doomed to demolition due to durability problems. Moreover, it was expected that road construction would decrease and the method of repair would shift from replacing to milling and applying an overlay. These trends would lead to an imbalance between the supply of demolished concrete and the demand for road sub-bases. Further, the population decline and the prolonging of the service life of the existing stock by way of refurbishment and conversion would continue to reduce the amount of new construction and concrete production. Accordingly, these aspects would culminate in

Tab. 1. History of quality requirements for recycled aggregate

Year	Formulator and name of standard		Coarse aggregate Density (g/cm^3)	Coarse aggregate Absorption (%)	Fine aggregate Density (g/cm^3)	Fine aggregate Absorption (%)
1977	Building Contractors Society Draft standard for the use of recycled aggregate and recycled concrete		2.2 or more	7 or less	2.0 or more	13 or less
1994	Ministry of Construction Provisional quality standard for reuse of concrete by-products	Type 1	–	3 or less	–	5 or less
		Type 2	–	5 or less	–	10 or less
		Type 3	–	7 or less	–	
1999	Building Centre of Japan Accreditation criteria of recycled aggregate for building concrete		2.5 or more	3.0 or less	2.5 or more	3.5 or less
2000	Ministry of International Trade & Industry TR A0006 (Low-quality recycled aggregate concrete)			7 or less		10 or less
2005	Japan Industrial Standards Committee Recycled aggregate for concrete	JIS A 5021 (Class H)	2.5 or more	3.0 or less	2.5 or more	3.5 or less
2006		JIS A 5022 (Class M)	2.3 or more	5.0 or less	2.2 or more	7.0 or less
2007		JIS A 5023 (Class L)		7.0 or less		13.0 or less
	Japan Industrial Standards Committee JIS A5005 (Crushed stone and manufactured sand for concrete)		2.5 or more	3.0 or less	2.5 or more	3.0 or less

the need to recycle aggregate into aggregate for concrete, and it was no exaggeration to say that recycled aggregate could in future account for the greatest part of aggregates for concrete [6]. It was therefore vital to convert recycling from *quantity*-oriented to *quality*-oriented as proposed in a "Promotion Plan for Construction Waste Recycling 2002" formulated by the MLIT. In other words, it was necessary to find optimum recycling methods with due consideration for the material balance, while promoting the production and supply of high-quality recycled aggregate.

2.2 Standardization

After a three-year study aimed at using demolished concrete as recycled aggregate for concrete, the Building Contractors Society established a "Draft standard for the use of recycled aggregate and recycled concrete" in 1977. This standard required that the oven-dry density and water absorption of recycled coarse aggregate should be not less than 2.2 g/cm^3 and not more than 7 % respectively, and those of recycled fine aggregate not less than 2.0 g/cm^3 and not more than 13 % respectively. This was followed by research and development work within the scope of a number of projects promoted by the Ministry of Construction (1981–1985 and 1992–1996) or semi-public research institutes, which resulted in the establishment of standards for recycled aggregate. Tab. 1 gives the quality requirements, showing the progressive improvement in the qualities of recycled aggregate achieved by advances in the technology for producing recycled aggregate, finally reaching a level comparable with natural aggregate. The Recycled Aggregate Standardization Committee was set up within the Japan Concrete Institute in 2002; its task was to formulate Japan Industrial Standards for recycled aggregate for concrete. The committee established three standards as follows:

- JIS A 5021 Recycled aggregate for concrete, Class H, hereinafter RA-H
- JIS A 5022 Recycled concrete using recycled aggregate, Class M, with Annex, Recycled aggregate for concrete, Class M, hereinafter RA-M
- JIS A 5023 Recycled concrete using recycled aggregate, Class L, with Annex, Recycled aggregate for concrete, Class L, hereinafter RA-L

Tab. 2. Physical properties requirements for recycled aggregate

	RA-H Coarse	RA-H Fine	RA-M Coarse	RA-M Fine	RA-L Coarse	RA-L Fine
Oven-dry density (g/cm^3)	not less than 2.5	not less than 2.5	not less than 2.3	not less than 2.2	–	–
Water absorption (%)	not more than 3.0	not more than 3.5	not more than 5.0	not more than 7.0	not more than 7.0	not more than 13.0
Material passing 75 μm sieve (%)	not more than 1.0	not more than 7.0	not more than 1.5	not more than 7.0	not more than 2.0	not more than 10.0
Scope of application	No limitations are placed on the type and segment for concrete and structures with a nominal strength of 45 MPa or less		Members not subjected to drying or freezing-and-thawing action, e.g. piles, underground beams and concrete filled into steel tubes		Backfill, blinding and levelling concrete	

Tab. 3. Limits to amounts of deleterious substances in RA-H & M

Category	Deleterious substances	Limits (% by mass)
A	Tiles, bricks, ceramics, asphalt concrete	2.0
B	Glass	0.5
C	Plaster	0.1
D	Inorganic substances other than plaster	0.5
E	Plastics	0.5
F	Wood, paper, asphalt	0.1
	Total	3.0

Three types of recycled aggregate are classified by water absorption and oven-dry density, each being recommended for concrete structures and segments as given in Tab. 2. This classification urges a shift to a design system that permits the use of each class for suitable structures and segments. High-quality recycled aggregate is suitable for structures and segments requiring high durability and strength, while moderate- to low-quality recycled aggregate, which can be produced with minimal cost and energy or powdery by-products, is suitable for other structures and segments.

JIS A 5021 includes the following policies and requirements:

- RA-H is the high-quality aggregate used for JIS A 5308 (ready-mixed concrete) in a similar way to good-quality natural aggregate.
- Concrete rubble from demolition work usually contains considerable amounts of brick, tile, plaster, plastics, etc. The amount of deleterious substances in RA-H is tested by comparing the RA-H thus produced with several reference samples that include each deleterious substance. Tab. 3 shows the limits of deleterious substances.
- The minimum rate of sampling and testing and the alkali-silica reactivity criteria for RA-H depend on whether the attribute of the original aggregate is identified. Unless it is identified, the RA-H produced must be sampled and tested at frequent intervals and treated as an aggregate that has potential alkali-silica reactivity.

RA-H must be produced in a plant where the quality of RA-H produced and the producer's production control are assessed and reviewed by an approved inspection body and then certified by an approved certification body.

A quality control system for construction materials has been established to ensure that materials, particularly JIS products and products conforming to JIS, are supplied with constant qualities that meet the specifications under strict quality controls, so that contractors and citizens can carry out construction work and use the resulting structures with peace of mind. While it is essential to establish such a system for promoting the wide use of recycled aggregate, a distinctive difference exists between crushed stone/sand for concrete and recycled aggregate with regard to materials procurement. Whereas crushed stone/sand that is deemed uniform to a certain extent can be procured in large quantities, the grading, density, water absorption, alkali-silica reactivity, etc. of demolished concrete may quite naturally vary from one lump to another, particularly when the recycled aggregate production plant is located remote from demolition sites (off-site plant) and accepts demolished concrete from various structures. To promote recycled aggregate as JIS products or JIS-conforming products, it is therefore necessary to (1) produce recycled aggregate from only specific structures at on-site plants, (2) carry out materials control by storing the concrete rubble from each structure separately at off-site plants, or (3) carry out quality control by substantially increasing the frequency of acceptance and product inspections at off-site plants.

3 History of recycling technology

3.1 Recycling technologies for existing structures

The uses for concrete rubble destined for recycling are determined by the qualities of the recycled materials, such as density and water absorption, which vary depending on

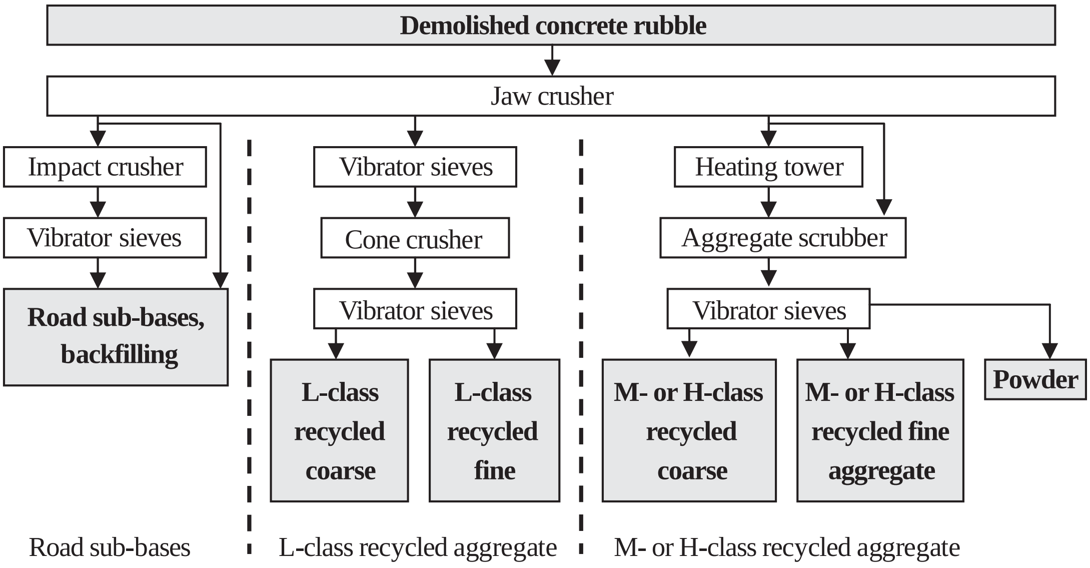


Fig. 6. General methods for concrete recycling

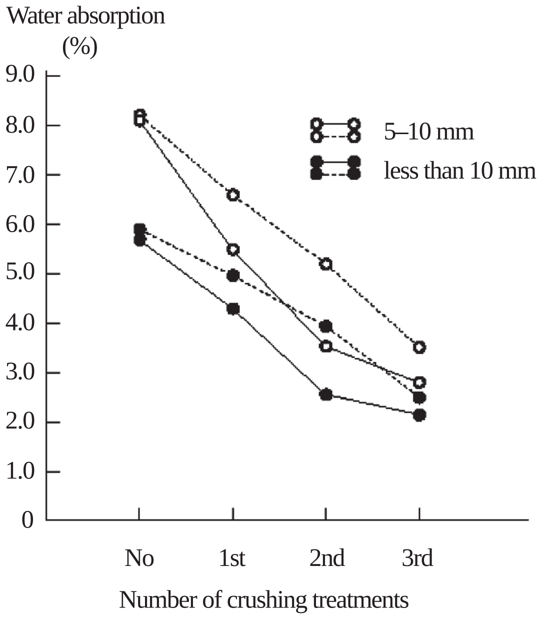


Fig. 7. Number of crushing treatments and quality of recycled aggregate [7]

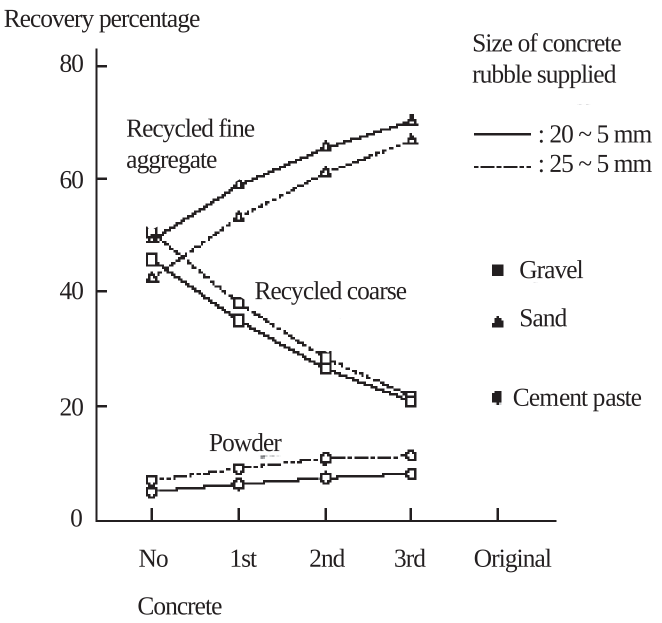


Fig. 8. Number of crushing treatments and recovery of recycled aggregate [7]

the percentage of cement paste contained within or adhering to the surfaces of the original aggregate, and the quality of recycled aggregate depends on the production method. Fig. 6 shows general methods for producing recycled road sub-bases, recycled aggregate for levelling concrete (low-quality recycled aggregate) and recycled aggregate having qualities comparable with those of natural aggregate and used for structural concrete (high-quality recycled aggregate).

Single toggle-type jaw crushers are generally used for the primary crushing of demolished concrete into pieces 40–50 mm in size regardless of the ultimate quality of the recycled aggregate. While the material is carried to the next process on a belt conveyor, foreign matter such as wood/plastic chips are removed manually and reinforcing steel/nails with a magnetic separator. The materials then undergo various treatments according to their intended uses.

Impact crushers are used for secondary and tertiary crushing when producing moderate- and low-quality recycled aggregate. While the quality of recycled aggregate produced by such equipment improves with the number of treatment processes, the recovery percentage of recycled aggregate decreases as the amount of powder by-products increases as the aggregate itself is crushed, as shown in Figs. 7 and 8 [7]. Other equipment in practical use for producing moderate- and low-quality recycled aggregate includes self-propelled or vehicle-mounted jaw crushers and impact crushers that save the energy normally expended to haul the demolished concrete. Special plant is therefore necessary for efficient production of high-quality recycled aggregate in order to minimize the adhering cement paste. Efficient equipment for producing high-quality recycled aggregate has been developed in recent years and put into practical use. Figs. 9, 10 and 11 show representative types.

The first is a technique called mechanical scrubbing, in which concrete rubble fragments scrub one another in an eccentric tubular vertical mill [8] or a screw mill to produce recycled coarse aggregate by removing adhering cement paste. Fine aggregate is then produced similarly from the recycled aggregate smaller than the specified size. Trial runs revealed that recycled aggregate conforming to the high-quality standard is obtained. However, the percentage of recovery varies widely depending on the type of original aggregate, and it was discovered that there

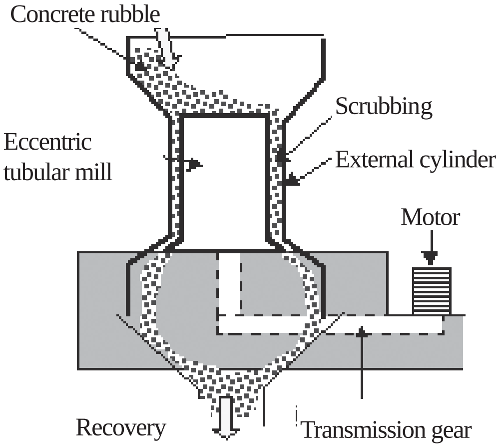


Fig. 9. Mechanical scrubbing equipment (eccentric tubular mill) [8]

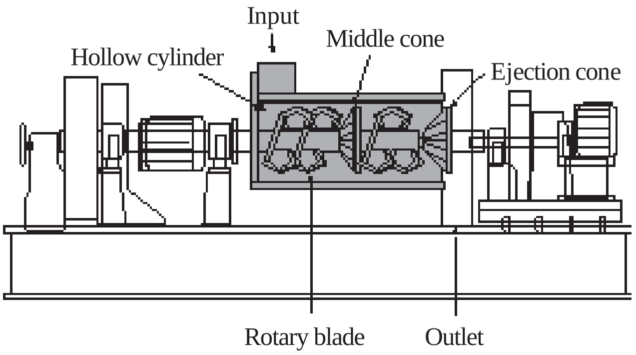


Fig. 10. Mechanical scrubbing equipment (screw mill)

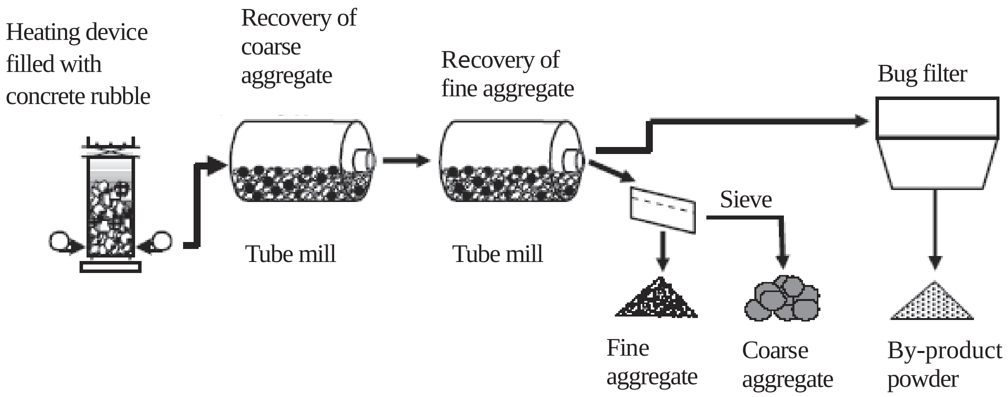


Fig. 11. Heated scrubbing equipment [9]

is a slight difficulty in producing high-quality recycled fine aggregate. Virgin fine aggregate is therefore considered necessary when using recycled aggregate produced by this method in structural concrete. The use of recycled coarse aggregate produced by this method is not classified as downcycling because the quality of the structural concrete is assured.

The second technology is called heated scrubbing [9], in which concrete rubble is charged in a heating furnace and subjected to a hot-air treatment to make the cement paste brittle and weak. It is then scrubbed in a mill to separate cement paste from aggregate. The heating temperature is about 300 °C. The quality of recycled aggregate attains the high-quality level, and the percentage of recovery is sufficiently high. The concrete qualities produced using this aggregate are virtually the same as the original concrete. Although this technique has acquired certain track records in the construction of actual structures, it requires the availability of infrastructures that provide the heat sources necessary for heating at an economical rate. And although the problems of the thermal energy-induced environmental impact and increase in costs currently remain unsolved, this technique assures the quality of the structural concrete, avoiding downcycling, while forming a closed loop in terms of the resource circulation of concrete materials. It should be noted that the above two techniques recover recycled aggregate, or a material having the same quality as natural aggregate, from waste concrete. Even though a significant amount of energy is input at the treatment stage in the production system, recycled aggregate is produced in a condition usable in parts of the same product or for other products for which the same or a higher performance is required. When this condition is ensured, the material is in a condition that can be circulated (i.e. recycled) in a closed system.

3.2 Completely recyclable concrete (CRC)

3.2.1 The CRC concept

We have now reached a stage at which it is definitely necessary to establish a new design concept for the complete recycling of structural concrete. The principle of complete recycling is that the concrete is subjected to material design to reduce waste generation and facilitate resource circulation in a closed system. Development technology based on such material design is regarded as proactive technology. The materials of concrete should be used as parts of concrete during the service life of concrete and remain usable after demolition as parts of similar or other products without quality deterioration, continuing circulation in various products as the media. This is defined as a performance called “resource conservability”. At the time of demolition, the components of the concrete can be completely recycled and used for structures provided the concrete was produced with due consideration for the resource conservability at the stage of material design. What needs to be done in the future is to introduce material design that permits complete recycling for the components of the concrete at least, i.e. aggregate and cement materials, to ensure the material conservability in concrete as the medium and then to achieve high strength and high durability of structures.

3.2.2 Cement recovery-type CRC

Cement recovery-type CRC is defined as “concrete whose materials are entirely usable after hardening as materials of cement, since all the binders, additions and aggregates are made of cement or materials for cement” [10]. In the most basic cement recovery-type CRC (e.g. using normal Portland cement, crushed limestone and crushed limestone sand), the waste material is crushed and the sample obtained is subjected to ingredient adjustment to turn it into the material for cement. This material is subjected to processes including calcination in an electric oven, gypsum addition and crushing to produce reprocessed cement. This cement has the same qualities as one available on the market and no problems have been observed in the fresh and mechanical properties of concrete made using this cement, as shown in Tab. 4. Blastfurnace slag, fly ash, etc., generated as by-products from industries other than construction, have been actively reused as materials for cement and cementitious materials for concrete. As these contain adequate amounts of SiO_2, Al_2O_3 and Fe_2O_3, which are necessary for the materials of cement, concrete containing several types of these industrial by-products in combination achieves complete recyclability as clinker material after demolition without adding any other ingredients. This CRC, with no need for ingredient adjustment, also contributes to the global environment from the stand-

Tab. 4. Properties of recycled cement and recycled concrete

Recycled cement	**Density**	**Specific surface area**	**Setting time**	
	(g/cm^3)	**(cm^2/g)**	**Initial**	**Final**
	3.13	**3340**	**2h:00min**	**2h:50min**
Recycled concrete	W/C	Compressive strength at 28 days (MPa)	Modulus of elasticity at 28 days (GPa)	
	0.58	35.2	39.0	

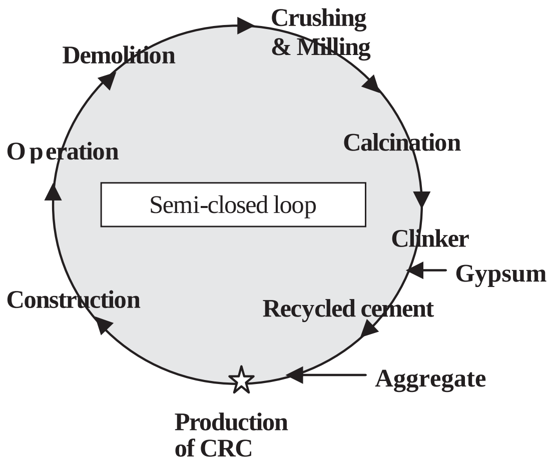
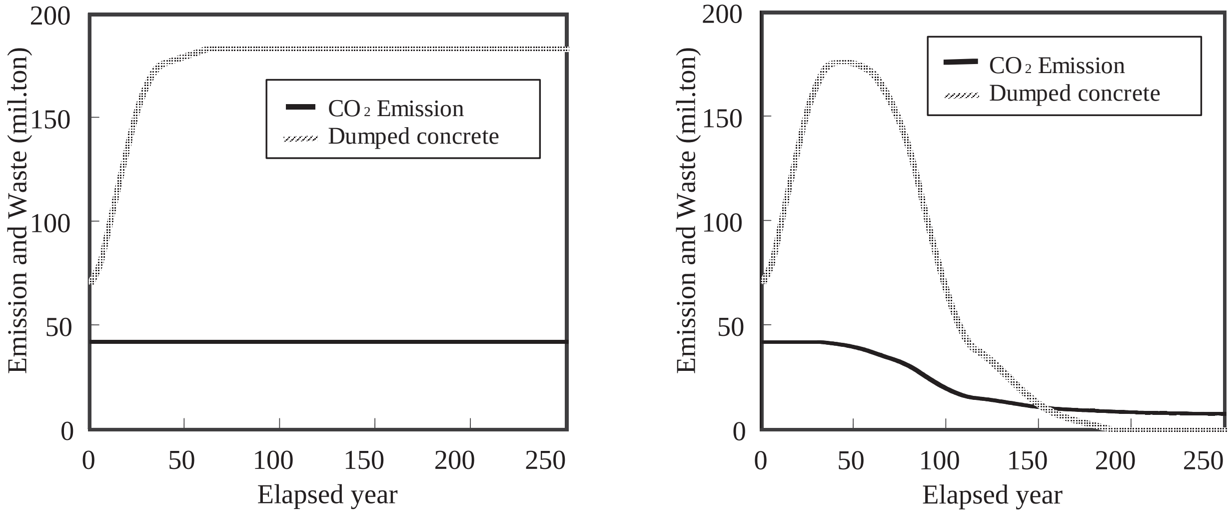


Fig. 12. Cement recovery-type CRC

point of effective use of industrial by-products. Cement recovery-type CRC can formulate a semi-closed loop circulation materials flow as shown in Fig. 12. Changing from conventional concrete to CRC will substantially mitigate the environmental problem of concrete waste generation and CO_2 emissions during cement production, while permanently preserving and storing the limestone resource in the form of structures. Fig. 13 shows the simulation of waste concrete amount and CO_2 emissions under the condition that 5 % of conventional concrete is replaced with the prototype CRC (using crushed limestone and crushed limestone sand) every year [10]. Fig. 13 reveals that the waste concrete peaks 50 years later and then rapidly decreases thereafter and that CO_2 emissions progressively decrease, beginning 30 years later. Accordingly, CRC greatly contributes to reducing the burden on the environment while permitting sustained construction investment.

3.2.3 Aggregate recovery-type CRC

Aggregate recovery-type CRC is defined as “concrete in which the aggregate surfaces are modified without excessively reducing the mechanical properties of the concrete in order to reduce the bond between the aggregate and the matrix, thus permitting easy recovery of the original aggregate” [11]. It can also form a closed circulating materials flow as shown in Fig. 14. In order to achieve 100 % circulation of concrete in a closed system, an aggregate supplier structure is necessary in addition to that of a cement materials supplier. By building a stock of structures keeping such an appropriate balance, all cement and aggregate can be exploited from built structures in the future. In aggregate recovery-type CRC, aggregate surfaces can be modified using one of two methods: chemical treatment or physical treatment [12]. Chemical treatment is a method in which the formation of cement hydrates on the aggregate/paste interfaces is chemically restricted due to a mineral oil coating, whereas physical treatment forms a film of water-soluble synthetic resin emulsion to smooth the fine irregularities on the interfaces, thus reducing the mechanical friction. Modification treatment can be carried out simply and economically by either method. Ex-



(1) Current situation

(2) Production of CRC

Fig. 13. Changes in CO_2 emissions and dumped concrete [10]

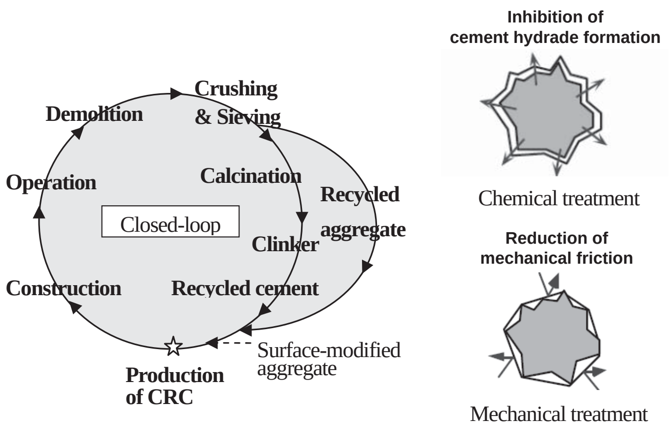


Fig. 14. Aggregate recovery-type CRC

periments were carried out to investigate the mechanical properties of the concrete and the aggregate recoverability. Two types of coarse aggregates with different particle shapes, i.e. gravel and crushed stone, were treated chemically and physically and concrete specimens were fabricated by adopting two levels of water/cement ratios, i.e. 40 and 60 %. Compressive strength and modulus of elasticity were measured at 28 days. The concrete was crushed in a two-phase process to find out the recovery ratio and evaluate the quality of the recycled aggregate. The primary crushing was carried out using an improved jaw crusher having a mechanism that slightly scrubs aggregate particles. The entire amount of the crushed aggregate was fed into a ball mill and subjected to scrubbing. The aggregate recovery ratio of concrete containing crushed stone was increased by aggregate surface modification regardless of the strength, as shown in Fig. 15. The effect of chemical treatment was particularly evident. On the other hand, the effect of aggregate surface treatment was less evident in concrete containing rounded aggregate, particularly in high-strength concrete. The surface treatment results in the recovery of high-quality recycled aggregate with little adhering paste from demolished concrete by means of a simple crushing technique. The compressive strength of concrete made with surface-modified aggregate decreased regardless of the water/cement ratio, as shown in Fig. 16. Concrete with angular crushed stone and a lower water/cement ratio exhibited a greater decrease in compressive strength due to the greater effect of surface modification than that with rounded gravel and a higher water/cement ratio. This was because surface modification causes the crack propagation zone to be predominantly formed in the weak portions at aggregate/matrix boundaries, leading to failure at a lower stress. Based on the experiments, the trade-off relationship between the mechanical properties of the concrete and the aggregate recoverability still remained unresolved.

3.2.4 Advanced aggregate recovery-type CRC

An advanced technology was developed by *Tsujino* et al. [13] to ensure compatibility of performance in a trade-off relationship between the mechanical properties of the concrete and aggregate recoverability. The proposed new technology consists of two technologies as shown in Fig. 17, i.e. concrete strength enhancement technology and aggregate recovery technology. Differing from conventional technologies, the former involves aggregate surface modification to increase the bonding force between the coarse aggregate and the mortar by applying an even coating of binder to the surface of the coarse aggregate;

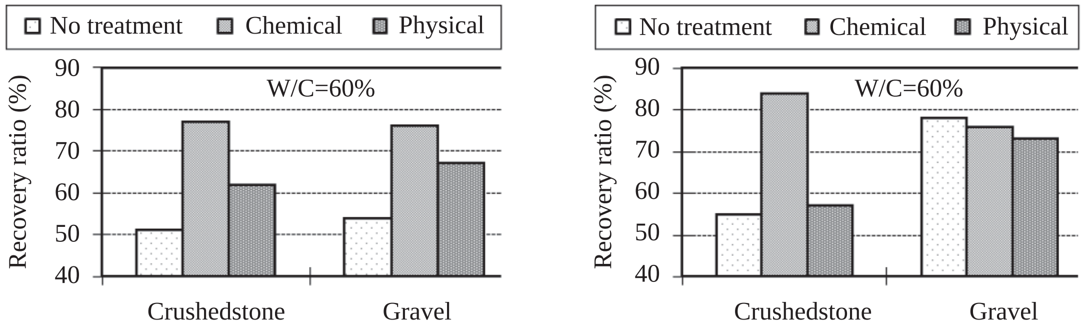


Fig. 15. Recovery ratios in aggregate recovery-type CRC

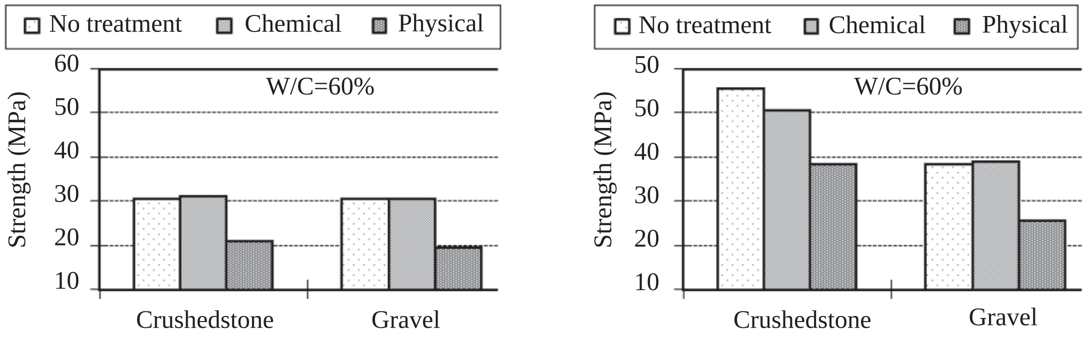


Fig. 16. Compressive strengths in aggregate recovery-type CRC

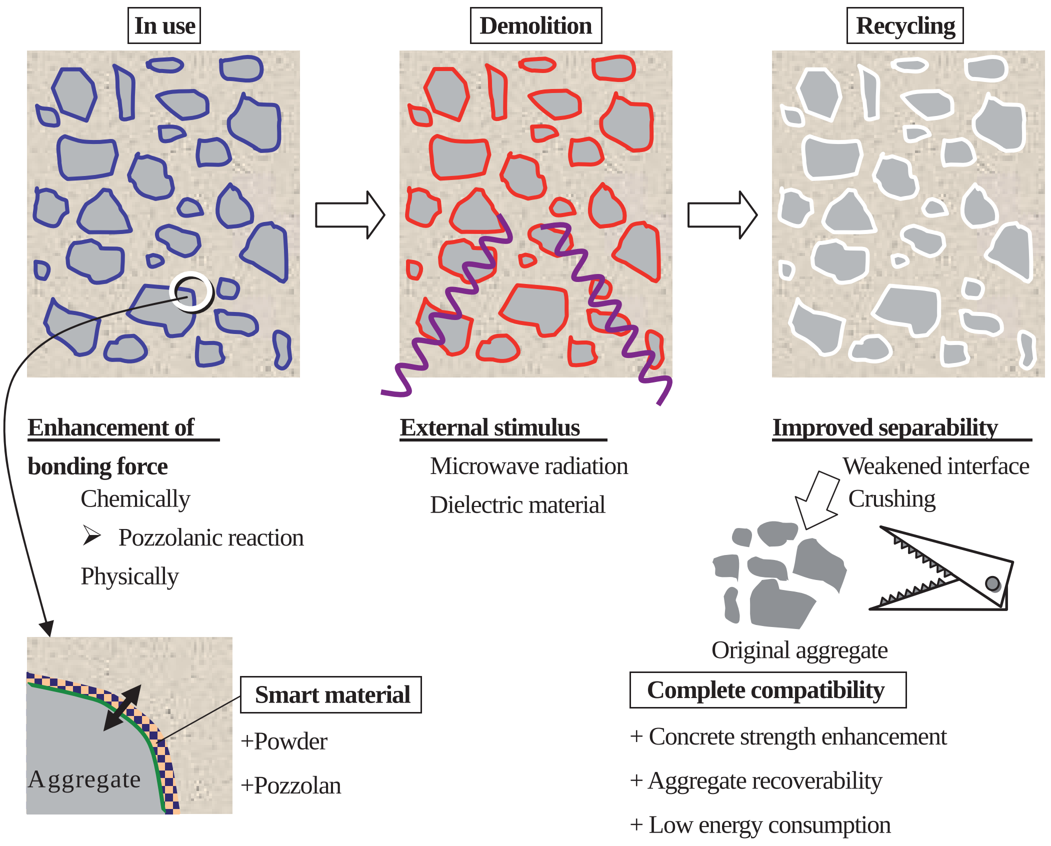


Fig. 17. Concept of the new technology for aggregate recovery-type CRC

silica fume and by-product powder were contained in the binder expecting to enhance chemical and physical bonding force due to pozzolanic reaction and mechanical friction. The latter method aims to recycle aggregate with low energy, which involves inclusion of dielectric material in the binder. When applied with microwave radiation, the dielectric material on the surface of the aggregate is heated and the interface between aggregate and mortar matrix is weakened locally, which improves the separability of the aggregate and mortar matrix. Crushed sandstone (surface-dry density 2.66 g/cm^3, water absorption 0.70 %) was used as a coarse aggregate to apply the modification, in which low-viscosity epoxy resin was used as an adhesive agent to attach silica fume and by-product powder (absolute density 2.35 g/cm^3, specific surface area 1877 cm^2/g) to the aggregate surface. The mixing ratios of the silica fume and the by-product powder are shown in Tab. 5. Each powder was applied to the adhesive agent after it was applied to the aggregate and before it hardened. Fig. 18 shows the compressive strengths at 3, 7 and 28 days and the modulus of elasticity at 28 days. When the content of silica fume is 10–20 % in the powder, such as specimens SP80 and SP90, the strength of the concrete is increased by 20 % or more compared with that of normal aggregate concrete. Assuming that the increase in the strength of specimen P is only due to the increase in the mechanical friction force, the increase in the chemical bonding force due to pozzolanic reaction is the reason for the 30 % increase in strength. This suggests that the combination of the increase in the mechanical friction force and the increase in the chemical bonding force results in a drastic increase in the concrete strength. The modulus of elasticity was, however, 10 % lower than that of the normal aggregate concrete due to the formation of the epoxy layer by applying

Tab. 5. Mixing ratios of silica fume and by-product powder

Symbol	Silica fume (%)	By-product powder (%)	Epoxy resin & dielectric material
O	0	0	Not applied
N	0	0	Applied
SP70	30	70	
SP80	20	80	
SP90	10	90	
P	0	100	

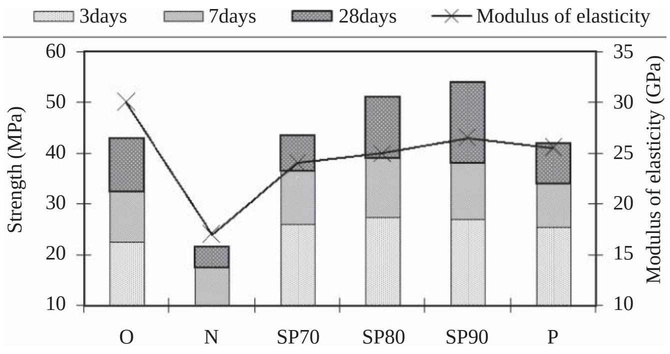


Fig. 18. Compressive strengths and elastic moduli in advanced aggregate recovery-type CRC

Tab. 6. Heating Conditions

Symbol	Dielectric material	Microwave heating	Electric oven heating
O1	Not applied	–	–
O2		2.45 GHz, 1800 W, 90 s	–
O3		–	300 °C, 60 min
SP80	Applied	2.45 GHz, 1800 W, 90 s	–

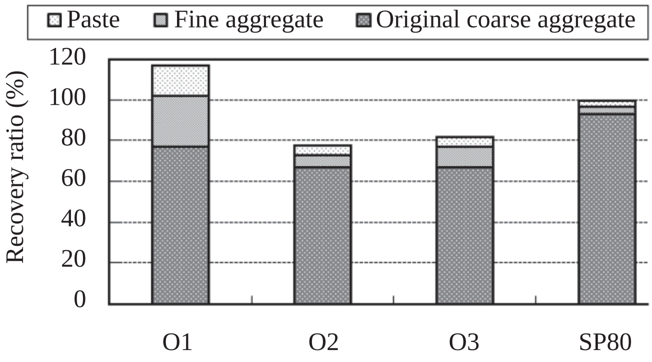


Fig. 19. Recovery ratios in advanced aggregate recovery-type CRC

this technology. Considering attenuation of the microwave within the concrete, the concrete was heated for 90 s with microwave radiation at a power of 1800 W. The specimens used were those cured for 28 days in water, with dimensions of ∅ 50 × 100 mm. After being heated with microwave radiation, the specimens were roughly crushed with a jaw crusher and subjected to a rubbing treatment with the "Los Angeles Abrasion Machine" to remove cement mortar. The aggregate recovery rate was measured for specimen O, prepared using normal aggregate, and specimen SP80, which exhibited high strength. Tab. 6 shows the heating conditions. Both microwave heating and conventional electric oven heating were applied to the specimen prepared using normal aggregate. Fig. 19 shows the recovery ratio of the recycled coarse aggregate. Specimen O1 (not heated) contains considerable cement paste despite undergoing rubbing treatment. With respect to specimen O2 heated by microwave radiation and specimen O3 heated in the electric oven, more cement paste is removed than is the case without heating, but it is not as much as a specimen that has undergone heated scrubbing as reported in past papers. The aggregate recovery rate of specimen SP80 heated by microwave radiation was about 93 %, indicating small amounts of residual paste and fine aggregate, and proved the high quality of the recycled coarse aggregate. Fig. 20 shows the CO_2 emissions during the treatment of 1 tonne of waste concrete mass. The CO_2 emitted using the microwave heating is extremely small compared with that from the aggregate production process based on heated scrubbing. When compared with the mechanical scrubbing that could produce moderately high-quality aggregate, the CO_2 emissions were almost the same. Considering the extremely high quality of recycled aggregate obtained using the new technology, it seems to offer great advantages over conventional technologies.

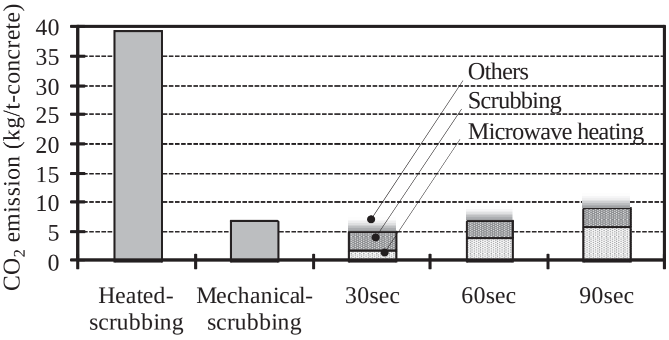


Fig. 20. CO_2 emissions in concrete recycling process

4 Conclusion

Care should be exercised regarding so-called cascade recycling, mixed/compound recycling, recycling into other industries and by-product utilization because all these tend to be unrepeatable. When a product utilizing a by-product is repeatedly recycled, the by-product will become useless as a material, ending up as waste. What is a truly recycling-oriented society? Utilization of recycling technology that consumes considerable energy generates another environmental impact: CO_2 emissions. True recycling should eliminate such scenarios. Unrepeatable recycling merely extends the material's stay on the human side without contributing to the basis for a truly recycling-oriented society. A recycling-oriented society in the true sense of the word is a society that continues to use resources, once they are transferred from nature into society, without returning them unless they do not represent an environmental impact. In such a society, the intake of resources from nature should be minimized and products and materials that cannot be recycled repeatedly and consume significant energy for recycling should be rejected.

In order to recycle concrete in a closed system, it is necessary to review the validity of the currently prevailing method of producing recycled aggregate and to solve technical problems hampering complete recycling in a closed system. To solve such problems, it is important to adopt a technology of enhancing the resource conservability of concrete and its components at the stage of designing products and structures. Completely recyclable concrete is a realistic technique for realizing the formulation of a sustainable resource-recycling society. The new technology using aggregate surface modification and microwave radiation has overcome the inherent conflicts in concrete recycling and achieved the high performance of concrete, energy-savings and low CO_2 emissions in concrete recycling and the full recovery of recycled aggregate at the same time.

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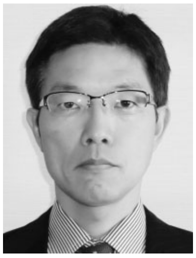

Takafumi Noguchi,
Associate Professor,
University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo 113-8656, Japan
Tel: +81-3-5841-6198,
Fax: +81-3-5841-6195
E-mail: noguchi@bme.arch.t.u-tokyo.ac.jp

Ryoma Kitagaki,
Assistant Professor,
University of Tokyo

Masato Tsujino,
Researcher,
Shimizu Corporation