Invited paper

The Way Concrete Recycling Should Be

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Abstract

Providing excellent performance as a structural material, concrete has long been deemed essential for modern civilization and recognized as a material that will continue to maintain and support the development of human society. Now that recycling of concrete in a completely closed loop has become technically feasible, concrete is being seen in a new light. This paper reviews the background to this development referring to changes in social systems and the introduction of new technologies. In view of the fact that consideration of the global environment will be required in the future at every step of the production of concrete and concrete structures, this paper goes on to overview the methods for identifying social needs related to concrete structures, the manner in which production systems of structures should meet such social needs, lifecycle design techniques for structures, and techniques for expressing the environmental performance of structures. The authors finally discuss the nature of true recycling and a truly recycling-oriented society, based on the above-mentioned discussions.

1. Introduction

Concrete is a useful cast material that has a close affinity to natural materials, consists of only common components, and hardens by itself just by being in contact with water in a natural environment. After hardening, it turns into a material with sufficient strength and durability to be applicable to various structures. Recent technology for high-strength concrete has realized a compressive strength exceeding 150 N/mm² for reinforced concrete skyscrapers.

Concrete has thus grown to be an essential material for modern society with great commonness, usefulness, and excellent performance characteristics as a structural material, and will continue to be vital for maintaining and developing human society.

However, 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. This issue has existed for a long time, as concrete has conventionally been regarded as being difficult to recycle. Being a major user of concrete, the construction industry has addressed this problem and carried out research and development regarding the recycling of concrete since the 1970s in cooperation with the public sector. However, the uses of recycled products have been limited to road bottoming, without leading to the establishment of a full-fledged recycling system, as the recycling process principally consisted of simply crushing the waste concrete, which inevitably entailed a degradation in quality. Nevertheless, the goal of technical development shifted in the mid-1990s to recycling of concrete into a material having qualities equal to those of normal concrete, and recycling of concrete in a completely closed loop has now become technically feasible.

This paper reviews this development and introduces the new technology while discussing the meaning of true recycling and a truly recycling-oriented society.

2. Current status and problems of construction waste

2.1 Analyses of construction waste

According to a White Paper on the Environment, the total material input of Japan ranged from 2.0 to 2.2 billion tons annually in 1999 and 2000, of which 1.0 to 1.1 billion tons (50%) were accumulated every year in the form of buildings and civil structures. These figures indicate the enormous consumption of resources by the construction industry compared with other industries. The production of concrete, a primary construction material for forming modern nations, amounted to approximately 500 million tons in 2000 in Japan, accounting for nearly 50% of the annual resource consumption of the construction industry. In other words, concrete accounts for nearly 25% of Japan's total material input. Incidentally, the construction industry's consumption of steel and wood, two other primary construction materials, amounted to 32,530,000 and 17,000 tons (34,219 m³ volume, converted by assuming the density to be 0.5), respectively, in 2001, both far less than concrete consumption.

Furthermore, the amount of waste in Japan totaled approximately 458,360,000 tons in 2000 (general waste:
52,360,000 tons; industrial waste: 406,000,000 tons) as shown in Fig. 1 (a). Waste from construction accounted for approximately 20% (79,000,000 tons) of the industrial waste. Moreover, in 2000, construction waste accounted for nearly 30% (12,800,000 tons) of the 45,000,000 tons of industrial waste destined for final disposal sites as shown in Fig. 1 (b) and approximately 60% (241,000 tons) of the 400,000 tons of illegally dumped industrial waste as shown in Fig. 1 (c). As concrete lumps account for approximately 42% (35,000,000 tons) of total construction waste, approximately 8% of total waste in Japan therefore consists of concrete lumps.

As stated above, concrete accounts for large percentages of both resource input and waste discharge. Thus promotion of the recycling of demolished concrete is a pressing social issue in Japan where the remaining capacity of landfill sites for industrial waste is diminishing every year.

2.2 Destinations of demolished concrete

With the aim of solving the construction waste problem, the Japanese Ministry of Land, Infrastructure and Transport (MLIT, formerly the Ministry of Construction) formulated an Action Plan for Construction Byproducts (Recycling Plan 21) 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, which includes principles, objectives, and measures for further promoting recycling of construction waste. Thanks to such active and continual policies, construction waste discharge began to decrease, with the recycling ratio of concrete lumps and asphalt concrete lumps exceeding 95%. In view of the still low recycling ratios of waste wood, slime, and mixed waste generated by construction, the MLIT then enforced the Basic Law for Establishing a Recycling-based Society, the Construction Material Recycling Act, and the Law on Promoting Green Purchasing.

However, concrete lumps, which boast a high recycling ratio, are entirely destined for bottoming and grading adjusters for arterial high-standard highways, urban expressways, and general roads designated by the Road Bureau of the MLIT. The quality of recycling is therefore completely different from that of asphalt concrete lumps, for which level-cycling is accomplished. As shown in Fig. 2, an enormous amount of demolished concrete lumps will be generated in the near future from concrete structures mass-constructed during Japan’s rapid economic growth being, which are doomed to demolition due to durability problems. Moreover, road construction is decreasing and the method of repair is expected to shift from replacing to milling and applying an overlay. These trends will lead to an imbalance between the supply of demolished concrete and the demand for road bottoming. Also, the volumetric reduction of future infrastructures based on population estimation and the extension of the service life of the existing stock by increased succession, utilization, and conversion will keep on reducing the amount of new construction of structures and concrete production. Accordingly, this will culminate in the need to recycle aggregate into aggregate for concrete, and it is no exaggeration to say that recycled aggregate can account for the greatest part of future aggregate for concrete. It is therefore vital to convert recycling from quantity-oriented to quality-oriented recycling as proposed in the Promotion Plan for Construction Waste Recycling 2002 formulated by the MLIT in 2002. In other words, it is necessary to find optimum recycling methods with due consideration to the material balance, while promoting the production and supply of high-quality recycled aggregate.

It should also be noted that a large discrepancy exists between the amount of demolished concrete generated at
Committee of the Building Contractors Society, which conducted by the Construction Waste Disposal Reuse in 1970s, dating back to a three-year study from 1974. Research and development aimed at using demolished concrete as aggregate for concrete will then become even more compelling.

3. Current state and problems of recycled aggregate for concrete

3.1 Quality standard and uses

Research and development aimed at using demolished concrete as recycled aggregate for concrete began in the 1970s, dating back to a three-year study from 1974 conducted by the Construction Waste Disposal Reuse Committee of the Building Contractors Society, which produced the Standard for the Use of Recycled Aggregate and Recycled Concrete (Draft) in 1977. This standard requires that the oven-dry density and water absorption of recycled coarse aggregate be not less than 2.2 g/cm³ and not more than 7%, respectively, and those of recycled fine aggregate be not less than 2.0 g/cm³ and not more than 13%, respectively. This was followed by research and development under two projects promoted by the Ministry of Construction (1981-1985 and 1992-1996), both titled the Comprehensive Technology Development Project, as well as the investigation of recycled concrete for the suspended World City Exhibition in Tokyo (1994), the investigation into authorization criteria by the building Center of Japan (1999), the establishment of a prestandard (TR A0006: Concrete containing recycled aggregate) by the Japan Standards Association, and the organization of the Standardization Committee for Recycled Aggregate in the Japan Concrete Institute (2002), which is tasked with formulating a draft JIS for recycled aggregate for concrete.

Table 1 gives the quality criteria established through the above-mentioned organizational activities, 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 classifies recycled aggregate into three classes -- H, M, and L -- 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.

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Table 1 Quality standard for recycled aggregate and uses for concrete containing recycled aggregate.

<table>
<thead>
<tr>
<th>Year</th>
<th>Formulated by</th>
<th>Name of standard</th>
<th>Coarse aggregate</th>
<th>Fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Ministry of Construction (MOC)</td>
<td>Provisional quality standard for reuse of concrete by use</td>
<td>Type 1</td>
<td>Type 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 or less</td>
<td>5 or less</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12 or less</td>
<td>10 or less</td>
</tr>
<tr>
<td>1999</td>
<td>Building Center of Japan</td>
<td>Accreditation criteria of recycled aggregate for building concrete</td>
<td>2.5 or more</td>
<td>2.5 or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0 or less</td>
<td>3.5 or less</td>
</tr>
<tr>
<td>2000</td>
<td>Ministry of International Trade and Industry (MITI)</td>
<td>JIS TR A0006 (Low quality recycled aggregate concrete)</td>
<td>2.5 or more</td>
<td>2.5 or more</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.0 or less</td>
<td>3.5 or less</td>
</tr>
<tr>
<td>2004</td>
<td>The Committee of standardization for structural recycled aggregate, Japan Concrete Institute</td>
<td>Draft JIS (Type H recycled aggregate (high quality) and its uses)</td>
<td>5.0 or less</td>
<td>7.0 or less</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Draft JIS (Type M recycled aggregate (medium quality) and its uses)</td>
<td>10.0 or less</td>
<td>13 or less</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Draft JIS (Type H recycled aggregate (low quality) and its uses)</td>
<td>13 or less</td>
<td>13 or less</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Backfill concrete, blinding concrete, and leveling concrete</td>
<td>No limitations are put on the type and segment for concrete and structures with a nominal strength of 36 or less</td>
<td>Members not subjected to drying or freezing and thawing action, such as piles slabs on grade, and concrete filled in steel tubes</td>
</tr>
<tr>
<td>JIS A 5005 (Crushed stone and sand for concrete)</td>
<td>2.5 or more</td>
<td>12 or less</td>
<td>10 or less</td>
<td></td>
</tr>
<tr>
<td>JIS A 5308 (Ready mixed concrete)</td>
<td>2.5 or more</td>
<td>12 or less</td>
<td>10 or less</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3 Estimated generation and discharge of concrete lumps from demolished buildings (Takegahara, K. 2002).
3.2 Production methods and equipment

Single toggle-type jaw crushers are generally used for the primary crushing of demolished concrete regardless of the ultimate quality of recycled aggregate. 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. Special equipment is therefore necessary for efficient production of high-quality recycled aggregate. 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.

Equipment in the stage of practical use for the efficient production of high-quality recycled aggregate is shown in Fig. 4 (a)-(d). A heating grinder, shown in Fig. 4 (a), incorporates a mechanism using a tube mill to separate aggregate from cement paste embrittled by heating concrete lumps roughly crushed to 40 to 50 mm in diameter to 300°C. This is the only device capable of also producing fine aggregate for concrete. An eccentric rotor-type mechanical grinder, shown in Fig. 4 (b), has a mechanism whereby concrete lumps charged into a space between the inner cylinder that rotates eccentrically and the outer cylinder are made to scrub one another to remove cement paste adhering to aggregate surfaces. It is capable of producing 60 tons of recycled aggregate per hour. A screw mill, shown in Fig. 4 (c), has a mechanism whereby concrete lumps charged into a cylinder having a twin cone are scrubbed by one another. This process is automatically repeated several times according to the required quality. A wet scrubber/levigator, shown in Fig. 4 (d), incorporates a mechanism whereby concrete lumps crushed in multiple stages using a crushe and wet scrubber are moved up and down in water to separate mortar and wood chips with a low density from coarse aggregate.

3.3 Importance of quality control

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 control, so that contractors and citizens can carry out construction 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 material 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 naturally vary from one lump to another, particularly when the recycled aggregate production plant is located away 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 material control by separately storing concrete lumps from each structure at off-site plants; or (3) carry out quality control.

Fig. 4 Equipment for producing recycled aggregate for structural recycled aggregate concrete.
by substantially increasing the frequency of acceptance inspections and product inspections at off-site plants.

3.4 Future issues
Apart from the above-mentioned quality control, quite a few problems remain unsolved, warranting further investigation of methods of recycling demolished concrete into aggregate for concrete, which will be inevitably required in the future as stated above. These include measures against the alkali-silica reaction and application development for powder byproducts. How to deal with the amount of alkali yielded from cement paste adhering to recycled aggregate is a serious problem for middle- and low-quality recycled aggregate. The alkali content of concrete made using such aggregate will be well over 3 kg/m³, the limit set by the regulation for total alkali content. It is therefore also necessary to review the effect of Type B blended cement in a highly alkaline environment. Since the production of high-quality recycled aggregate entails a large amount of powder byproducts, research and development are necessary for the effective use of such powder. The uses under study include addition to road bottoming, cement material, addition to concrete, ground-improving material, asphalt filler, and inorganic board material, which always compete with other inexpensive natural resources. It is therefore necessary to stabilize the quality of byproduct powder and reduce the quality control cost.

4. Environmental aspect of concrete structure production

4.1 Introduction of environmental aspect for concrete structures
Environmental aspect is defined in ISO 14050 (Environmental management – Vocabulary) as follows:

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“Element of an organization’s (1.4) activities, products or services that can interact with the environment (1.1)”
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*1.1 environment
Surroundings in which an organization (1.4) operates, including air, water, land, natural resources, flora, fauna, humans, and their interrelation

*1.4 organization
Company, corporation, firm, enterprise, authority or institution, or part or combination thereof, whether incorporated or not, public or private, that has its own functions and administration

Figure 5 shows a classification and targets of sustainability considerate of global environmental aspects. According to the above definition, the environment is a concept to be recognized as a factor covering a wide range. As environmental aspects are composed of wider concepts, possible events to be considered can increase in the future. It should be noted that the construction industry, which is responsible for the activities using products made using recycled aggregate and recycled aggregate concrete, is by nature prone to be involved in social and environmental events through industrial activities due to the properties of the materials and the mass circulation systems the industry uses. In other words, extensive social responsibilities may be assigned for the production of finished articles and raw produce. Stakeholders may therefore be required to monitor market expansion while maintaining continuous awareness of the boundaries of environmental aspects. Such practice will ultimately lead to risk management for producing concrete structures.

Meanwhile, an essential concept for considering social
activities deeply related to the environment is sustainable development. The first comprehensive proposal was made in Our Common Future, a report prepared by the World Commission on Environment and Development that was published in 1987, in which the following principles were included.

1. Social equity (social aspect)
2. Environmental prudence (environmental aspect)
3. Economic efficiency (economic aspect)

The environmental aspect is regarded as being composed of a social aspect, environmental aspect, and economical aspect. This suggests that conscious consideration of the social aspect and environmental aspect in addition to the conventional economic aspect will become an important part of production activities. This means that any development may be inappropriate from the viewpoint of sustainability unless it is based on these three principles to ensure sustainable development.

The Sustainability Reporting Guideline in the Global Reporting Initiative (GRI), which is highly regarded for the formulation of environment reports, names three factors of sustainability rating, i.e. economic, environmental, and social aspects, and stresses the need for extracting specific factors and clarifying their mutual relationship.

As stated above, the conventional practice of production falls short in terms of holistic strategy, specifically the application of a manufacturing strategy in consideration of social and environmental aspects in addition to the economic aspect.

4.2 Grounds for identifying social needs for concrete structures
From a broad perspective, even in the era of the global environment, the world as a whole makes its way under the banner of the human-oriented goal of leading a sustainable social life premised on the development of economic activities. It is predicated on the theory that a system for distributing goods produced through economic activities to markets and benefiting from them is necessary for satisfying (or stabilizing) people, in order to achieve an affluent social life in the future. (It has been made clear through past discussions that this cannot be a universal and optimum form of human activity considerate to the global environment.) Systems for such stability and affluence become more complicated and hard to accomplish as the range expands from the level of individuals to organizations, regions, nations, and to the earth[8]. It is now vital to recognize that we are, for better or worse, at the ultimate stage of active worldwide efforts aiming for global stability, including measures against global warming committed to by the Kyoto Protocol. By way of explanation, Fig. 6 shows the order of dependence for the conditions of stability of a global system. This figure does not imply a hierarchical relationship but shows an order of dependence in which the upper factor is realized depending on the support from the lower factor. Stabilization on the individual and organizational levels, for instance, is important for social stabilization in developing countries, whereas in developed countries, where environmental consideration is mandated by ratified treaties, it is necessary to give consideration to stabilization on the regional and global level rather than on the individual and organizational levels.

Stabilization on the global level can be achieved by maintaining the three cycles, i.e., the hydrological cycle, atmospheric cycle, and material cycle, to maintain without damaging it the self-cleaning action of the earth as inferred from the ISO 14000 series. It is self-explanatory that stability on the global level as a superordinate concept is essential for ensuring stable conditions in smaller regions as a subordinate concept on a long-term basis while maintaining equitability between generations.

To put it plainly, an essential condition required of concrete structures for the stabilization of the earth is that a system for assuring the three cycles, i.e., the hydrological, atmospheric, and material cycles, should be inherent in such structures. Focusing on the material cycle, which is closely related to the act of production, the condition is consolidated into a commitment to ensure resource circulation of the structure and its materials beforehand. As recycled aggregate concrete is a factor that strongly affects the material cycle of structures, it is important to extend the radius of influence from individual consumers to organizations/groups and to districts/regions to give develop efficient resource circulation of structures and materials and to capture related needs.

4.3 Factors of social systems composing environmental aspects
The environmental aspects of concrete structures are embodied by focusing on their social and environmental aspects in addition to conventional economic aspects with respect to various types of information (international treaties, laws, rules, policies, and guidelines) that serve as factors for extracting environmental aspects.

Figure 7 shows the order of dependence for environmental aspects in the broad sense of the word. Although this figure classifies the environmental aspects into three factors (needs of individuals/society, formative factors of
social systems, and formative factors of global systems),
this section deals with the formative factors of social
systems that can be used to clearly define environmental
aspects. Note that the global systems at the bottom of the
pyramid consist of the three cycles of the earth and re-
gional factors, but that the environmental aspects may
vary widely depending on the country and area. The
radius of influence of the same environmental aspect can
vary widely depending on the effect of factors on the
regional level. It can therefore be said that the contents
and degrees of the needs of individuals and society based
on such global and social systems can also vary from one
society to another.

The formative factors of social systems are roughly
classified into three categories. The first category con-
sists of legal factors primarily comprising international
charters/treaties, domestic laws (fundamental laws and
normal laws), and local regulations. In a law-abiding
society, the boundaries of acceptable social/economic
activities and industrial activities are defined by these
legal factors.

The second category covers policy factors that are
depently involved in the formation of actual social order.
Policy factors, which form a concept smaller than that
formed by legal factors, comprise national poli-
cies/strategies, and guidelines. Since these factors directly affect the boundaries of
activities, they concretely shape the way society func-
tions.

The third category comprises technical factors for
conducting social activities safely and rationally under
the influence of the legal and policy factors. Technical
factors primarily comprise specifications, methods, and
 techniques, whose contents and spread steer social trends.
Note that information on the needs of individuals and
society can be fed back to design techniques for struc-
tures through technical factors (e.g., architectural design
briefing). These permit investigation in specific terms
into the needs of individuals and society derived from
their inherent desires.

4.4 Formative factors of individual and social
needs
The factors forming the needs of individuals and society
are considered to be the inherent desires of individuals
and organizations. It is therefore desirable to extract
various needs from the inherent desires of individuals
and society to identify the needs for structures, which are
to be ultimately reflected in the essential functions of the
structures. Figure 8 shows the order of dependence of
inherent desires of individuals and society that affect the
essential functions of structures. Inherent desires of indi-
viduals can be objectively grasped by Maslow's theory
of motivation and human needs and the concept of the
need for self-transcendence to change oneself into
something beyond one's present state. Maslow's theory
of motivation and human needs consists of levels of
needs for physical safety and security, social safety and
security, communication and response, self respect and
acceptance, and fulfillment of goals and dreams, in
which the fulfillment of the lower level is essential for
fulfilling the next higher level.

It is not easy to grasp inherent desires of organizations
and society, but the existence of such desires is indubi-

Fig. 7 Order of dependence for environmental aspects in a broad sense.
table. Their needs can be clarified to a certain extent by research. For instance, when an enterprise, a typical social group, is explained as integrating production factors and continuously operating a business with the aim of production and profit making, or the subject of such activities, the fundamental desire of enterprises corresponding to the needs on the bottom level as defined by Maslow (physical needs of enterprises) may be the desire to conduct a business operation that is economically viable and does not cease to produce profits, and this is considered to be an essential desire of enterprises. Enterprises are therefore understood as groups that seek for their identities driven by the bottom needs defined by Maslow (physiological needs of enterprises). In this case, the likelihood that their activities will fulfill the desires of the upper levels is considered very low. This explains the difference between individuals and organizations from the aspect of needs.

A large number of firms recently carry out their industrial activities while promoting environment protection. These can be recognized as activities for fulfilling the desire for self-respect and acceptance, which complements the physiological desire of enterprises. On the other hand, the activities of environmental nonprofit organizations can be recognized as activities for fulfilling their desire for self-transcendence placing top priority on the global environment. Although the desires of organizations and societies differ from the order of dependence of individual desires as explained above, organizational activities are important, as they produce large-scale and immediate effects on actual activities for solving environmental problems.

The production of structures generally has a strong impact on society. Moreover, interests in structures include individuals as well as their relationships with society. It is therefore important to simultaneously extract the needs of individuals and society and fulfill them in the form of essential functions of structures.

5. Lifecycle design techniques for concrete structures

5.1 Future production systems

This section objectively discusses the production system for existing concrete structures. A conventional manufacturing system can be regarded as a system focusing on cost saving and efficiency without consideration of ease of disassembly of the products and component materials, based on which most existing concrete structures have been produced. Since the technology for recycling the products of such a system is inevitably required to treat used products not intended for recycling at the design stage, recycling can be regarded as an alternative for waste disposal. This is a typical end-of-pipe approach leading to down-cycling, but is still essential, as the enormous stock of existing concrete structures will somehow demand treatment of concrete lumps in the future. If, recycled products happen to be in great demand with a low level of performance requirements, down-cycling can be an effective solution for a certain period until such demand disappears. Road bottoming can be regarded positively as an instance of such a solution. Despite continuous research and development since the early 1970s, structural recycled aggregate has not been actively used. This is presumably due to the absence of application development based on social needs for the product or technological development in view of equitability between generations.

In consideration of the problems inherent in the conventional end-of-pipe approach, a new solution should be an integrated inverse manufacturing system defined as a manufacturing system in which downstream processes are consistent with upstream processes for the purpose of ensuring resource circulation using component materials that can be assembled and disassembled by similar work loads. This system is characterized by ease of disassembly as well as assembly incorporated at the design stage. Figure 9 shows a model concept of integrated inverse
manufacturing. A characteristic of construction products distinctive from those in other industrial segments is that their overall performance can be brought into full perspective by substituting the quality of the members and component materials for physical performance and the quality of human work and deeds for metaphysical performance.

In view of this characteristic, the application of the concept of minimizing the number of separate processes in the design method by aiming for ease of assembly/disassembly to concrete structures is attempted in this section. This design method includes common processes whereby the ease of disassembly is proportional to the ease of assembly, with easy-disassembly design leading to easy-assembly design, and counter-processes whereby the ease of disassembly is inversely proportional to the ease of assembly, with easy-disassembly design making assembly difficult. Minimization of counter-processes is a design technique whereby the effects of the latter design factors are minimized to derive a rational disassembly-assembly performance. Assuming that various metaphysical performances are included as information among the material performances as the structure that is the ultimate result, (a) the disassembly performance is not included in the metaphysical performance as the structure that is the ultimate result, (b) the ease of disassembly is not considered in the metaphysical performance as the structure that is the ultimate result, and (c) a forward-process manufacturing system with an added inverse process is derived while achieving long service life for structures and component material conservation. It is therefore necessary to clarify the essential functions the structures possess.

Table 2 gives the relationship between the essential functions of the components and the individual design factors for reinforced concrete buildings. Figure 10 shows the order of dependence of lifecycle design composed of individual design factors. From the bottom up, the order of dependence of building components consists of raw materials, materials, member elements, members, and buildings. Focusing on the elements of structures, eight functions ((1) to (8)) are derived as essential functions, as well as four individual design factors (A to D) to introduce the functions to structures. In other words, the essential functions of buildings and member elements lead to reducing design under items (1) and (2); the essential functions of buildings, members, and member elements lead to maintenance design under items (3) and (4); the essential functions of member elements and materials lead to reuse design under items (5) and (6); and the essential functions of materials and raw materials lead to recycling design under items (7) and (8) (see Table 2). The four individual design elements permit the composition of a lifecycle design hierarchy in consideration of the resource values of the materials.

5.2 Inherent needs of structures

Generally speaking, if a structure can retain the required performance throughout its lifecycle, then it can be used semi-permanently without losing its value. In the lifecycle design technique taking into consideration the resource values of materials to be discussed in this section, an integrated inverse manufacturing system should be derived while achieving long service life for structures and component material conservation. It is therefore necessary to clarify the essential functions the structures possess.

Accordingly, the resource recycling through concrete structures based on integrated inverse manufacturing suggests the possibility that concrete can be efficiently recycled, inspiring hope for the closed-loop recycling of concrete structures.
Long life (Skeleton)

Table 2 Essential functions of components of structures and individual design factors derived from the functions.

<table>
<thead>
<tr>
<th>Building elements</th>
<th>Fundamental functions of building elements</th>
<th>Design contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural frame</td>
<td>Long life, stable and durable against earthquakes (1. Long life) Use of suitable amount of natural resources in construction (2. Resource saving)</td>
<td>Reduce</td>
</tr>
<tr>
<td>Structural frame, Beams and Columns</td>
<td>Maintain quality toward required performances (3. Maintain quality) Easily changed into a high grade level at replacement (4. Upgrade)</td>
<td>Maintenance</td>
</tr>
<tr>
<td>Beams, Columns and Concrete</td>
<td>Reusable as member with no degraded quality (5. Level-cycle reuse) Reusable as member with degraded quality (6. Down-cycle reuse)</td>
<td>Reuse</td>
</tr>
<tr>
<td>Concrete and Construction materials</td>
<td>Recyclable as material with no degraded quality (7. Level-cycle recycle) Recyclable as material with degraded quality (8. Down-cycle recycle)</td>
<td>Recycle</td>
</tr>
</tbody>
</table>

Fig. 10 Order of dependence of lifecycle design composed of individual design factors.

5.3 Lifecycle design technique

Table 3 gives the properties of structures derived from lifecycle design. Component details and reuse techniques after renewal can be clarified to a certain extent by determining the eight design objectives representing the essential functions in the physical performance hierarchy and establishing the basic components to be designed. Figure 11 shows the relationship between design objectives representing the essential functions of structures. This schematically expresses the eight design objectives included in the four individual design elements while incorporating the side factors of the essential functions (resource wasting, disposal, etc.). This scheme serves as the basic factors for indexing the degree of satisfaction of the essential functions of structures while permitting the assumption of appropriate methods of renewal and disposal of the structures and their components. For instance, when a structure is produced with the design objective of level-cycling (D7), materials that permit recycling into structural concrete at the time of renewal are selected, and methods of demolition and disposal with low work loads are selected and carried out.

The lifecycle design taking into consideration the resource values of materials thus succeeds in realizing a mechanism to incorporate the essential functions derived from the environmental aspect the structure is involved with. As a result, the lifecycle design technique inherently incorporates the concept of recycling, which is the so-called inverse manufacturing and which characterizes the technique and distinguishes it from existing manufacturing. In other words, this technique can be recognized as a factor of recycling design strategy aiming for the introduction of recycling technology to accelerate resource cycling within closed systems.

5.4 Examples of lifecycle design

Application examples of the lifecycle design technique are described in this section. The following two social needs derived from the environmental aspects closely related to current concrete structures in Japan are extracted: 1) the durable use of structural framing premised on resource conservation to address the issues of resource depletion and the global environment; and 2) active recycling into structural concrete when the demand for road bottoming disappears, in view of the diminishing capacities of final disposal sites. Let us now try to find the essential functions of structures to meet...
these needs and carry out lifecycle design giving priority to these functions as the design objectives. The design procedure begins with the specification of the design level determined from the combination of the individual design factor and the design objective, through selection from the combination matrix. Select A1: Service life extension of the structure in reducing design and B3: Performance retention of the structure components in maintenance design to satisfy the first requirement, and select D7: Level-cycling of concrete materials in recycling design to satisfy the second requirement. Select D8: Down-cycling of concrete materials in recycling design and Final disposal result as secondary factors of essential functions. Therefore, four design levels were finally specified including these two.

This permits the estimation of the recycling conditions and product properties (see Table 4).

At Level 1, resource-conserving and life-extending design, which permits the use of recycled materials with no limitations as to applications is applied and a renewal design aimed at recycling as given in Table 5 is a prerequisite for retaining the resource value of the materials in consideration of equitability between generations.

Cement recovery type completely recyclable concrete was applied for the first time to an actual structure in 2000 (Fig. 12). The target structure consisted of the foundations of a residential building constructed as part of the project for completely recyclable houses mainly promoted by Ojima Laboratory at Waseda University. Due to the strong need to promote structures that reduce environmental impact by reducing waste, completely recyclable concrete is considered to be an essential material for such structures.

Table 3 Properties of structures derived from lifecycle design.

<table>
<thead>
<tr>
<th>Order of dependence of building</th>
<th>Design contents of lifecycle design</th>
<th>Design aims for developing design contents</th>
<th>Building elements</th>
<th>Example of building elements</th>
<th>Utilization after replacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>A Reduce design</td>
<td>1. Long life</td>
<td>Structural frame</td>
<td>Reinforced concrete beams, Column and wall etc.</td>
<td>Same as the left</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Resource saving</td>
<td>Structural infill</td>
<td>Dynamic core, Air conditioning unit, Electronic units, Water supply unit</td>
<td>Same as the left</td>
</tr>
<tr>
<td>Flame</td>
<td>B Maintenance design</td>
<td>3. Maintenance quality</td>
<td>Composite units for structural frame</td>
<td>Concrete Unit, Non-structural wall, Sub-member, Concrete club, etc.</td>
<td>Same as the left</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Upgrade</td>
<td>Composite units for structural infill</td>
<td>Part of water supply unit</td>
<td>Same as the left</td>
</tr>
<tr>
<td>Unit</td>
<td>C Reuse design</td>
<td>5. Level-cycle reuse</td>
<td>Beams and column of concrete</td>
<td>Concrete Unit, Non-structural wall, Sub-member, Concrete club, etc.</td>
<td>Reinforced concrete column and beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6. Down-cycle reuse</td>
<td></td>
<td></td>
<td>Non-structural wall, Sub-member</td>
</tr>
<tr>
<td>Material</td>
<td>D Recycle design</td>
<td>7. Revolve-cycle recycling</td>
<td>Concrete constituting materials</td>
<td>Coarse aggregate, Fine aggregate, Cementitious materials, etc.</td>
<td>Original aggregate Cementitious materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8. Down-cycle recycling</td>
<td></td>
<td></td>
<td>Low quality recycled aggregate, Additives</td>
</tr>
</tbody>
</table>

Table 4 Classifications of design levels and concrete types by life cycle design.

<table>
<thead>
<tr>
<th>Design level</th>
<th>Reduce design</th>
<th>Maintenance design</th>
<th>Recycle design</th>
<th>Conditions of recycling</th>
<th>Properties of products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long-life A1</td>
<td>Maintain quality B3</td>
<td>Level cycle D7</td>
<td>Down cycle D8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Property of</td>
<td>Property of crushing</td>
<td>Type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>original material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 1</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Level 2</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Level 3</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Level 4</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>
5.5 Evaluation of the fulfillment of lifecycle design requirements

In order to retain the essential functions of structures for a long time, an index is necessary at least for the user and purchaser of the structure, with which the design objectives representing the essential functions can be recognized. A system of performance evaluation/indication is therefore important. Recent proposals include BEES for evaluating the degree of environmental impact throughout the entire lifecycle of materials by NIST and CASBEE, a comprehensive environmental evaluation system incorporating the effects of environmental load factors other than physical performance of buildings.

Figure 13 shows a stereoscopic index expressing the degree of inclusion of the design objectives in the individual design factors. These are configured by the superposition of individual design factors, serving as an index to the degree of inclusion of the design objectives, as well as a simple tool for expressing the essential functions of structures.

Figure 14 shows four typical forms of mass hierarchy of design levels in the implementation models by the lifecycle design technique described in the previous section. As the degree of inclusion of the essential functions in the design objectives increases, the occupied area generally increases, resulting in increases in the volume ratio of the colored portion of the stereoscopic index. The form of Level 1, which shows an ideal structure, is conical, representing a structure designed taking into consideration the environment and equitability between generations while achieving structural safety. This can be recognized as an index for a stable condition. Conversely, (d) the form of Level 4 is poorly balanced, giving an impression of instability.

6. Toward a veritable recycle-oriented society

As stated above, conventional concrete recycling through low-quality recycled aggregate has yet to be marketable, whereas recycled aggregate having qualities equal to normal aggregate can be used for general structural concrete, though with drawbacks related to the cost.

Promotion of recycling is essential for establishing a recycling-oriented society. However, it is difficult for low-quality products to achieve marketability simply because they are recycled, as illustrated by this example.

The authors consider that recycling technology should fulfill the following principles.

1. Recycling should be of high quality.
2. Recycling should be repeatable.

The former means that recycled products are not marketable unless they are of a quality that satisfies users, and recycling is not a viable proposition in spite of the accurate description as a "recycled product." Low quality of recycled products should be considered to indicate the immaturity of the recycling technology and the need for technology improvement or new technology development to achieve quality recycled products.

The latter means that, if a recycled product has to be dumped in a landfill after use with no chance of recycling, then the recycling is no better than producing waste of the following generation, contradicting the formulation of a recycling-oriented society. Such a product also burdens the purchaser with the responsibility of waste disposal. Potential purchasers will hesitate to purchase the product the moment they realize this pitfall, preventing the recycling loop from closing (Old Maid rule).

Accordingly, to be repeatable, recycling must aim for the reproduction of the same product in the original sense of the word to form a loop.
Care should be exercised regarding so-called cascade recycling, mixed/compound recycling, recycling into other industries, and byproduct utilization, as these tend to be unrepeatable. When a product utilizing a byproduct is repeatedly recycled, the byproduct as a material will become useless, ending up as waste. What is a truly recycling-oriented society? Humans live on a cycle of resource use in which they take various resources from nature into their society, obtain benefits from them for a given period by processing and using them, and return them back to nature as waste when their cease to be useful. Once taken into human society, the resources are altered or modified and by the time they are returned to nature for final disposal, their state has changed to a certain extent. Just one or two recycling phases represent a short stay of resources in human society, which ends up with disposal (return) to nature. True recycling should eliminate such return of resources to nature. Unrepeatable recycling merely extends their stay on the human side without contributing to the basis for a truly recycling-oriented society. The only acceptable case for this type of cycle is the use of resources in such a way that the product returned to nature does not represent an environmental load.

A recycling-oriented society in the true sense of the word is a society that continues to use resources, once they are taken from nature into the society, without returning them unless they do not represent an environmental load. In such a society, the intake of resources from nature is minimized and products and materials that cannot be recycled repeatedly are rejected. While this vision may be overly idealistic, it should be kept in mind when evaluating and developing recycling technology.

7. Concluding remarks

Recycling technology for concrete has significantly developed in recent years, making the material sufficiently recyclable. Though problems remain regarding the cost, distribution, and system, the prospect appears to be favorable.

Through many years of research and development of concrete recycling and investigation of the difficulties and problems of recycling practice, the authors learned that the two principles above-mentioned are vital for recycling to be a viable proposition. This approach to recycling has long been practiced for electric steel, aluminum, and paper and has been adopted for various types of products including PET bottles recycled into PET bottles, and the reuse and recycling of materials for automobiles and electrical appliances. Efforts for closed-loop recycling have also begun in the fields of glass, gypsum board, and other construction materials. This trend will eventually prevail in all fields in the future, leading to a society in which materials recyclable in closed loops or disposable in a nature-friendly form banish those that are not, as illustrated by chlorofluorocarbons, which are being driven out of the market.

In this sense, the greatest challenge for mankind is the formulation of a recycling system for carbon dioxide gas and other greenhouse gases, which account for the vast majority of waste on earth.
References


