Development of a sustainable concrete waste recycling system: Application of recycled aggregate concrete produced by aggregate replacing method

Y. Dosho
Construction Department, Tokyo Electric Power Company (TEPCO), Tokyo, Japan

ABSTRACT: The generation of huge amounts of construction waste is anticipated due to the demolition of older structures such as power stations built more than 30 years ago. On the other hand, the reuse of construction waste is highly essential from the viewpoint of Life Cycle Assessment (LCA) and effective recycling of construction resources. In order to promote the reuse of construction waste, it is necessary to achieve three basic concepts: (1) assurance of safety and quality, (2) decrease of environmental impact, and (3) increase of cost effectiveness of construction. This paper outlines the development of a recycling system, application of recycled aggregate concrete produced by the aggregate replacing method, which is effective in reducing both cost and environmental impact from the viewpoint of LCA for concrete waste generated by the demolition of large-scale buildings such as powerhouses.

1 INTRODUCTION

1.1 *Background*

According to an investigation conducted in 2002 by the Ministry of Land, Infrastructure and Transport (hereinafter referred to as MLIT), the amount of construction waste produced in Japan is approximately 83 million tons per year, most of which is recycled in compliance with related laws and ordinances. Of the total construction waste, concrete waste accounts for approximately 35 million tons per year. Although the recycling rate of concrete waste has reached 98%, most of it is used for roadbed gravel.

Tokyo Electric Power Company (TEPCO) currently owns about 5,800 buildings (as of 2004) excluding 700 nuclear power facilities. These buildings include thermal power plant powerhouses, substations, head and branch office buildings, etc.

Figure 1 shows the breakdown and amount of construction waste that will be produced when these 5,800 buildings are demolished. The total predicted amount of construction waste is about 7.8 million tons of which 7.6 million is concrete waste. If the total amount of construction waste is treated through dumping in public/private disposal facilities, the amount of CO_2 emissions is predicted to be about 0.67 million tons. Moreover, thermal power plants, particularly those built in the 1970s, will be replaced by a new type of thermal power plant in the near future and a huge amount of concrete waste will be produced within a short-term construction period.

In view of this situation, establishing an effective recycling method for concrete waste is highly anticipated from the standpoint of resource circulation and environmental preservation.

1.2 *Present condition of concrete waste*

Although concrete waste is presently used almost entirely for roadbed gravel, the demand for roadbed gravel is not expected to increase, largely due to a decrease in new road construction. Meanwhile, toxic substances such as hexavalent-chromium and lead are present in the concrete waste since they are originally contained in cements. Taking soil contamination into consideration, it is necessary to develop other uses apart from roadbed gravel. The most promising alternatives are recycled aggregate and recycled aggregate concrete.

TEPCO has been conducting research on the application of recycled aggregate concrete to buildings since 1993. They have subsequently applied it to their new buildings with the approval of MLIT obtained in January 2002 and September 2004.

2 APPLICATION OF RECYCLED AGGREGATE AND RECYCLED AGGREGATE CONCRETE

2.1 *Concept*

When recycled aggregate concrete is applied to buildings, etc., the quality required is generally the equivalent to natural aggregate such as gravel and sand. However, in the case of manufacturing such recycled aggregate, the manufacturing cost and amount of CO_2 emissions is likely to rise sharply, consequently limiting the extent to which recycled aggregate concrete is used. As shown in Figure 2, in order to promote the application of recycled aggregate concrete, it is necessary to secure a suitable balance between 1) safety and quality, 2) cost-effectiveness, and 3) environmental impact.

2.2 *Transition of techniques used for recycled aggregate concrete*

Concrete waste was mainly reused as a substitute for aggregate resources or cement during revival from a catastrophe or war. According to Buck [1977], there are several research papers on recycled aggregate concrete immediately after World War II: physical properties (strength, etc.) by Glruzhge in 1946, Russia, and the influence of mixture impurities (gypsum) by Graf in 1948, Germany.

Research on recycled aggregate concrete in Japan started with the Building Contractors Society (BCS project) and the Ministry of Construction (first project) with the key theme "A Cure for Resource Depletion" after the 1973 oil crisis. The Synthesis Technical Development Project (second project) of the Ministry of Construction started in 1992 and was carried out for the purpose of preparing a more practical basis for recycled aggregate concrete.

Based on the results, JASS 5 of 2003 prescribed that recycled aggregate may be treated as natural aggregate if it fulfills the quality equivalent to gravel and sand. Furthermore, the Japanese Industrial Standard (JIS A 5021) for recycled aggregate for concrete-class H "high-quality recycled aggregate" was enacted in March 2005, and JIS A 5023 for recycled concrete using recycled aggregate Class L "low-quality recycled aggregate" was enacted in March 2006. Moreover, the establishment work about JIS of recycled concrete using recycled aggregate Class M "middle-quality recycled aggregate" is carrying out now.

Thus, the maintenance of specifications related to applying recycled aggregate to structural concrete aggregate has been progressing.

2.3 *Results of approval by MLIT*

Table 1 shows the actual results of acquiring MLIT approval for the application of recycled aggregate concrete by TEPCO.

According to MLIT, there are 22 approvals for recycled aggregate concrete during May 2001 to September 2005. Except two MLIT approvals in Table 1, all of 20 approvals of recycled aggregate are based on the production methods of removing the original mortar contained in the recycled aggregate during the refinement stage (aggregate refining method) [Dosho 2005; Kawai et al. 2006; Shintani et al. 2006].

On the other hand, TEPCO obtained the approval of MLIT for a method that reduces the influence of the original mortar and produces concrete with the required performance capability by mixing natural aggregate and recycled aggregate at the concrete manufacturing stage (aggregate replacing method).

Based on the approval of MLIT, the recycled coarse aggregate concrete was applied to two buildings. One is the Biotope Soga symbiosis building (Project No. 1) installed in the Chiba Heating Power area. The application of recycled coarse aggregate concrete to Project No. 1 was approved by MLIT in January 2002, and construction (concrete placing) started in June 2002.

The other is the waste incinerator building (Project No. 2) installed in the Yokohama Thermal Power Plant premises. The application of recycled coarse aggregate concrete to Project No. 2 was approved by MLIT in September 2004, and construction started in May 2005. The application situation for these two projects is shown in Figure 3.

3 RECYCLED AGGREGATE CONCRETE BY AGGREGATE REPLACING METHOD

The appearance of recycled aggregate is shown in Figure 4. Recycled aggregate consists of original aggregate and original mortar.

Recycled aggregate using the aggregate refining method is manufactured for the purpose of acquiring equivalent quality to natural aggregate such as gravel and/or sand, and being used as a substitute. However, in order to manufacture such recycled aggregate removing the original mortar, an advanced processing technique using special facilities is needed. The aggregate refining method in Japan mainly comprises four methods, "Heated Scrubbing (heating and rubbing)", "Mechanical Scrubbing- 1 (eccentric tubular type)", "Mechanical Scrubbing- 2 (screw type)" and "Wet Scrubbing and Gravity Classification" [Noguchi 2005]. High-quality recycled aggregate satisfying the requirements of JIS A 5021 can be manufactured with these methods.

For example, heating and rubbing that can produce high-quality recycled aggregate best among aggregate refining methods consists of recycled coarse aggregate of about 35% and recycled fine aggregate of about 21% for the entire concrete waste [Kuroda et al. 2003; Kuroda & Hashida 2005]. The remaining 44% is fine powder contains a large amount of original mortar. Although several recycling applications for the fine powder to cement materials is reported, a wide dissemination is believed to be difficult under the present condition because there are problems with quality control such as establishment of preparedness at cement plants and the cost-effectiveness on its execution [Kuroda et al. 2003]. Therefore, more advanced processing techniques and facilities are needed for the reuse of the fine powder to be applied other than to concrete-related materials hence the cost and/or environmental impact may increase accordingly. For this reason, the aggregate replacing method, which does not remove the original mortar, becomes effective.

The standard plan for the aggregate replacing method was created by the Ministry of Construction (first project). However, examples of actual application to buildings or structures did not exist due to the absence of a suitable quality assessment index.

TEPCO confirmed the validity of the aggregate replacing method through a feasibility study [Dosho et al. 1998a], basic experiment [Dosho et al. 1998b; Kikuchi et al. 1998], and actual machine manufacturing experiment [Teranishi et al. 1998]. As a result, a quality assessment index has been established and application of recycled aggregate concrete has been made possible.

3.1 *Recycling system*

Figure 5 shows an outline of the recycling system developed by TEPCO.

The advantages of this system are that the manufacturing process is simple and recycled coarse aggregate can be manufactured using general-purpose facilities including mobile ones. The manufacturing situation (test case) of an actual recycled aggregate is shown in Figure 6.

Using this method, 55–73% of the entire concrete waste can be used as recycled coarse aggregate for structural concrete. The remaining 27–45% can also be used as recycled fine aggregate for the manufacturing of precast concrete products. In addition, since the recycled fine aggregate contains a large amount of original mortar that remarkably deteriorates the quality of concrete, a wet grinding treatment process is added for improved quality.

3.2 *Simulation of cost-effectiveness and evaluation of environmental impact*

In the simulation, it is assumed that the recycled coarse aggregate is manufactured at the construction site using a mobile-type facility such as Figure 6.

Recycled coarse aggregate concrete having a 30–50% replacement ratio is assumed to be applied to new building construction. The recycled fine aggregate is assumed to be treated by the wet grinding method at a factory outside the construction site and applied to the manufacturing of precast concrete products such as boundary block or RC box culvert for market delivery.

Figure 7 shows the simulation results in the case of a thermal power plant (power-generation output: 350,000-kW class).The results indicate that the recycling system shown in Figure 5, using the replacing method, can reduce costs (LCC) by about 34-41% and CO_2 emissions ($LCCO_2$) by about 23-28% for dumping in public/private disposal facilities.

3.3 *Appraisal method for recycled aggregate concrete*

The value of relative quality is an index used for assessing aggregate quality and is given by Eq. (1).
A clear correlation is admitted between the value of relative quality and the main properties of recycled aggregate concrete (compressive strength, Young's modulus, drying shrinkage, accelerated carbonation depth). Therefore, in the case of recycled aggregate concrete to be produced by the aggregate replacing method, the concrete mix design can be made using this index so as to comply with the required quality.

$$QCt = \frac{QCvG \times a + QCvS \times b + QCrG \times c + QCrS \times d}{a + b + c + d} \quad (1)$$

where
QCt (%): Relative absorption rate;

QCvG (%): Absorption rate of natural coarse aggregates (river gravel, pit gravel, crushed stone, etc.) in recycled aggregate concrete;
QCvS (%): Absorption rate of natural fine aggregates (river sand, pit sand, crushed sand, etc.) in recycled aggregate concrete;
QCrG (%): Absorption rate of recycled coarse aggregate in recycled aggregate concrete;
QCrS (%): Absorption rate of recycled fine aggregate in recycled aggregate concrete;
a, b, c, d (L/m^3): Absolute volume of natural coarse aggregate, natural fine aggregate, recycled coarse aggregate, and recycled fine aggregate, respectively.

3.4 *Use of recycled coarse aggregate concrete*

Table 2 lists the specifications for recycled coarse aggregate concrete (Project No. 1: Fc = 24 N/mm^2, Project No. 2: Fc = 21–33 N/mm^2) approved by MLIT in the aggregate replacing method at TEPCO.

The specified slump is 15 and 18 cm and the replacement ratio, which is the volume ratio to be replaced by recycled coarse aggregate, is 30 and 50%.

In addition to ordinary Portland cement, low-heat Portland cement (Fc = 21–27 N/mm^2), which can be used for mass concrete, is also included in the approval.

3.4.1 *Quality*

In using the aggregate replacing method, the quality required as structural concrete can be secured by mix proportion design (material design) in accordance with the appropriate index such as relative absorption rate, replacement ratio, etc. The replacement ratio can be determined by the relative quality value method.

Figure 8 shows the correlation between the relative absorption rate and the main properties of recycled aggregate concrete (compressive strength, drying shrinkage, accelerated carbonation depth).

3.4.2 *Determination of replacement ratio*

In the case of Project No. 2 (N-type cement), the relative absorption rate corresponding to the threshold value (in this case, 800 μm drying shrinkage) of demanded quality is estimated at 2.93% (Figure 8). Therefore, the upper limit of the average strength required (mF) in the same strength range (W/C) of recycled coarse aggregate concrete decided with a relative absorption rate of 2.93% satisfies the required qualities, such as in terms of drying shrinkage and accelerated carbonation depth.

Moreover, when a recycled coarse aggregate concrete is used in a cold district, etc., in principle the quality must be confirmed by conducting freezing and thawing examination.

3.4.3 *Material design*

According to the author's studies [Dosho et al. 2005, 2006a], the cement-water ratio corresponding to the qualities required for building concrete can be determined by regression analysis. Furthermore, it is necessary to examine the difference in compressive strengths of concretes manufactured in actual plant and laboratory.

Figure 9 shows the relationship between compressive strength and cement-water ratio for an actual plant and laboratory. In the figure, the compressive strength of an actual plant is about 90% of laboratory. That is, the estimated value (σ) of compressive strength of an actual plant falls on the safe side, decreasing by 10% from the value of laboratory. Figure 10 shows the presumed cement-water ratio that satisfies nominal strength under both a 30% replacement ratio and 1.90% relative absorption rate in accordance with compressive strength under the replacement ratios of 0 and 50%. Since the difference in water-cement ratio between the estimated values assuming an actual plant and the tested values is very small and on the safe side, the strength estimated using the relative absorption rate is considered to be valid and it is possible to determine the water-cement ratio at any replacement ratio. This result shows that it is necessary to determine the cement-water ratio based on the required compressive strength.

3.4.4 *Quality control*

The flow of quality control from investigation of the original concrete to application of the recycled coarse aggregate concrete is shown in Figure 11.

Quality control is carried out according to the construction specifications and manufacturing guidelines for recycled coarse aggregate concrete.

Quality control covers the three respective processes for the material: (a) original concrete, (b) recycled coarse aggregate, and (c) recycled coarse aggregate concrete. As a result of examination, any material that does not adapt the quality requirements of the construction specifications and/or manufacturing guidelines at any of the three processes is restricted from use.

3.4.5 *Original concrete*

As shown in Table 3, the main quality control items for original concrete consist of alkali-silica reaction, chloride ion content, and compressive strength (core). If the necessary data is available, such as from construction records, and the data indicates the production district and quality of aggregate, and the design strength of the original concrete, etc., it is possible to reduce the examination frequency.

When there are no construction records, investigation is conducted for one unit to 500m^3 of original concrete used. On the other hand, when there are construction records, investigation is conducted for one unit to 1000m^3. For example, in the case of Project No. 2, investigation was conducted for one unit to 500m^3 due to the absence of construction records.

3.4.6 *Recycled coarse aggregate*

The main quality control items for recycled coarse aggregate consist of density (oven-dry condition), absorption rate, grain size, content of materials finer than 75 μm sieve, alkali-silica reaction, and chloride content. The recycled coarse aggregate used under the approval of MLIT was manufactured from the concrete waste of the demolished turbine mount and chimney foundation of the Chiba and Yokohama Thermal Power Plants, which were about 40 years old.

In addition, the quality of the recycled coarse aggregate manufactured from the original concrete extracted from the walls of the 40-year-old office building is also shown for comparison. An example of the quality of the recycled coarse aggregate is shown in Table 4.

3.4.7 *Impurities*

Impurities due to finished building materials, etc. become a factor causing fluctuation in the quality of recycled aggregate concrete. An example of the measurement results of an impurity is shown in Table 5. In order to ensure that the minimum amount of finishing material be used for thermal power plant structures, the quantity of the impurity was about 1/100 to the rated value of JIS. Furthermore, the case of the office building shown for comparison was about 1/10 to the rated value.

This is because the finishing material was carefully removed before demolition of the structure.

In the case of thermal power plants, the content of impurities is very little compared to ordinary buildings as their main RC parts are not covered with finishing materials. The original concrete of the recycled coarse aggregate applied to the actual structure was supplied from the machine foundation, etc. Dirt was treated by water washing and screening, and a manual removal process was adopted in consideration of the mixing of other impurities.

3.4.8 *Recycled coarse aggregate concrete*

For the mix design of recycled coarse aggregate concrete, the control items comprising compressive strength, drying shrinkage, carbonation depth, etc. are specified in order to secure the target quality.

Although quality control at manufacturing and delivery is carried out according to JIS A 5308 in principle, a severe value is provided for chloride content in consideration of salt eluting from the original mortar. Moreover, it must be confirmed by examination prior to construction that the recycled coarse aggregate concrete is free from alkali-silica reaction. The alkali-silica reaction is regarded as the strictest quality control item of all the processes relevant to recycled coarse aggregate concrete, and a high rate of examination frequency is required.

3.4.9 *Quality control system*

The quality control committee organized by the construction supervisor (TEPCO), building designer, builder (general contractor) and manufacturer (ready-mixed concrete factory, etc.) shall carry out the quality and schedule control.

3.4.10 *Quality control results*

The mix proportions of recycled coarse aggregate concrete applied to the actual structures are shown in Table 6. Typical examples of the quality control results are shown in Table 7.

In order to ensure that all quality requirements were satisfied, the validity of material design using a value of relative quality method was confirmed.

3.4.11 *Monitoring*

For self-management purposes, samples of the recycled coarse aggregate concrete are installed near the site and monitored for confirmation of long-term quality (crack situation, compressive strength, Young's modulus, carbonation depth, salt penetration depth, etc.) [Kondo et al. 2005, 2006].

Figure 12 shows an outline of monitoring samples installed at the Chiba and the Yokohama Thermal Power Plant sites. On-site tests were conducted at the Chiba Thermal Power Plant (Project No. 1) after about three years, and at the Yokohama Thermal Power Plant site (Project No. 2) after about one year, the results of which were used to observe any performance decrement in comparison with normal-weight concrete (natural aggregate concrete).

The results revealed that performance was not deteriorating compared with natural aggregate concrete.

3.5 *Recycled fine aggregate concrete*

This section describes the results of examination [Dosho 2006b] as to the feasibility of applying recycled fine aggregate concrete to precast concrete products.

3.5.1 *Physical properties of recycled fine aggregate*

Recycled fine aggregate was manufactured using the original concrete (Table 3) of Project No. 2, as shown in Figure 5. The physical properties of the manufactured recycled fine aggregate are shown in Table 8. It is possible to improve the main properties such as absorption rate by applying the wet grinding method, which reduces the original mortar content.

The concept of the wet grinding method is shown in Figure 13. The aggregate is ground by the rotation of a rotor positioned inside a cylindrical shell. Recycled fine aggregate and fine powder of 5 mm or less is manufactured by passing through a screen. Impurities such as fine powder and wood chips are removed by a wet-type high-speed centrifuge, or cyclone. The analysis results of the minor constituents in aggregate before and after wet grinding treatment are shown in Table 9 (by JIS K 1029). Although “lead and its compounds” (about 160 mg/kg) was detected before the wet grinding treatment, it was halved by treatment. Minor constituents such as hexavalent-chromium, etc., were not detected and the content in the wash water showed values below the drainage rated value.

3.5.2 *Properties of recycled fine aggregate concrete*

The mix proportions of the natural aggregate concrete (CS-0) and the concrete using recycled fine aggregate (RS2) of the wet grinding method are shown in Table 10. The cycle for steam curing is shown in Figure 14.

3.5.3 *Fresh concrete*

The properties of fresh concrete are shown in Table 11. In the range of “Slump 8 ± 2.5 cm” and “Air Content 4.5 ± 1.5%”, it is possible to knead the concrete using the same mix proportion as with natural aggregate concrete.

3.5.4 *Strength and durability*

The test results on strength (compressive strength, Young's modulus) and durability (drying shrinkage, accelerated carbonation depth) are shown in Figure 15. A tendency has been observed in which the quality of recycled fine aggregate concrete deteriorates as the relative absorption rate becomes higher. A comparatively clear correlation between them is admitted. The strength and durability of recycled fine aggregate concrete with standard curing decline according to the increase in replacement ratio. However, the deterioration in quality is eased by the adoption of steam curing, a tendency remarkably observed in compressive strength.

Although the results of the freezing and thawing examination are shown in Table 12, the durability factor (DF) is not influenced by the replacement ratio and the steam curing.

3.5.5 *Material design*

Material design is made using the value of relative quality method. In the case of steam curing as shown in Figure 15, the relative absorption rate pertinent to the quality requirement of 0.08% or less for length change in hardening and 25 mm or less for accelerated carbonation depth becomes 3.14%. This is the most important factor for recycled fine aggregate concrete.

Figure 16 shows the relationship between the cement-water ratio (C/W) and compressive strength (F_{28}) using the results shown in Figure 15. The cement-water ratio corresponding to the compressive strength within the range of the standard value (JIS) for precast concrete products can be determined by regression analysis. Furthermore, the compressive strength of an actual plant becomes conjecture on the safe side, decreasing by about 10% from the value of examination (steam curing). That is, the compressive strength of an actual plant is calculated by presuming ($1.1F_{28} = a \times (C/W) + b$) that the examination value (compressive strength at 28 days by steam curing) is multiplied by 1.1. This result reveals the necessity to determine the cement-water ratio based on the required compressive strength.

A water-cement ratio (W/C) of 35 N/mm^2 (JIS A 5372) becomes 49.8%, and W/C of 24 N/mm^2 (JIS A 5371) becomes 59.3%. Incidentally, maximum replacement ratio in steam curing becomes about 84% in the case of 35 N/mm^2 (JIS A 5372), and about 80% in the case of 24 N/mm^2 (JIS A 5371).

4 CONCLUSIONS

This paper presented a recycling system for concrete waste generated by the demolition of large-scale buildings such as thermal power plants from the viewpoint of LCA.

The study results are summarized as follows:

(1) Recycled coarse aggregate concrete using the aggregate replacing method can acquire sufficient quality as structural concrete through material design by using material conforming to all related quality standards.

(2) Recycled fine aggregate concrete, as well as recycled coarse aggregate concrete, can also be designed by applying the value of relative quality method. Therefore, it is considered applicable as aggregate for use in precast concrete products.

(3) With the adoption of the developed recycling system, it is possible to recycle concrete waste produced from the demolition of TEPCO's buildings in a highly effective manner reducing both recycling cost and environmental impact.

(4) The developed recycling system may be applicable to scrap and build of general buildings, etc. other than TEPCO's, on condition that suitable quality control is performed.

5 FUTURE DEPLOYMENT

From this point on, the following developments will be advanced:

(1) To expand the scope of approval by MLIT for recycled coarse aggregate concrete;

(2) To produce and secure a sales base for precast concrete products using recycled fine aggregate concrete;

(3) To establish a recycling system enabling sustainable development by expanding the application areas and extent of the system described in this paper.

ACKNOWLEDGMENTS

I am deeply indebted to Dr. M. Kikuchi, Professor of Meiji University, for his invaluable guidance. I also thank Dr. Y. Otabe of Sumitomo Osaka Cement Co., Ltd., Mr. A. Nakagome of Maeda Co., Ltd., Mr. Y. Mura of Tokyo Electric Power Service Co., Ltd. (TEPSCO), Mr. Y. Kaneko (TEPSCO), Mr. Y. Saito (TEPCO), Mr. M. Kondo (TEPCO) and Mr. T. Ue (TEPCO) for their assistance in the study and project.

REFERENCES

AIJ 1991. "*Recommendations for Design and Construction Practice of High Durable Concrete*."

Buck, A. D. 1977. "Recycled concrete as a source of aggregate", *Journal of American Concrete Institute*, 212-219.

Building Construction Society of Japan 1978. "Study on recycled aggregate and recycled aggregate concrete." *Concrete Journal*, 16(1), JCI, 18-31.

Building Research Institute 1986. "*Report on studies concerning recycling technologies for materials in construction projects*." Ministry of Construction (Japan).

Concrete Library 111 2003. "*Leaching of Minor Elements from Concrete*." Japan Society of Civil Engineers.

Dosho, Y., Narikawa, M., Nakagome, A. & Kikuchi, M. 1998a. "Application on recycled aggregate concrete for structural concrete, Part 2 – Feasibility study on cost-effectiveness and environmental impact." *Sustainable Construction*: *Use of Recycled Concrete Aggregate*, London, UK, University of Dundee, 389-400.

Dosho, Y., Kikuchi, M., Narikawa, M., Ohshima, Y., Koyama, A. & Miura, T. 1998b. "Application of Recycled Concrete for Structural Concrete, Experimental Study on the Quality of Recycled Aggregate and Recycled Aggregate Concrete." *Proceedings of Fourth CANMET/ACI/JCI International Conference on Recent Advances in Concrete Technology*, Tokushima, Japan, 1073-1101.

Dosho, Y., Nukui, Y., Saito, Y., Kondo, M., Mura, Y., Harada, S., Yamashita, Y. & Ozaki, M. 2005. "Recycling System of Concrete Waste Incurred from Building Demolition – The quality control method of recycled aggregate concrete produced by the aggregate replacing method." *AIJ Journal of Technology and Design*, 21, 15-20.

Dosho, Y. 2005. "Applicability of Recycled Aggregate Concrete for Structural Concrete – A Recycling System for Concrete Waste." *Proceedings CANMET/ACI/JCI, Three-Day International Symposium on Sustainable Development of Cement, Concrete and Concrete Structures*, Toronto, Canada, 459-478 (Revised edition: 249-271).

Dosho, Y., Ue, T., Kaneko, Y. & Otabe, Y. 2006a. "Application of Recycled Coarse Aggregate Concrete based on Aggregate Replacing Method to Building Structure." *Proceedings of the Japan Concrete Institute*, 28(1), 1493-1498.

Dosho, Y., Kondo, M., Mura, Y. & Kaneko, Y. 2006b. "Recycling System of Concrete Waste Incurred from Building Demolition – Basic investigations of using recycled fine aggregate for precast concrete products based on aggregate replacing method." *AIJ Journal of Technology and Design*, 23, 33-38.

Environment Agency Japan "*Fundamental Law for Establishing a Sound Material-Cycle Society (Tentative translation).*" Law No.110 of 2000.

JASS 5 1975. "*Japanese Architectural Standard Specification for Reinforced Concrete Work.*" AIJ.

JASS 5 2003. "*Japanese Architectural Standard Specification for Reinforced Concrete Work.*" AIJ.

Kawai, E., Yanagibashi, K., Iwashimizu, T. & Takiguchi, H. 2006. "An Application of Structural Concrete Using Recycled Aggregate – A Case of Rebuilding Apartment House at Shinsenri Sakuragaoka Area." *Concrete Journal*, 44(2), JCI, 46-53.

Kikuchi, M., Dosho, Y., Narikawa, M. & Miura, T. 1998. "Application on recycled aggregate concrete for structural concrete, Part 1 – Experimental study on the quality of recycled aggregate concrete." *Sustainable Construction: Use of Recycled Concrete Aggregate*, London, UK, University of Dundee, 55-68.

Kondo, M., Nukui, Y. & Dosho, Y. 2005. "Recycling System of Concrete Waste Incurred from Building Demolition – Long-term properties of recycled coarse aggregate concrete produced by means of the aggregate replacing method." *AIJ Journal of Technology and Design*, 21, 7-10.

Kondo, M., Dosho, Y., Koyama, A. & Kikuchi, M. 2006. "Use of Recycled Aggregate Concrete for Large Scale Electric Power Stations, Part 31 – Drying shrinkage crack of recycled aggregate concrete applied to a real structure." *Summaries of Technical Papers of Annual Meeting AIJ*, 687-688.

Kuroda, Y., Mori, K. & Miyachi, Y. 2003. "Application of Closed-Loop Concrete System to Replacement Work." *Concrete Journal*, 41(1), JCI, 150-153.

Kuroda, Y. & Hashida, H. 2005. "A Closed-Loop Concrete System on a Construction Site." *Proceedings CANMET/ACI/JCI, Three-Day International Symposium on Sustainable Development of Cement, Concrete and Concrete Structures*, Toronto, Canada, 371-388 (Revised edition: 667-683).

Ministry of Construction (Japan) 1997. "*Development of Technology for the Suppression of Construction Byproducts or for their Recycling and Reuse*."

Noguchi, T. 2005. "An Outline of Japanese Industrial Standards (JIS) as Related to Sustainability Issues." *Proceedings CANMET/ACI/JCI, Three-Day International Symposium on Sustainable Development of Cement, Concrete and Concrete Structures*, Toronto, Canada, 407-422 (Revised edition: 507-548).

Shintani, A., Yoda, K., Onodera, T. & Kawanishi, T. 2006. "Application of two types of recycled coarse aggregate to a reinforced concrete building." *Proceedings of the Japan Concrete Institute*, 28(1), 1463-1468.

Teranishi, K., Dosho, Y., Narikawa, M. & Kikuchi, M. 1998. "Application on recycled aggregate concrete for structural concrete, Part 3 – Production of recycled aggregate by real-scale plant and quality of recycled aggregate concrete." *Sustainable Construction: Use of Recycled Concrete Aggregate.*, London, UK, University of Dundee, 144-156.