Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Proceedings of Honouree sessions ed. T Naik, F Canpolat, P Claisse, E Ganjian,
ISBN 978-1-4507-1487-7 http://www.claisse.info/Proceedings.htm

# Toward Sustainable Resource Recycling in Concrete Society

**Takafumi Noguchi**[1]

*[1]7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan, Department of Architecture, The University of Tokyo. E-mail: <noguchi@bme.arch.t.u-tokyo.ac.jp>,*

## ABSTRACT

The sheer amount of concrete in use and in stock compared with other materials brings up the issue of the enormous amount of waste generated when concrete is disposed of. Besides, aggregate resources are beginning to be depleted at a high speed. 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 profiles various concrete related problems from the viewpoint of resource recycling, reviews development history of concrete recycling. Then it proposes a design concept for closed-loop recycling and introduces a new technology realizing sustainable resource recycling in concrete society.

## INTRODUCTION

The development of material civilization and industrialization since the Industrial Revolution have caused various environmental problems on a global scale, such as global warming, ecosystem disruption, resources depletion and waste accumulation. Since the adoption of the Kyoto Protocol, the reduction of $CO_2$ emission to curb global warming is a crucial task for all industries. Urgent measures are required particularly for construction-related industries, whose $CO_2$ emission in the production and transportation of materials, the execution of constructions, the operation of buildings, etc. accounts for around 40% of the total [Noguchi 2009]. Production of $1m^3$ of concrete, a primary construction material for forming modern nations, needs approximately 330kg of Portland cement. As Portland cement, which is made from limestone, is decarbonized during incineration, the production of 1 ton of Portland cement generates approximately 0.75 to 1.0 ton of $CO_2$ [WBCSD 2002] which is caused by decarbonation of limestone (60%) and fossil fuel combustion (30%) in the process of clinker production. Therefore manufacturing $1m^3$ of concrete generates approximately 0.25 ton of $CO_2$ from the cement production and additionally 0.1 to 0.2 ton of $CO_2$ from the aggregate production, the transportation of materials and the concrete production [Sakai 2009]. 20 billion ton of concrete is produced annually worldwide and consequently concrete-related industries emit approximately 7 to 10% of global manmade $CO_2$.

Nearly 50% of the total material input is accumulated every year in the form of buildings and civil structures in Asian countries [Noguchi 2008]. It indicates the enormous consumption of resources by the construction industry compared with other industries. The production of concrete accounts for nearly 50% of the annual resource consumption of the construction industry [Noguchi 2008]. In other words, concrete accounts for nearly 25% of the total

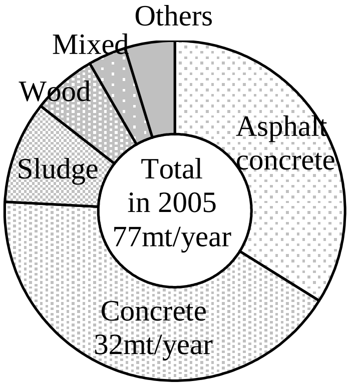

**Fig. 1. Construction Waste in Japan**

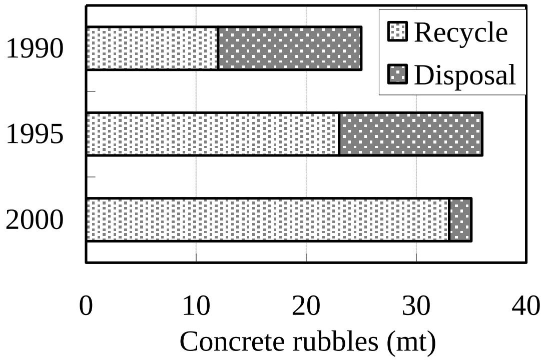

**Fig. 2. Recycling of Concrete Rubbles**

material input while steel and wood is far less consumed than concrete. Concrete structures are generally expected to last for decades or more than a century. However, most of them built in the past in Japan have been demolished and removed much earlier than their intended service lives. Why? Of course, this is mostly attributed to such reasons as the outdated design, the limitations in the space renewability, and the technical problems including performance degradation of the equipment and the structural bodies. Recycling of concrete rubbles, which account for 30 to 40% of the total construction-related waste as shown in Figure 1 [Noguchi 2009], for road bottoming has particularly been promoted as a national policy. Nevertheless, reductions in the length of new road construction in recent years have undermined the demand for road bottoming, requiring increased efforts to seek technical and social solutions for reducing the amount of concrete rubbles to be disposed of. The scarcity of the residual capacity of final disposal areas in Japan, which has become increasingly serious in recent years, also alerts us to formulate a resource-recycling society.

As stated above, concrete accounts for large percentages of both resource input and $CO_2$ emission. Considering natural resource conservation and prevention of global warming, resource recycling system which does not generate extra $CO_2$ emission should be urgently established in concrete-related industries. This paper profiles various concrete related problems from the viewpoint of resource recycling, reviews development history of concrete recycling. Then it proposes a design concept for closed-loop recycling and introduces a new technology realizing sustainable concrete society.

## HISTORY OF CONCRETE WASTE AND RECYCLING IN JAPAN

### Political measures

With the aim of solving the construction waste problem, the Japanese Ministry of Land, Infrastructure and Transport (MLIT, formerly the Ministry of Construction) formulated “Action Plan for Construction By-products” in 1994, which called for halving the amount of final disposal of construction waste by 2000, and “Promotion Plan for Construction Waste Recycling” in 1997. Thanks to such active and continual policies, construction waste discharge began to decrease, with the recycling ratio of concrete rubbles exceeding 95% in 2000 as shown in Figure 2. In view of the still low recycling ratios of waste wood, slime, and mixed waste generated by construction, the MLIT then enforced “Basic Law for Establishing a Recycling-based Society”, “Construction Material Recycling Act”, and “Law on Promoting Green Purchasing.” However, concrete rubbles, which boasted a high recycling ratio, were entirely destined for bottoming and grading adjusters for arterial high-standard

**Table 1. History of Quality Requirements for Recycled Aggregate**

| Year | Formulator and Name of Standard | | Coarse aggregate | | Fine aggregate | |
|---|---|---|---|---|---|---|
| | | | Density ($g/cm^3$) | Absorption (%) | Density ($g/cm^3$) | Absorption (%) |
| 1977 | Building Contractors Society<br>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<br>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 Center of Japan<br>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 and Industry<br>TR A0006 (Low quality recycled aggregate concrete) | | | 7 or less | | 10 or less |
| 2005 | Japan Industrial Standards Committee<br>Recycled aggregate for concrete | JIS A5021 (Class H) | 2.5 or more | 3.0 or less | 2.5 or more | 3.5 or less |
| 2006 | | JIS A5022 (Class M) | 2.3 or more | 5.0 or less | 2.2 or more | 7.0 or less |
| 2007 | | JIS A5023 (Class L) | | 7.0 or less | | 13.0 or less |
| | Japan Industrial Standards Committee<br>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 |

highways, urban expressways, and general roads designated by the Road Bureau of the MLIT. The quality of recycling was therefore completely different from that of asphalt concrete rubbles, for which level-cycling was accomplished. It was expected that an enormous amount of demolished concrete rubbles would be generated in the future from concrete structures mass-constructed during Japan's rapid economic growth being, 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 bottoming. Also, the population reduction and the extension of the service life of the existing stock by increased succession, utilization, and conversion would keep on reducing the amount of new construction of structures and concrete production. Accordingly, these aspects would culminate in the need to recycle aggregate into aggregate for concrete, and it was no exaggeration to say that recycled aggregate could account for the greatest part of future aggregate for concrete [Tomosawa et al. 2005]. It was therefore vital to convert recycling from quantity-oriented to quality-oriented recycling as proposed in "Promotion Plan for Construction Waste Recycling 2002" formulated by the MLIT in 2002. In other words, it was necessary to find optimum recycling methods with due consideration to the material balance, while promoting the production and supply of high-quality recycled aggregate.

## Standardization

After a three-year study aiming at using demolished concrete as recycled aggregate for concrete, the Building Contractors Society established “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 be not less than 2.2g/cm$^3$ and not more than 7%, respectively, and those of recycled fine aggregate be not less than 2.0g/cm$^3$ and not more than 13%, respectively. This was followed by researches and developments under some projects promoted by the Ministry of Construction (1981-1985 and 1992-1996) or semi-public research institutes, through which standards for recycled aggregate have been established. Table 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 to natural aggregate. The Recycled Aggregate Standardization Committee was set up in the Japan Concrete Institute in 2002, which was tasked with formulating Japan Industrial Standards for recycled aggregate for concrete. The committee established three standards as follows:

- JIS A 5021 (Recycled aggregate for concrete - Class H)
- JIS A 5022 (Recycled concrete using recycled aggregate Class M) with Annex (Recycled aggregate for concrete - Class M)
- JIS A 5023 (Recycled concrete using recycled aggregate Class L) with Annex (Recycled aggregate for concrete - Class L)

Three types of recycled aggregate is classified by water absorption and oven-dry density, each being recommended for concrete structures and segments as given in Table 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 middle- 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.

## PROBLEMS OF CONVENTIONAL SYSTEM

### Production

Currently the principal use for waste concrete is road bottoming - down cycling in which the quality of a recycled product is lower than that of the original one. Meanwhile, aggregate resources for concrete are rapidly depleting. In other words, sustained development is impossible for concrete-related industries as long as they maintain the current system of treatment and use. Such a situation is an environmental aspect that was unforeseeable through the technical system of post-war forward-process production that focuses on cost reduction and efficiency without taking account of the easy decomposability of products. The forward-process production system drastically improved the technology for constructing structures in a short time, resulting in the manifestation of an abundant supply of structures. In recent years, however, there has been a growing suspicion that such existing structures may not provide long-lasting structural and functional satisfaction. Inconsistency of the results brought about by rationality-oriented forward-process production has also become

**Table 2. Recommended Applications of Recycled Aggregate**

| Type | Application |
|---|---|
| Class H | No limitations are put on the type and segment for concrete and structures with a nominal strength of 45MPa or less |
| Class M | Members not subjected to drying or freezing-and-thawing action, such as piles, underground beam, and concrete filled in steel tubes |
| Class L | Backfill concrete, blinding concrete, and levelling concrete |

evident. This may have resulted from the lack of consciousness in the forward-process production systems that technical development should optimize “cost and quality” on the premise of “finiteness of resources.” Such systems still continue to produce structures latently chained to a vicious circle.

**Recycling**

Recycling technologies currently prevalent in concrete practice are relevant to existing structures made by the forward-process production systems and based on the concept of “regenerating used products to which no recycling-conscious design was applied.” In other words, recycling is carried out as an alternative to the disposal of concrete rubbles while maintaining the forward-process production systems. This is a typical nosotropic technology whereby materials are diffused into a wide range of industries where they continue down cycling of their resources. Recycled concrete produced in this manner is seeded with potential problems such as quality degradation of concrete, unstable supply, unstable price, unstable distribution and increasing environmental impact [Tamura 2002]. Nevertheless, being saddled with the structural stock produced by the forward-process systems, there is a feeling of desperation in the need to deal with the concrete rubbles that will be generated in the future. Fortunately, reworked products originating from the forward-process systems can function as an effective means for a certain period until the demand disappears, provided the uses are ubiquitous with low levels of quality requirements. One such example is the use of concrete rubbles for road bottoming.

## REVIEW OF RECYCLING TECHNOLOGY

The uses for concrete rubbles to be recycled are determined by the qualities of the recycled material, such as density and water absorption, which vary depending on the percentage of cement paste contained within or adhering to the surfaces of original aggregate, and the quality of recycled aggregate depends on the production method. Figure 3 shows general methods for producing recycled road bottoming, recycled aggregate for levelling concrete (low-quality recycled aggregate), and recycled aggregate having qualities comparable to those of natural aggregate and used for structural concrete (high-quality recycled aggregate).

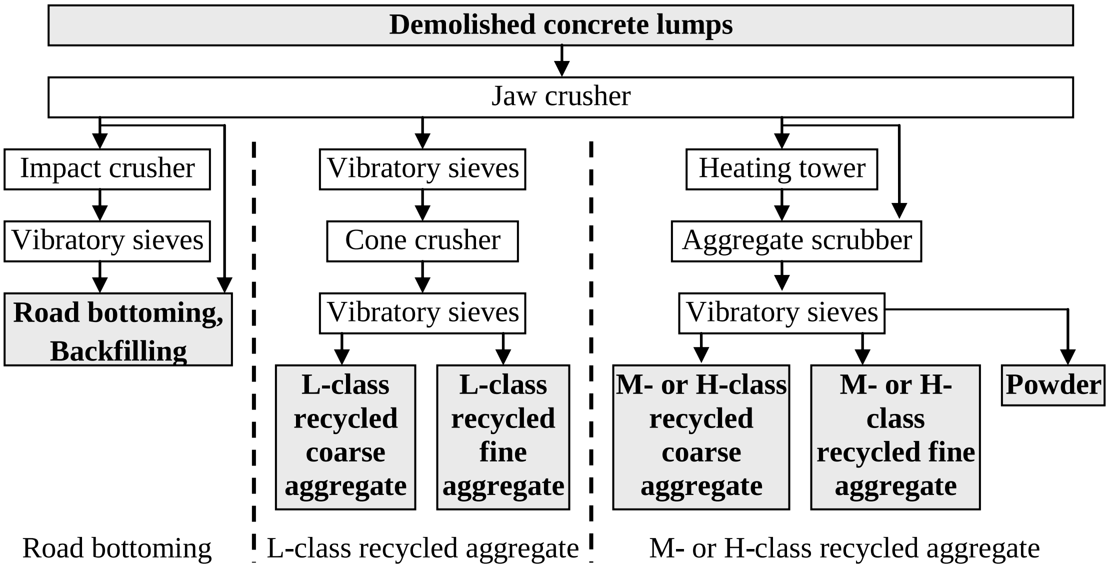

**Fig. 3. General Methods for Concrete Recycling**

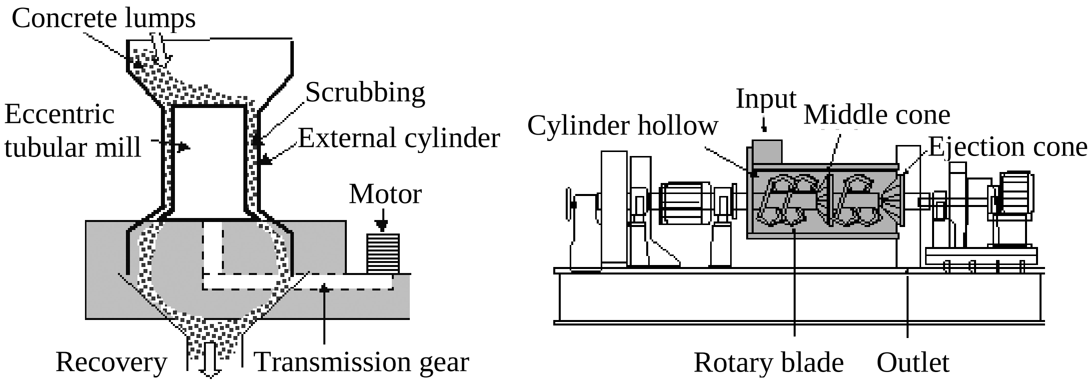

**Fig. 4a. Mechanical-scrubbing Equipments**

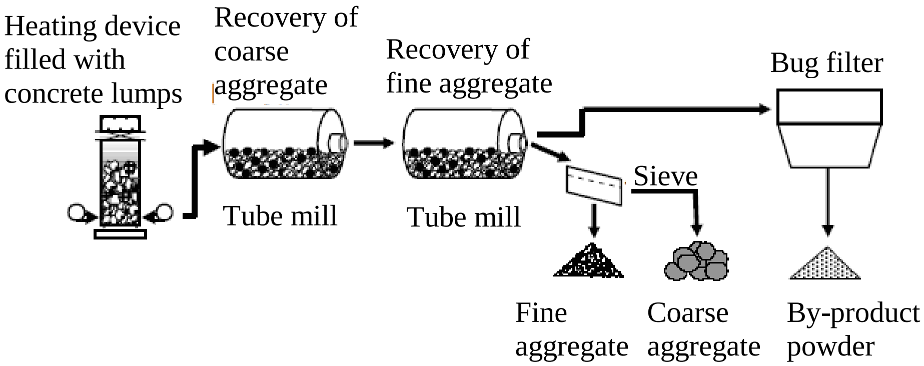

**Fig. 4b. Heated-scrubbing Equipments**

Single toggle-type jaw crushers are generally used for the primary crushing of demolished concrete into pieces 40 to 50mm in size regardless of the ultimate quality of recycled aggregate. While the material is carried to the next process on a belt conveyor, foreign particles such as wood/plastic chips and reinforcing steel/nails are removed manually and with a magnetic separator, respectively. The materials then undergo various treatments according to their uses. Impact crushers are used for secondary and tertiary crushing when producing middle- and low-quality recycled aggregate. While the quality of recycled aggregate produced by using such equipment is improved as the number of treatment processes increases, the recovery percentage of recycled aggregate decreases with increased amounts of powder byproducts as the aggregate itself is crushed. Other equipment in practical use for producing middle- 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 equipment is therefore necessary for efficient production of high-quality recycled aggregate in order to minimize the adhering cement paste. Efficient equipments for producing high-quality recycled aggregate have been developed in recent years and put into practical use. Figure 4 shows representative types.

The first is a technique called mechanical-scrubbing, in which concrete rubbles are scrubbed by one another using an eccentric tubular vertical mill [Yanagibashi 2004] 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 high-quality standard is obtained. On the other hand, the percentage of recovery widely varied depending on the type of original aggregate, and slight difficulty in producing high-quality recycled fine aggregate was found.

Virgin fine aggregate is therefore considered necessary when applying recycled aggregate produced by this method to structural concrete. The use of recycled coarse aggregate produced by this method is not classified as down cycling, as the quality of structural concrete is assured.

The second technology is called heated-scrubbing [Shima et al. 1999], in which concrete rubbles is charged in a heating furnace and subjected to hot air 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 around 300°C. The quality of recycled aggregate attains the high-quality level, while the percentage of recovery is sufficiently high. The qualities of concrete made using this aggregate are virtually the same as the original concrete. Though this technique has acquired certain track records in the construction of actual structures, it requires the availability of infrastructures that economically provide the heat sources necessary for heating. Though the problems of the thermal-energy-induced environmental impact and cost increase currently remain unsolved, this technique assures the quality of structural concrete, avoiding down cycling, 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. Though a significant amount of energy is input at the stage of treatment in the production system, recycled aggregate is produced in a condition usable as parts for the same product or for other products for which the same or higher performance is required. When this condition is ensured, the material is in a condition that can be circulated (i.e. recyclable) in a closed system.

## COMPLETELY RECYCLABLE CONCRETE (CRC)

### Concept of CRC

The time has come when establishment of a new design concept for complete recycling of structural concrete is definitely necessary. The principle of complete recycling is that the concrete is subject 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. If concrete produced with due consideration to the resource conservability at the stage of material design is applied to structures, then the components of the concrete can be completely recycled at the time of demolition. What should be done in the future is to introduce material design that permits complete recycling for at least the components of concrete, 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.

### Cement recovery-type

Cement recovery-type CRC was defined as “concrete whose materials are entirely usable after hardening as materials of cement, since all the binders, additions, and aggregate are made of cement or materials for cement” [Tomosawa and Noguchi 1996]. After the most basic cement recovery-type CRC (e.g., using normal Portland cement, crushed limestone, and crushed limestone sand) was crushed, the obtained sample was subjected to ingredient adjustment to make it the material for cement. This material was subjected to processes including calcination in an electric oven, gypsum addition, and crushing, to produce reprocessed cement. This cement had the same qualities as one available on the market and no problem was observed in fresh and mechanical properties of the concrete made using this cement as shown in Table 3. Blast-furnace 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. Since these contain adequate amounts of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ that are necessary for 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 contributes to the global environment from the standpoint of effective use of industrial by-products as well. Cement recovery-type CRC can formulate a semi-closed-loop circulation material flow as shown in Figure 5. Conversion from conventional concrete to CRC will substantially mitigate the environmental problem of concrete waste generation and $CO_2$ emission during cement production, while permanently preserving and storing the limestone resource in the form of structures.

### Aggregate recovery-type

Aggregate recovery-type CRC was 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 aggregate and the matrix, thereby permitting easy recovery of original aggregate” [Noguchi and Tamura 2001]. It can also form a closed circulating material flow as shown in Figure 6. In order to achieve 100% circulation of concrete in a closed system, a structure is necessary as an aggregate-supplier in addition to one as a cement material 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

**Table 3. Properties of Recycled Cement and Recycled Concrete**

| Recycled cement | Density ($g/cm^3$) | Specific surface area ($cm^2/g$) | Setting time | | Compressive strength at 28days (MPa) |
|---|---|---|---|---|---|
| | | | Initial | Final | |
| | 3.13 | 3,340 | 2h-00m | 2h-50m | 43.0 |
| Recycled concrete | W/C | Compressive strength at 28 days | | Modulus of elasticity at 28 days | |
| | 0.58 | 35.2 MPa | | 39.0 GPa | |

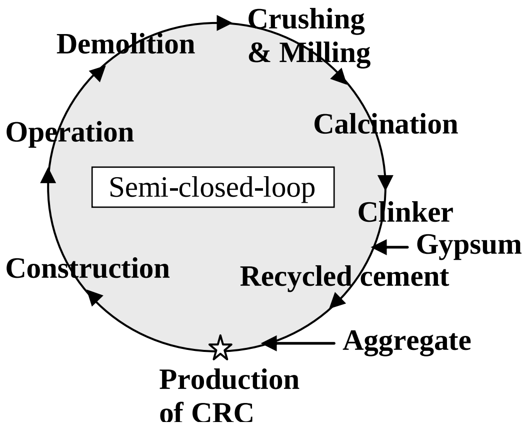

**Fig. 5. Cement Recovery-type CRC**

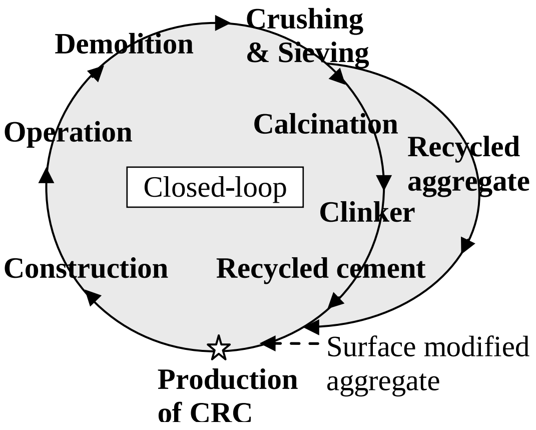

**Fig. 6. Aggregate Recovery-type CRC**

aggregate recovery-type CRC, aggregate surfaces can be modified by two methods: chemical treatment and physical treatment. Chemical treatment is a method in which formation of cement hydrates on the aggregate-paste interfaces is chemically restricted due to the coating by mineral oil coating, whereas physical treatment forms a film of a water-soluble synthetic resin emulsion to smooth the fine irregularities on the interfaces, thereby reducing the mechanical friction. Modification treatment can be carried out simply and economically by either method. Experiments were carried out to investigate the mechanical properties of 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-to-cement ratios, i.e. 40% and 60%. The compressive strength and modulus of elasticity were measured at an age of 28 days. Concrete was crushed in a two-phase process to grasp the recovery ratio and evaluate the quality of 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 charged 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 Figure 7. The effect of chemical treatment was particularly evident. On the other hand, the effect of aggregate surface treatment was less evident in concrete containing round aggregate, particularly in high strength concrete. The surface treatment realizes recovery of high quality recycled aggregate with little adhering paste from demolished concrete by a simple crushing technique. The compressive strength of concrete made with surface modified aggregate decreased regardless of the water-cement ratio as shown in Figure 8. Concrete with angular crushed stone and lower water-to-cement ratio exhibited more decrease in compressive

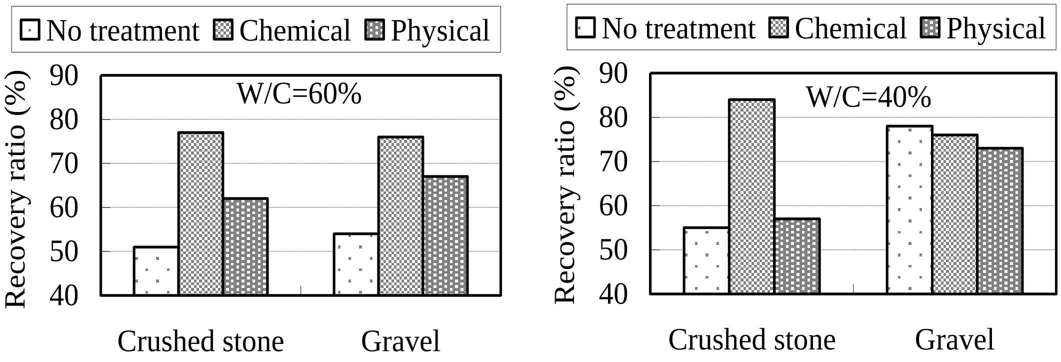

**Fig. 7. Recovery Ratio of Original Aggregate in Aggregate Recovery-Type CRC**

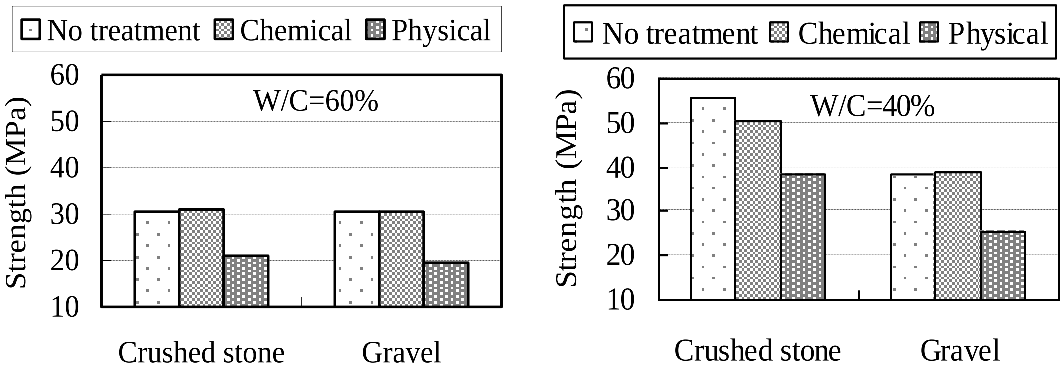

**Fig. 8. Compressive Strength in Aggregate Recovery-type CRC**

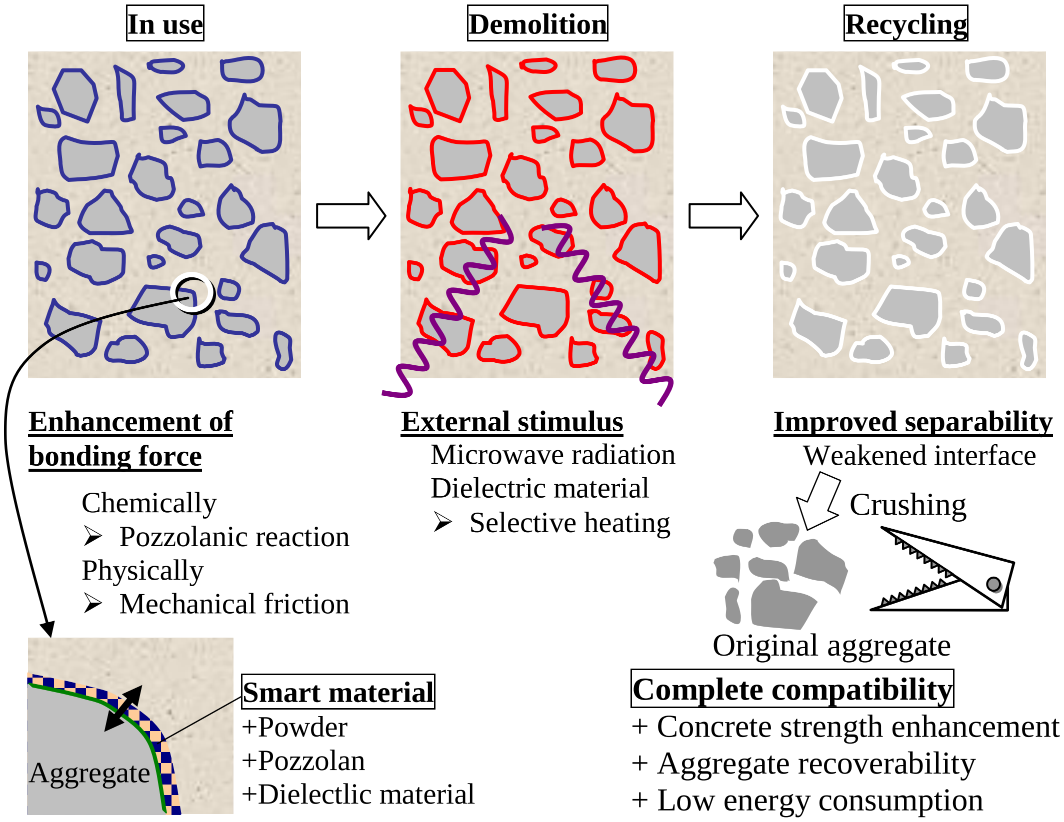

**Fig. 9. Concept of the new technology for aggregate recovery-type CRC**

strength due to higher effect of surface modification than that with round gravel and higher water-to-cement ratio. It 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 concrete and the aggregate recoverability still remained unresolved.

### Advanced aggregate recovery-type

An advanced technology [Tsujino et al. 2008] was developed to ensure compatibility of the performances in a trade-off relationship between mechanical properties of the concrete and aggregate recoverability. The proposed new technology consists of two technologies as shown in Figure 9, i.e. concrete strength enhancement technology and aggregate recovery technology. The former involves, differing from conventional technologies, aggregate surface modification to increase the bonding force between the coarse aggregate and the mortar by coating a binder evenly on the surface of the coarse aggregate. 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 aims at recycling 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 the aggregate and mortar matrix is weakened locally and thus the separability of the aggregate and mortar matrix is improved. Crushed sandstone (surface-dry density: 2.66g/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: 2.35g/cm$^3$, specific surface area: 1,877cm$^2$/g) to the aggregate surface. The mixing ratios of the silica fume and the by-product powder are shown in Table 4. Each powder was applied to the adhesive agent after it was coated on the aggregate and before it hardened. Compressive strengths at the ages of 3, 7 and 28 days and modulus of elasticity at the age of 28 days are shown in Figure 10. Both silica fume and by-product powder are used in the range of silica fume content of 10-20 % such as specimen SP80 and SP90, the strength of the concrete will be increased by 20% or more compared to that of normal aggregate concrete. Assuming that the increase in the strength of the specimen P is only due to the increase in the mechanical friction force, the increase in the chemical bonding force due to pozzolanic reaction served the increase in the strength by 30%. This suggests that the combination of the increase in the mechanical friction force and the increase in the chemical bonding force results in drastic increase in strength of concrete. The modulus of elasticity was however smaller than that of the normal aggregate concrete by 10% due to the formation of the epoxy layer by applying this technology. Considering attenuation of the microwave within the concrete, the concrete was heated for 90 seconds with microwave radiation at the power of 1,800W. The specimens used were those cured for 28 days in water, with a dimension of φ50×100mm. After 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 the specimen O prepared using normal aggregate and the specimen SP80 that showed high strength. The heating conditions are shown in Table 5. For the specimen prepared using normal aggregate, both the

**Table 4. 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 | |

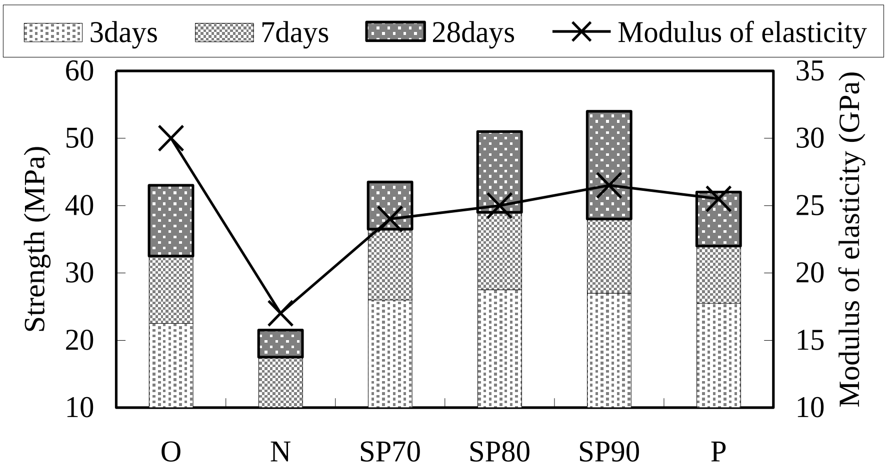

**Fig. 10. Compressive Strength and Modulus of Elasticity in Advanced Aggregate Recovery-type CRC**

**Table 5. Heating Conditions**

| Symbol | Dielectric material | Microwave heating | Electric oven heating |
|---|---|---|---|
| O1 | Not applied | - | |
| O2 | | 2.45GHz, 1800W, 90sec | - |
| O3 | | - | 300℃, 60min |
| SP80 | Applied | 2.45GHz, 1800W, 90sec | - |

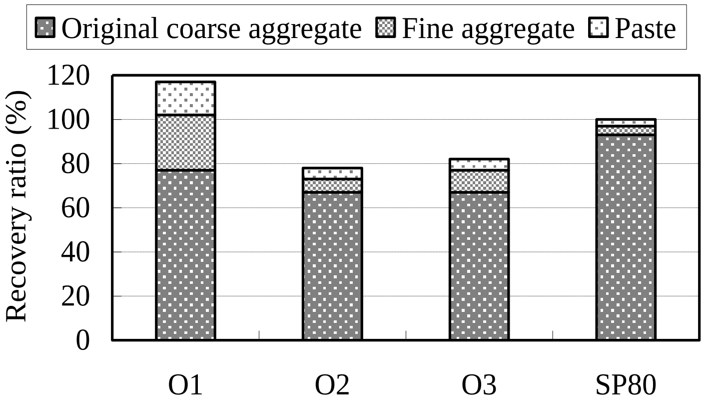

**Fig. 11. Recovery Ratio in Advanced Aggregate Recovery-type CRC**

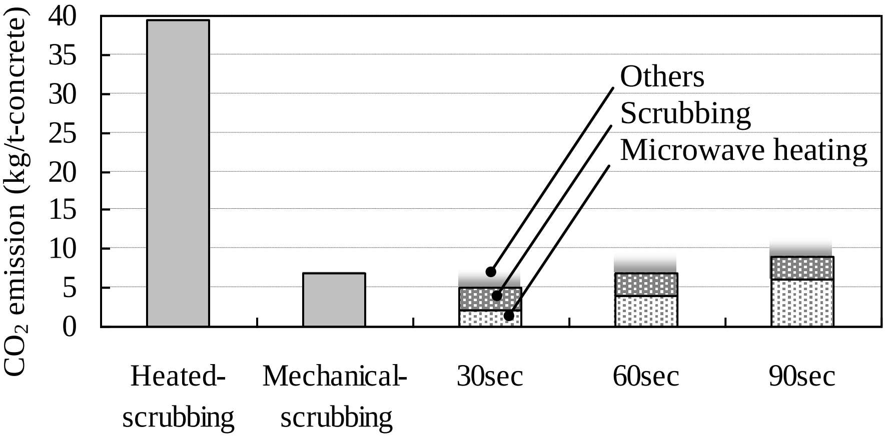

**Fig. 12. $CO_2$ Emission in Concrete Recycling Process**

microwave heating and the conventional electric oven heating were applied. The recovery ratio of the recycled coarse aggregate is shown in Figure 11. The specimen O1 (not heated) contains much cement paste in spite of undergoing rubbing treatment. With respect to the specimen O2 heated by microwave radiation and O3 heated in the electric oven, more cement paste is removed than that without heating, but it is not so much compared to that of specimen undergone heated-scrubbing as reported in the past papers. The aggregate recovery rate of the specimen SP80 heated by microwave radiation was around 93%, indicating small amount of the paste and fine aggregate remained, proved a high quality of the recycled coarse aggregate. The $CO_2$ emission during the treatment of 1 ton of waste concrete mass is shown in Figure 12. The $CO_2$ emitted using the microwave heating is extremely small compared to that from the aggregate production process based on the heated-scrubbing. When compared to the mechanical-scrubbing that could produce moderately high quality aggregate, $CO_2$ emission was almost the same. Considering the extremely high quality of recycled aggregate obtained by the new technology, it seems highly advantageous than conventional ones.

## CONCLUSIONS

In order to recycle concrete in a closed system, it is necessary to solve social systematic problems and review the validity of the currently prevailing method of producing recycled aggregate. Even if all such problems were solved, the eventually desired circulating social system will not be formulated unless technical problems hampering complete recycling in a closed system are solved. 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 structures and products. Completely recyclable concrete is a realistic technique for realizing the formulation of sustainable resource-recycling society. The new technology using the aggregate surface modification and the microwave radiation has overcome the inherent conflicting properties in concrete recycling and achieved the high performance of concrete, the energy saving and small $CO_2$ emission in concrete recycling and the full recovery of recycled aggregate at the same time.

## REFERENCES

Noguchi, T. and Tamura M. (2001). “Concrete design toward complete recycling.” *Structural Concrete*, fib, 2(3), 155-167

Noguchi, T. (2008). “Resource recycling in concrete: Present and future.” *Stock Management for Sustainable Urban Regeneration,* Springer.

Noguchi, T. (2009). “Outline of recommendations for environmentally conscious practice of RC buildings published by AIJ.” *Proceedings of the fib Symposium; Concrete 21st Century Superhero; Building a Sustainable Future,* London, UK.

Sakai, K. (2009). “Towards environmental revolution in concrete technologies.” *Proceedings of the fib Symposium; Concrete 21st Century Superhero; Building a Sustainable Future,* London, UK.

Shima, H., et al. (1999). “New technology for recovering high quality aggregate from demolished concrete.” *Proceedings of the Fifth International Symposium on East Asian Recycling Technology,* Japan.

Tamura, M., et al. (2002). “Life cycle design based on complete recycling of concrete.” *Proceedings of the 1st fib Congress*, Osaka, Japan.

Tomosawa, F. and Noguchi, T. (1996). “Towards completely recyclable concrete.” *Integrated Design and Environmental Issues in Concrete Technology*, E & FN SPON, 263-272

Tomosawa, F., et al. (2005). “The way concrete recycling should be.” *Journal of Advanced Concrete Technology*, JCI, 3(1), 3-16.

Tsujino, M., et al. (2008). “Completely recyclable concrete of aggregate-recovery type by using microwave heating technology.” *Proceedings of the 3rd ACF International Conference,* Ho Chi Minh, Vietnam.

World Business Council for Sustainable Development (WBCSD). (2002). *Toward a Sustainable Cement Industry Substudy 8: Climate Change,* Battelle.

Yanagibashi, K., et al. (2004). “A new recycling process for coarse aggregate to be used for concrete structures.” *Proceedings of RILEM International Symposium on Environment-Conscious Materials and Systems for Sustainable Development*, Koriyama, Japan