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Research Paper

Contributions of Concrete Recycling Technology toward Sustainable Development: Standards and Technologies Related to Recycled Aggregate Concrete in Japan

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ABSTRACT

Concrete is durable and can last for centuries. The waste from demolished concrete structures can be reused to reduce the environmental burden during their life cycle and ensure economic use of the construction resources. This study aims to improve the use of recycled aggregates prepared using the aggregate replacement method, effectively reducing both the environmental burden and costs associated with concrete waste. A high-value recycling method should be developed for concrete waste that offers improvements in terms of resource diversion and environmental preservation. New uses of concrete waste should be sought to counter the expected increase in the production of concrete waste with newer construction projects. Concrete waste contains harmful trace elements due to the use of cement, such as hexavalent chromium and lead. The most promising alternative materials are recycled aggregate concrete prepared using the aggregate replacement method, the uses of which are confined to concrete prepared from original mortar and/or original cement paste that contain toxic substances such as hexavalent chromium. The results of this study provide evidence for the effectiveness of using low-quality recycled aggregate concrete, such as of Class L, specified in the Japanese industrial standard (JIS) directive (JIS A 5023).

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1 Introduction

1.1 Background

Concrete is the second-most consumed material after water and is fundamental to the modern urban environment. Between 21 and 31 billion tons of concrete were used globally in 2006 compared to 2.0 to 2.5 billion tons in 1950 [1]. Concrete is extremely durable and can last for hundreds of years in various applications. As requirements vary and as old

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concrete structures are demolished, a large volume of construction waste is generated, which can also last for centuries. In Japan, a survey conducted in the fiscal year 2018 by the Ministry of Land, Infrastructure, and Transport showed that 74.4 million tons of construction waste is being produced per year, most of which is recycled in compliance with the related laws and ordinances. Concrete waste accounts for 36.9 million tons of the total waste. Although the rate of concrete recycling has reached 99.3%, most of the waste is used as roadbed gravels or backfill materials [2]. Therefore, a high-value recycling method should be developed for concrete waste that offers improvements in terms of resource diversion and environmental preservation.

1.2 Present status of concrete waste recycling

Concrete waste is presently used almost entirely for roadbed gravel such as RC-40 (recycled crusher run 0 to 40 mm); however, the demand for roadbed gravel is not expected to increase because of the declining construction of new roads [2]. New uses of concrete waste should be sought to counter the expected increase in the production of concrete waste with newer construction projects.

Concrete waste contains harmful trace elements due to the use of cement, such as hexavalent chromium and lead. These trace elements may leach into the environment when fine mortar grits (diameter $\leq 5\ mm$), such as recycled fine aggregates and powders, and are subjected to wetting [3]. Therefore, reducing the amount of fine powder may help reduce the environmental risks of soil contamination associated with concrete waste recycling.

The most promising alternative materials are recycled aggregate concrete prepared using the aggregate replacement method, the uses of which are confined to concrete prepared from original mortar and/or original cement paste that includes toxic substances such as hexavalent chromium. Because the Japanese industrial standard (JIS) directives (JIS A 5021 [4], JIS A 5022 [5], and JIS A 5023 [6]) concerning the recycled aggregate concrete were enacted from 2005 to 2007 [7], the usage performance of recycled aggregate concrete was investigated by the Ministry of Land, Infrastructure, Transport and Tourism in the fiscal year 2018 [2]. According to the results of a survey conducted by this agency, the amount of recycled concrete used was found to be 119,000 tons, which was approximately twice (55,000 tons) that generated in the fiscal year 2012; nevertheless, it was still a small amount. Regarding the total amount of recycled concrete, 64,000 tons were recycled aggregate concrete of Class H, 50,000 tons were recycled aggregate concrete of Class M, and 5,000 tons were recycled aggregate concrete of Class L, among which the use of recycled aggregate concrete of Class M increased by 48,000 tons. On the other hand, the revision of JIS A 5022 (recycled aggregate concrete of Class M) in 2018 stipulated that recycled aggregate of Class L can be mixed with normal aggregate of a suitable amount under the upper threshold of the replacement ratio [5]. Therefore, the use of low-cost recycled aggregate of Class L can be disseminated. For this reason, to increase the use of recycled aggregate of Class L, it is necessary to promote the use of recycled aggregate concrete of Class M.

2 Application of Recycled Aggregate Concrete

2.1 Concept

When recycled aggregate is used for buildings and other structural purposes, the required quality is generally equivalent to that of normal aggregate such as gravel, sand, crushed stone, and crushed sand (Note 1). However, when manufacturing recycled aggregates, the manufacturing costs and CO_2 emissions are likely to increase considerably; therefore, the usage of recycled aggregate concrete is limited. To encourage the use of recycled aggregate, the related processes must ensure an appropriate balance between safety and quality as well as environmental impact and cost-effectiveness [8].

Environmental impact is particularly important when performing risk assessments on human health, social capital, etc. This study confirmed the possibility and effectiveness of using low-quality recycled aggregate such as Class L aggregate (JIS A 5023 [6]). The scrapping and rebuilding of an actual thermal power plant was evaluated in terms of the environmental impact using the life cycle impact assessment method based on endpoint modeling (LIME).

2.2 Production method of recycled aggregate

Figure 1 shows a recycled aggregate comprising aggregate, mortar, and cement paste. The concrete waste contains chlorides and/or toxic substances, such as hexavalent chromium, because of the presence of mortar and cement [7]. Recycled aggregate is manufactured from concrete waste. The treatment of the original mortar and original cement paste during manufacturing affects the environmental impact of the recycled aggregate. Two main production methods are employed to generate recycled aggregate concrete in Japan [7].

The first one is an aggregate refinement method that uses recycled aggregate from which most of the original mortar and original cement paste has been removed. Another is an aggregate replacement method that uses recycled aggregate that still contains the original mortar and cement paste.

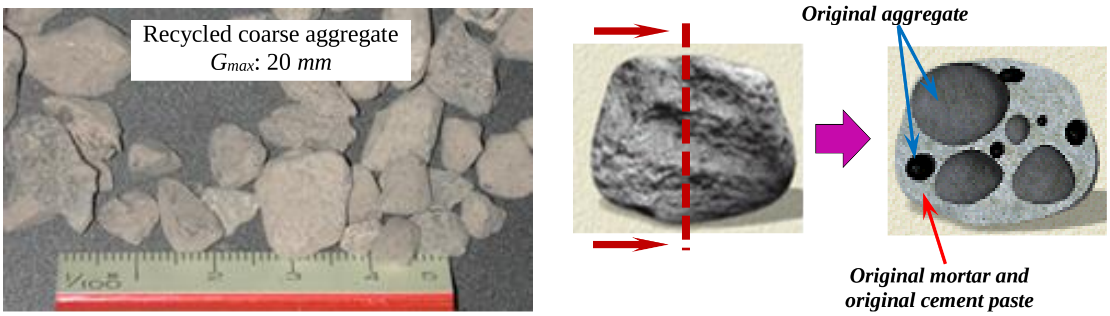


Fig. 1 – Appearance of recycled coarse aggregate.

2.2.1 Aggregate refinement method

The recycled aggregate produced using the aggregate refinement method is refined to attain a quality equivalent to that of normal aggregates. Advanced processing techniques and specialized equipment are required for the refining process to eliminate the original mortar and/or cement paste from the recycled aggregate. In Japan, four aggregate refinement methods are mainly practiced; using which high- or medium-quality recycled aggregates can be prepared while meeting the specified requirements. The best among these four methods uses heating and rubbing to yield 35% high-quality recycled coarse aggregate and 21% recycled fine aggregate from concrete waste. The remaining 44% is fine powder containing a large amount of original mortar and cement paste. Although several recycling applications that convert fine powder to cement materials have been proposed, their extensive use remains difficult because of problems related to quality control and cost-effectiveness [8].

Advanced processing techniques and facilities are required to reuse the fine powder in materials other than concrete, while the cost and environmental burden are likely to remain high. The aggregate refinement method in Japan is typically performed using one of the following four methods: heated scrubbing (or heating and rubbing), mechanical scrubbing–1 (eccentric tube type), mechanical scrubbing–2 (screw type), and wet scrubbing and gravity classification [8]. These are used to manufacture high- or medium-quality recycled aggregates that satisfy the requirements of JIS A 5021 [4] or JIS A 5022 [5, 7].

2.2.2 Aggregate replacement method

In contrast to aggregate refinement, the aggregate replacement method does not require removing the original mortar and cement paste. Instead, the influences of the original mortar and cement paste are controlled by mixing normal aggregate or high-quality recycled aggregate during the concrete manufacturing stage. Therefore, the aggregate replacement method is proven to be effective in terms of cost and CO_2 emissions [8]. Before its application to the large-scale study discussed in this work, the aggregate replacement method practiced in Japan received three approvals from the Minster of Land, Infrastructure, Transport and Tourism (MLIT) [7]. Based on such MLIT approvals, the recycled aggregate concrete was used in two buildings [8], and one structure [9] was used as the base for temporarily storing a used transformer. In addition, for self-management purposes, the recycled aggregate concrete samples were installed near the sites and monitored for three to five years to confirm their long-term properties (crack situation, compressive strength, Young's modulus, carbonation depth, and salt penetration depth) [10]. These tests revealed that the performance did not deteriorate to an extent greater than that observed in the case of normal aggregate concrete (Note 2).

Furthermore, the recycled aggregate concrete prepared using the aggregate replacement method has been used on a trial basis for manufacturing precast power-utility manhole segments [11], where recycled fine aggregate and recycled coarse aggregate were used for constructing a new structure. Figure 2 illustrates these processes. In addition, these preliminary tests demonstrate that with a suitable quality control, the recycled aggregate concrete produced using the aggregate replacement method can exhibit sufficient quality.

Building-1 (2002)

Approval of MLIT: No. MCON-0171, 18 January 2002.
Volume of concrete placement: about 200 m^3
Application parts: foundation, footing beam
Specifications of recycled coarse aggregate concrete;
Fc = 24 N/mm^2 (OPC[*1]), Slump = 18 cm
Replacement ratio of recycled coarse aggregate: 30%.

Building-2 (2005)

Approval of MLIT: No. MCON-0979, 15 September 2004.
Volume of concrete placement: about 1,000 m^3
Application parts: structural member except steel frame parts.
Specifications of recycled coarse aggregate concrete;
Fc = 24 N/mm^2 (OPC[*1]), Slump = 15 and 18 cm,
Fc = 24 and 27 N/mm^2 (LPC[*2]), Slump = 15 cm
Replacement ratio of recycled coarse aggregate: 30%.

Structure (2008)

Approval of MLIT[*3:] No. MCON-0979, 15 September 2004.
Volume of concrete placement: about 620 m^3
Application parts: foundation
Specifications of recycled coarse aggregate concrete;
Fc = 30 N/mm^2 (OPC[*1]), Slump = 18 cm
Replacement ratio of recycled coarse aggregate: 50%.

Precast reinforced concrete products

Volume of concrete: 0.95m^3 per one piece
Specifications of recycled aggregate concrete;
Fc = 39.2 N/mm^2 (OPC[*1]), Slump = 18 ± 2.5 cm,
Curing method: Steam curing.
Trial model A (recycled coarse aggregate concrete)
Replacement ratio of recycled coarse aggregate: 50%.
Trial model B (recycled aggregate concrete)
Replacement ratio of recycled coarse aggregate: 50%
Replacement ratio of recycled fine aggregate: 30%.

*1 OPC: Ordinary Portland cement *2 LPC: Low-heat Portland cement *3 In order not to apply the Building Standard Law for this structure, approval of MLIT was not needed, but quality control was carried out based on the contents of approval of MLIT.

Fig. 2 – Appearance of recycled application examples of recycled aggregate concretes produced by the aggregate replacement method [8-11].

3 Environmental Impact Assessment

3.1 Evaluation of the environmental impact

Generally, the influence of recycling on the environment is estimated on the basis of CO_2 emissions [8]. However, to objectively evaluate the environmental impact, it is necessary to consider the reduced consumption of natural resources and the diversion of waste involved while conducting recycling. Further, a theoretical consideration of the several risk factors related to resource circulation can help enhance the objectivity of the environmental impact assessment.

3.2 LIME

LIME was introduced in 2003 following the LCA national project in Japan [12].

3.2.1 LIME in LCA

During the 1990s, the main integration problem involved in LCA was that of comparison (the method of deducing a single factor by weighting the influence domains). Eco-Indicator '95, developed in the Netherlands, is a classic example [13]. However, although this method quantifies the environmental impact of a substance, it is difficult to correlate its scale with the specific measures of the effects on human health and biodiversity.

The development of an improved LCA method (e.g. Eco-Indicator'99 [14]) called "endpoint modeling," which estimates the amount of damage at the endpoint, began in 2000. In Japan, the LCA project was inaugurated in 1998, and the Japanese version of the life cycle impact assessment (LCIA) method was developed on the basis of endpoint modeling. This protocol was released as LIME in 2003 when the LCA project ended [12].

The LIME evaluation method for concrete construction has been discussed in case studies by the Japan Society of Civil Engineers in "Recommendations on Environmental Performance Verification for Concrete Structures (Draft)" [15]. Because it can be evaluated in terms of conventional CO_2 emissions [8] and is popular in Japan [12, 16], LIME was adopted for evaluating the environmental impact in this study.

3.2.2 Evaluation method using LIME

As shown in Figure 3, the main steps involved in the LCIA, such as characterization, damage assessment, and weighting, are also included in LIME and are evaluated as the "integration index" [12]. As listed in Table 1, the damage factor represents the influence of a material on the parameter to be protected such as human health. Table 2 lists the weighting factor for each single index as four protection subjects (Figure 3 shows two exemplary "protected subjects") considered by LIME.

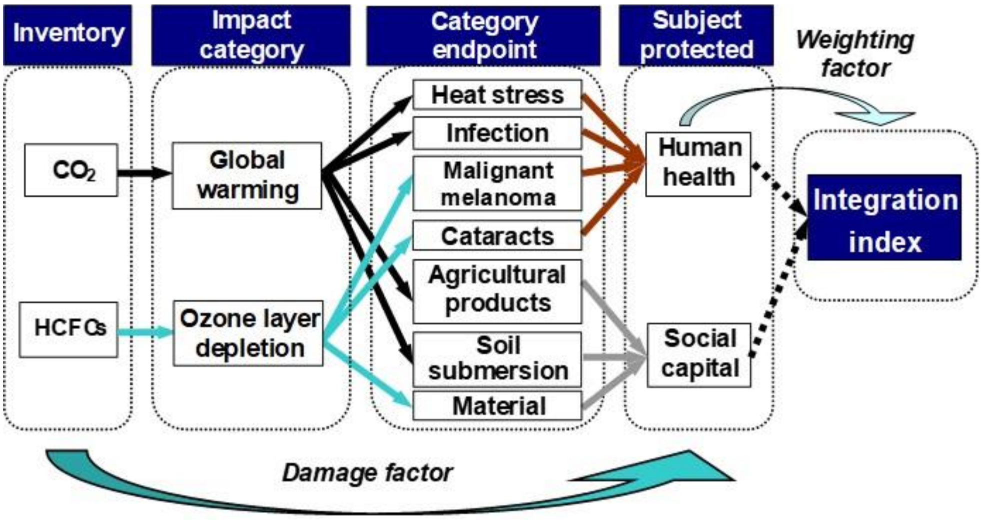


Fig. 3 – Step concept of impact evaluation using LIME [12].

In LIME, human society and ecosystem are specified as the main protected concerns. Subsequently, the concerns are classified under qualitative (human health and biodiversity) and quantitative (social capital and primary production) groups. The weighting factors are calculated using these values [16]. With respect to the items reflecting the quality, the disability-adjusted life years are used as the damage index of human health. This index is calculated from the years lived with a disability in terms of disturbed health and years of life lost due to premature death [12].

Furthermore, the expected increase in the number of extinct species is used as the damage index for biodiversity. This index is calculated as the amount of damage suffered in terms of biodiversity with respect to the changes in species extinction risks from exposure to a toxic substance or physical alteration of the ecosystem [12].

As for the items reflecting the quantity, the degree of influence on social capital is calculated using the equivalent damage value (¥: Yen) [12]. To quantify the influence on the primary production, the net primary productivity (NPP) is used. The NPP is the production quantity (i.e. the production rate) per time and is generally expressed as the dryness of a vegetal object per annual unit land area [12]. This method is based on a latest study on environmental science and is expected to contribute to improving the quality of the LCIA methods and promoting the implementation of LCA in Japan's concrete industry.

Table 3 lists the integration indices calculated in this study by multiplying the damage and weighting factors. For example, the integration index of the damage per unit mass is a value in which the industrial waste equivalent to the rubble is extremely high.

The range for the evaluation is calculated from the CO_2 emissions and resource consumption in terms of the energy used in the post-demolition recycling stage [17].

Table 1 - Damage factors [16].

Subject item		**Subject protected**			
		Primary production ***(kg^{*1}/kg)***	**Biodiversity** ***(EINES^{*2}/kg)***	**Human health** ***(DALY^{*3}/kg)***	**Social capital** ***(¥^{*4}/kg)***
Industrial waste	Rubble	8.60E-03	1.18E-13	-	1.38E+01
Air pollution	CO_2	-	-	1.62E-07	5.08E-01
Resource consumption	Gravel	1.98E-03	1.35E-15	-	-
	Crude oil	-	-	-	2.96E+00

*1 kg: NPP (Net primary productivity), *2 EINES: Expected increase in the numbers of extinct species, *3 DALY: Disability-adjusted life year, *4 ¥: Yen (Damage amount equivalent).

Table 2 - Weighting factors [16].

Primary production **(*¥/kg*)**	**Biodiversity** **(*¥/EINES*)**	**Human health** **(*¥/DALY*)**	**Social capital** **(*¥/¥*)**
3.79E+01	1.28E+13	1.43E+07	1.00E+00

Table 3 - Integration index.

Subject item		**Integration index**	
		Yen/kg	**Yen/L**
Industrial waste	Rubble	LM 1: 1.56E + 01	-
Air pollution	CO_2	LM 2: 2.82E + 00	-
Resource consumption	Gravel	LM 3: 9.23E - 02	-
	Crude oil	LM 4: 2.96E + 00	LM 5:2.43E + 00
Gas oil equivalent PL: 2.640 $kg\cdot CO_2/L$			

3.3 Method of simulation

Table 4 presents an outline of the thermal power station chosen as the simulation case study in this work; Table 5 presents an outline of the case study. Figure 4 and Table 6 present the boundary conditions used in the simulation, which dictate the purposes for which the concrete waste were employed. Table 7 lists the emission intensities of CO_2 used to calculate the CO_2 emissions.

Table 4 - Outline of the simulation model.

Type of building	Demolition	Oil-fired thermal power station
	Establishment	Oil-fired thermal power station*
Location		City suburbs
Site area (m^2)		280,000
Total floor space (m^2)		89,000
Amount of concrete waste produced (m^3) (weight)		35,000 (80,500 *tons*)
Application	Structural concrete (m^3) (weight)	35,000 (80,500 *tons*)
	Precast concrete products (m^3)	3,000
	Backfill material and roadbed gravel at site (m^3)	20,000

* Combined-cycle power generation system.

Table 5 - Outline of the model case.

Case		Usage	Outline
1		Roadbed gravel and/or backfill materials	This case uses as much concrete waste as possible for roadbed gravel and/or backfill materials at the construction site, with 20,000 m^3 of concrete waste being reused on the site. Any remaining concrete waste is taken off the site to an intermediate treatment facility.
2	2-1 2-2 2-3	Roadbed gravel and/or backfill materials, recycled aggregate concrete (aggregate replacement method)	Case 2 involves reuse as roadbed gravel and/or backfill materials, and the recycled coarse and fine aggregates are used in the concrete for new buildings at the construction site. It is classified further into three cases, Cases 2-1, 2-2, and 2-3, based on the usage of recycled fine aggregates. Case 2-1: Recycled fine aggregate that was manufactured only by crushing and classified for use in building concrete. The remaining concrete waste was taken to an off-site intermediate treatment facility. Case 2-2: Recycled coarse (other than used for building concrete) and fine aggregates that were manufactured only by crushing and classified for being used as the precast reinforced concrete products. Any remaining concrete waste was taken to an off-site intermediate treatment facility. Case 2-3: Recycled fine aggregate, whose quality was enhanced by adding a wet grinding treatment process 8, was used for the precast reinforced concrete products, and any fine powder generated was taken off the site for final disposal.
3	3-1 3-2	Roadbed gravel and/or backfill materials, recycled aggregate concrete (aggregate refinement method)	Case 3 involves reuse as roadbed gravel and/or backfill materials used for concrete in new buildings and precast reinforced concrete products as recycled aggregate for concrete–class H (JIS A 5021 4) at the construction site. It is classified further into two cases, 3-1 and 3-2, based on the method of manufacturing the recycled aggregate. Case 3-1: The eccentric tubular type for "mechanical scrubbing" 21 was used as the aggregate refinement method. Case 3-2: Heating and rubbing for "heated scrubbing" 22 was used as the aggregate refinement method.

3.3.1 Simulation model

The buildings designated for rebuilding are the main plant and related facilities of a 350,000 *kW* thermal power station located in the suburbs of a mid-size city. After the demolition of the old (oil fired, 350,000 *kW* class) thermal power station, a new turbine building (concrete amount: 24,000 m^3) and several related buildings (concrete amount: 11,000 m^3) will be rebuilt as a new thermal power station (oil fired with combined-cycle power generation, 1,500,000 *kW* class) on the same site (area: 280,000 m^2). The model assumes that the quantities of concrete waste generated from the demolition of old buildings and the concrete required for the new construction are approximately the same. The amount of concrete required was assumed to be 3,000 m^3 for precast concrete products at the outset when building a new power station. These include RC box culverts (JIS A 5372 [18]) and boundary blocks (JIS A 5371 [19]). A 20,000 m^3 concrete waste (absolute volume) was assumed for use as roadbed gravel for the parking area and as backfill material for the demolished underground structures, as well as for other miscellaneous uses.

Table 6 - Calculation condition.

Item	Conditions*			Adopted values
Rm1 (mass %)	Rate of recycled coarse aggregate recovered	Method A		5–20 mm: 54.8 [8] 5–25mm: 73.2 [8]
		Method B	Type 1	27 [20]
			Type 2	35 [21]
Rm2 (mass %)	Rate of recycled fine aggregate recovered	Method A	-	100 – Rm1
			After wet grinding treatment	29 [8]
		Method B	Type 1	31 [20]
			Type 2	21 [21]
Rm3 (mass %)	Rate of recycled fine powder recovered	Method A	After wet grinding treatment	71
		Method B	Type 1	42 [20]
			Type 2	44 [21]
Replacement ratio of recycled coarse aggregate (%)	*Rr1* Structural concrete	Method A		0, 30, 50 [8]
		Method B		100 [20, 21]
	Rr2 Precast concrete products			0, 50, 100 [8]
Replacement ratio of recycled fine aggregate (%)	*Rr3* Method A	Structural concrete		0, 20 [22]
		Precast concrete products	Wet grinding treatment	0, 80, 84 [8]
			-	0, 20, 30 [11]
	Method B			100 [20, 21]
Density of concrete (t/m^3)				2.3

* Method A: Aggregate replacement method, Method B: Aggregate refinement method, Type 1: Mechanical scrubbing (eccentric tubular type), and Type 2: Heated scrubbing (heating and rubbing).

Table 7 - CO_2 unit requirement.

Symbol	Item	CO_2 unit requirement
Fe	Fuel oil	Gas oil: 2,620 $kg\cdot CO_2/L$ [17]
Ee	Electric power	0.564 $kg\cdot CO_2/kWh$ [23]
We	Water	Industrial water: 0.07 $kg\cdot CO_2/m^3$ [23]
Me_1	Intermediate treatment	77.000 $kg\cdot CO_2/con.t$ [23]
Me_2	Backfill in site	Multiply the product of fuel consumption by heavy industrial machine and Fe: 4.508 $kg\cdot CO_2/m^3$
$Me_{2.1}$	Roadbed gravel	Crushed stone: 11.000 $kg\cdot CO_2/t$ [23]
Me_3	Recycled aggregate production (Aggregate replacement method)	Multiply the product of fuel consumption by heavy industrial machine and Fe: 8.097 $kg\cdot CO_2/con.t$
Me_4	Recycled coarse aggregate use	Crushed stone: 11.000 $kg\cdot CO_2/t$ [23]
Me_5	Recycled fine aggregate use	Crushed stone: 11.000 $kg\cdot CO_2/t$ [23]
Me_6	Wet grinding treatment	35.153 $kg\cdot CO_2/t$[*1]
$Me_{6.1}$	Fine powder disposal	77.000 $kg\cdot CO_2/con.t$ [23]
Me_7	Recycled aggregate production (Aggregate refinement method)	Mechanical Scrubbing: 16.0 $kg\cdot CO_2/t$ [20] Heated Scrubbing: 71.148 $kg\cdot CO_2/t$ [21]
$Me_{7.1}$	Recycled fine aggregate sale	11.000 $kg\cdot CO_2/t$ [23]
Me_{8n}	Transportation	Dump truck (ex. 10 *ton*, 60 *km*): 5.280 $kg\cdot CO_2/t$[*2]

*1 Actual measurement, *2 $Tm/Uf\cdot Fe/L$, Total of mileage: Tm, Used fuel: Uf, Load: L.

3.3.2 Boundary conditions

Figure 5 shows the boundary conditions for all the cases. Recycled aggregates, except for fine powder, were assumed to be treated at a temporary plant within the construction site and a factory outside the construction site, applied to the construction of a new building or sold for manufacturing precast concrete products and structural concrete for delivery to the market. The evaluation range is from the point at which the recycled aggregate is transported to the concrete manufacturing plant. The effect of using recycled aggregate is calculated in terms of the reduction in use of normal aggregate for the new construction. Because the conditions of all the considered processes are identical, they were excluded from this calculation. In the aggregate replacement method (Method A) [8], we assumed that the recycled coarse aggregate is produced at the construction site using a mobile device.

In this case, recycled coarse aggregate concrete with a replacement ratio in the range of 30%–50% is assumed to be used for constructing a new building. Furthermore, we assumed recycled aggregate concrete with a recycled coarse aggregate added at a 30% replacement ratio and recycled fine aggregate added at a 20% replacement ratio (Case 2-1) to be used for constructing a new building. Based on the results of a basic review into the quality of recycled fine aggregates intended for use as an aggregate for structural concrete [22], the reduction in quality is small at a replacement ratio of 30% or less in case of a 45% water-to-cement ratio. However, under the conditions of this study, because a 55% water-to-cement ratio was assumed, the upper limit for the replacement ratio was assumed to be 20%.

In Cases 2-2 and 2-3, the recycled fine aggregate was assumed to be treated at a factory outside the construction site; the treated aggregate was used to manufacture precast concrete products, such as boundary blocks or reinforced concrete box culverts, for market delivery. Incidentally, the recycled fine aggregate used for a prototype model of a power-utility manhole segment [11] was obtained using the same method as in Case 2-2. In other words, the wet grinding treatment was not performed. However, as with the aggregate replacement method in Case 2-3, because the recycled fine aggregate contains a large amount of original mortar, which significantly affects the quality of the concrete, a wet grinding treatment process was added to improve the quality [8]. In the aggregate refinement method (Method B), the material was assumed to be treated at a temporary plant within the construction site and applied for constructing a new building; the remainder was used to manufacture precast concrete products for market delivery. In this simulation, we selected an eccentric tubular process (Type 1) [20] for mechanical scrubbing and heating and rubbing (Type 2) [21] for heated scrubbing as the aggregate refinement method. These methods are evaluated for their effectiveness in the recycling system compared with reusing the material only as roadbed gravel or backfill material.

3.3.3 Calculation method

The integrated economic index (*EI*) is used to evaluate the environmental impact and is expressed in Equation (1). The crude oil consumption, land use for waste disposal, and use of normal aggregates are evaluated under the integration index as listed in Table 3. In addition, CO_2 emissions (*Te*) are included in the evaluation of *EI* and are expressed in Equation (2).

The CO_2 emissions are calculated by multiplying and adding to the used volume of items corresponding to the calculation conditions of each case based on the CO_2 unit requirement listed in Table 7. Note that although field survey results for several facilities are available in terms of the CO_2 unit requirements for concrete waste intermediate treatment (Me_1) [24] and recently for the final disposal of fine powder ($Me_{6.1}$), this study used CO_2 unit requirements based on the inter-industry relations table [23].

$$\begin{aligned} EI = Te \cdot LM_2 + \frac{Te}{PL} \cdot LM_5 + LM_1^{'} \cdot \left(rv_1 + rv_{5.1} + rv_{6.4} + rv_{7.3}\right) \\ - LM_3^{'} \cdot \left(rv_2 + rv_{4.1} + rv_{4.2} + rv_{4.3} + rv_{5.2} + rv_{5.3} + rv_{6.3} + rv_{7.1} + rv_{7.4} + rv_{7.5}\right) \end{aligned} \qquad (1)\ [25]$$

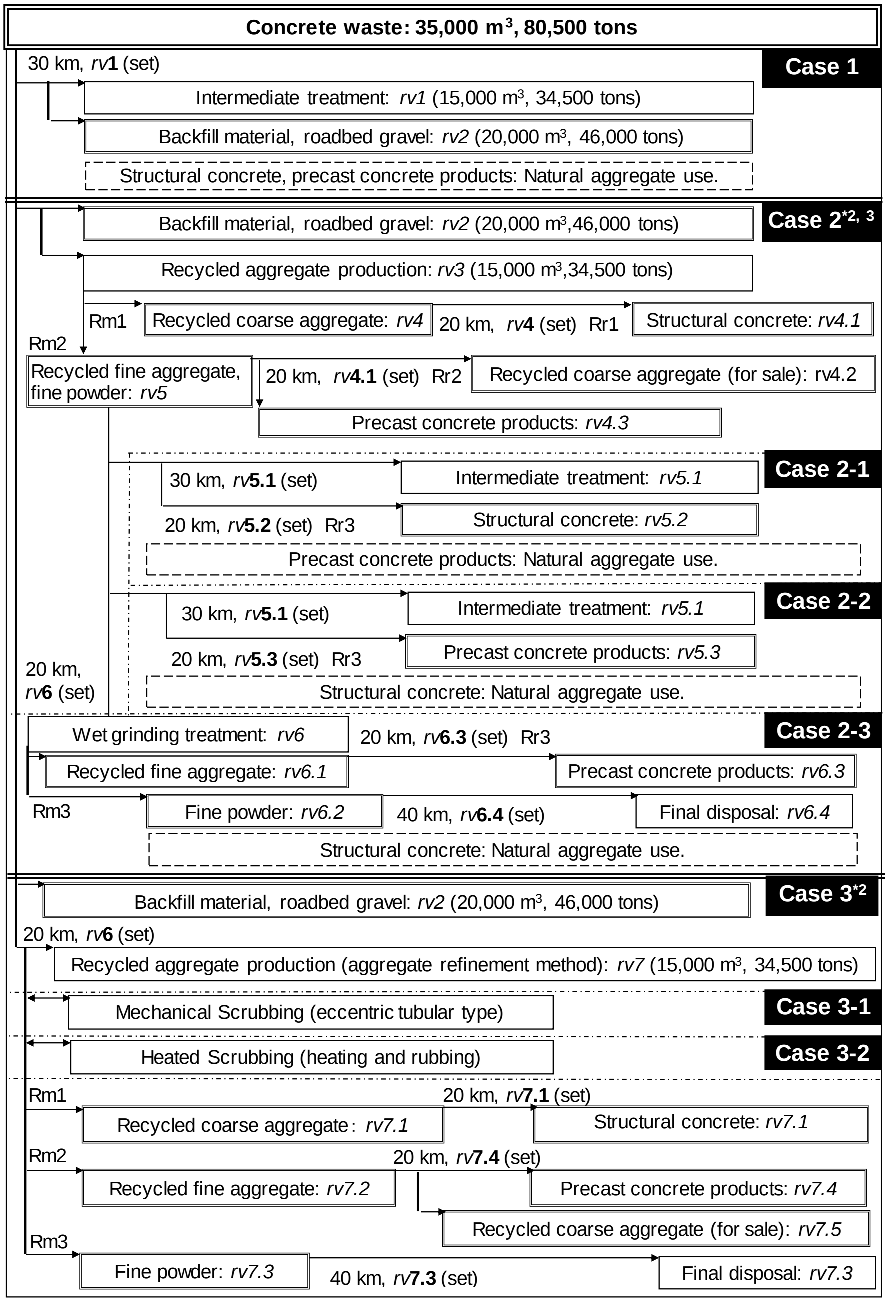
where, EI : economic index (Yen); LM and PL : integration index;

$rv_n\left(m^3, ton\right)$; $n = 1, 2, 4.1, 4.2, 4.3, 5.1, 5.2, 6.3, 6.4, 7.1, 7.3, 7.4$ and 7.5 (mass tons): represents the volume;

$LM_1^{'}$ and $LM_3^{'}$: Mass (*tons*); and Te is the CO_2 emission ($kg \cdot CO_2$) and expressed in Equation (2).

$$\begin{aligned} Te = {} & rv_1 \cdot Me_1 + rv_1 \cdot Me_{8n} + rv_2 \cdot Me_2 - rv_2 \cdot Me_{2.1} + rv_3 \cdot Me_3 - \left(rv_{4.1} + rv_{4.3}\right) \cdot Me_4 - rv_{4.2} \cdot Me_{2.1} + rv_{5.1} \cdot Me_2 \\ & - rv_{5.2} \cdot Me_5 - rv_{5.3} \cdot Me_5 + rv_6 \cdot Me_6 - rv_{6.3} \cdot Me_5 + rv_{6.4} \cdot Me_{6.1} + rv_7 \cdot Me_7 - rv_{7.1} \cdot Me_4 - rv_{7.4} \cdot Me_5 \\ & - rv_{7.5} \cdot Me_5 + rv_{7.3} \cdot Me_{6.1} + rv_n \cdot Me_{8n} \end{aligned} \qquad (2)\ [25]$$

where, $rv_n\left(m^3, ton\right)$; $n = 1, 4.1, 4.2, 4.3, 5.1, 5.2, 6.3, 6.4, 7, 7.1, 7.4, 7.5$ (mass tons): represents volume; $n = 2, 3\left(m^3\right)$: bulk volume; $rv_n\left(set\right)$: set equivalent; and $n = 1, 4, 4.1, 5.1, 5.2, 5.3, 6, 6.3, 6.4, 7.1, 7.3, 7.4$; Me_n (*kg·CO₂*): *CO₂* unit requirement (*n*: based on Figure 4 and Table 7).



*1: *rvn* (m³, tons): Represents amount. Volume (m³) or weight (ton).
*rv***n** (set): Value of equivalent., Rm**n** (mass %): Recovery rate of recycled aggregate. (**n** = 1, 2), Incidence rate of fine powder. (**n** = 3), Rr**n** (%): Replacement ratio. (**n** = 1, 2, 3)
*2: The surplus of recycled coarse aggregate in Case 2 and recycled fine aggregate in Case 3 are sold as aggregate and/or roadbed gravel on site.
*3: In Case 2-2, the recycled coarse aggregate is used in precast concrete products.

Fig. 4 – Calculation flow for simulation.

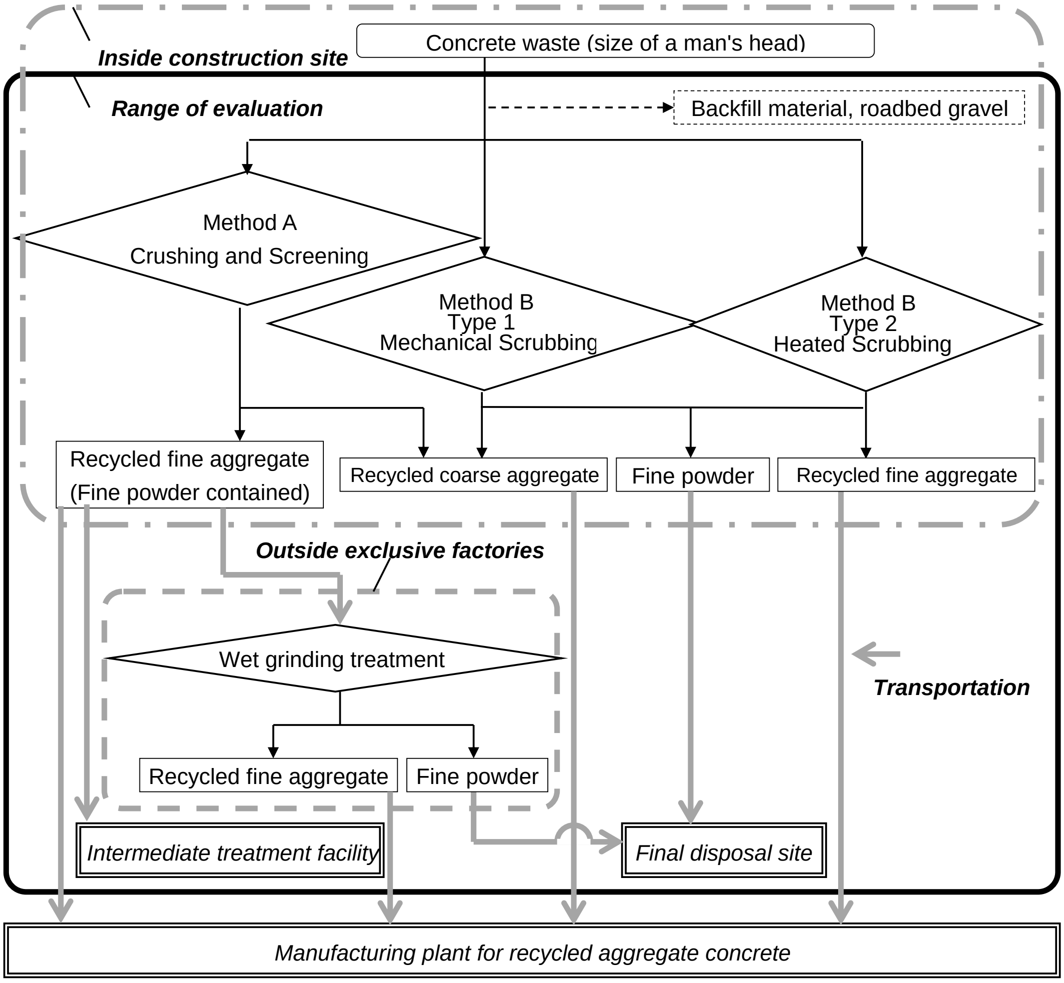


Fig. 5 – Flowchart of basic calculation conditions for recycled aggregate.

3.4 Simulation results

Figure 6 shows the simulation results. The recovery rate of recycled aggregate, the production of fine powder, and the replacement of recycled aggregate were varied as listed in Table 6. The amount of recycled aggregate manufactured, the intermediate treatment of the recycled fine aggregate and concrete waste, and the fine powder disposal were varied; further, cases involving the aggregate replacement method were varied widely (Case 2).

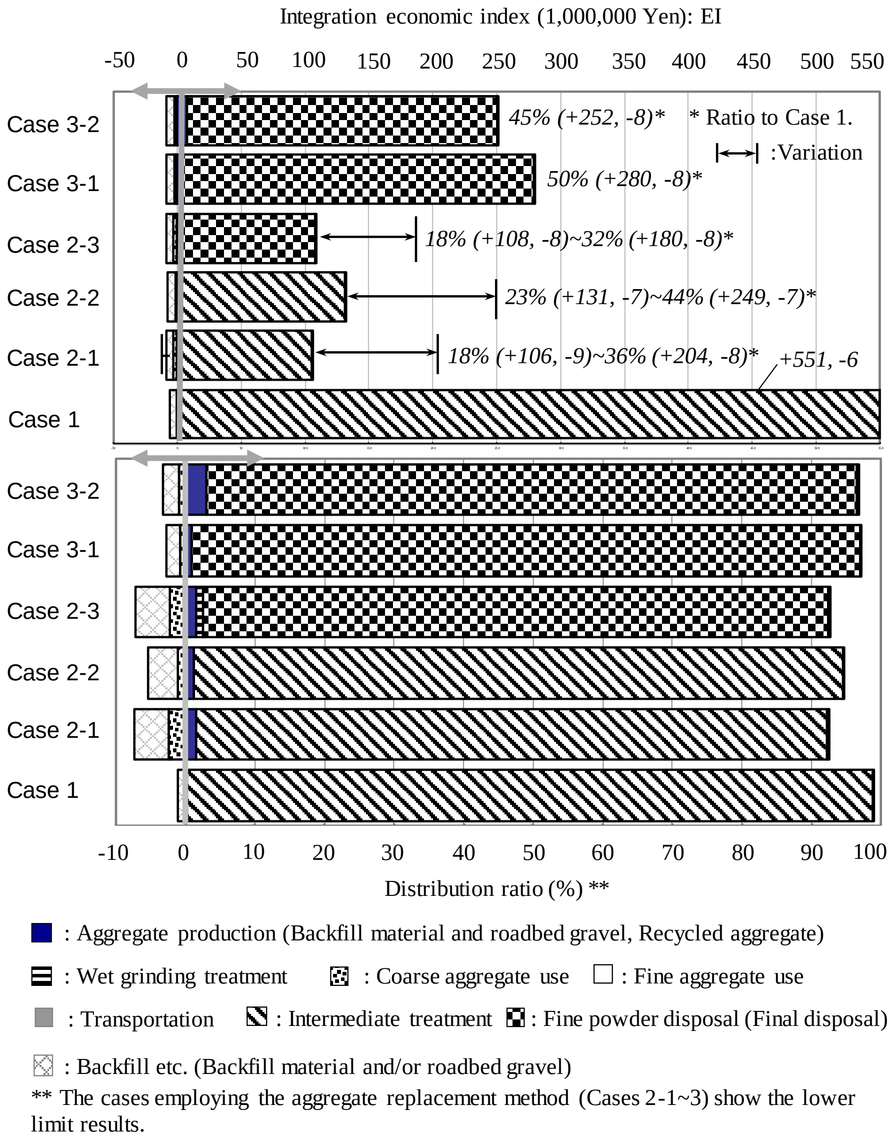
The simulation results indicate that the recycling system featured in Case 2, using the aggregate replacement method, can reduce the integration *EI* by 56%–82% compared with that in Case 1, in which reuse is limited to roadbed gravel and backfill. In contrast, in Case 3, which uses the aggregate refinement method, *EI* is reduced by 50%–55% as compared with that in Case 1.

Furthermore, the influence exerted by the treatment and disposal of industrial waste compared with the production of recycled aggregate is clearly made evident using the *EI* evaluation.

3.4.1 Verification of the evaluation result

The influence of the recycling system on the impact of concrete waste on the subjects in question is clearly apparent. Because the integration index (15.6 ¥/*kg*) for industrial waste is higher than the integration index (2.82 ¥/*kg*) for CO_2 emission and the integration index (0.092 ¥/*kg*) for resource consumption, industrial waste is considerably influenced by the recycling method, according to the *EI* evaluation.

In addition, the intermediate treatment of the non-recycled concrete waste and recycled fine aggregate and the disposal of fine powder have greater effects when compared with the manufacturing of recycled aggregate. In particular, the distribution ratios for Cases 2-3, 3-1, and 3-2 are clearly different in terms of the use of recycled aggregate in manufacturing systems, which generate a large quantity of fine powder; thus, the effect of recycling on the environmental impact is quite apparent.



** The cases employing the aggregate replacement method (Cases 2-1~3) show the lower limit results.

Fig. 6 – Simulation results.

3.4.2 Evaluation of the recycling system

In this simulation result, the recycling system that uses aggregate replacement, which generates less fine powder, has a lower environmental burden than the aggregate refinement method.

In terms of the distribution ratio (aggregate manufacturing, wet grinding treatment, and fine powder disposal), which are directly relevant to the manufacturing of recycled aggregate, when compared with Case 2-1 (1.1%) and Case 2-2 (1.5%), Cases 2-3, 3-1, and 3-2 have a high demand grade for aggregate quality and account for 92.3%–97.0% of the fine powder disposal.

Therefore, reducing the production of fine powder to prevent the leaching of toxic substances, such as hexavalent chromium 3, may mitigate the environmental burden associated with concrete recycling.

4 Utilization of Recycled Aggregate Concrete

In accordance with the environmental impact assessment reported in Section 3, a recycling system that uses recycled aggregate concrete in the aggregate replacement method, such as Case 2 in Figure 4, can be designed. This method generates less fine powder, presenting a lower environmental burden than aggregate refinement methods such as Case 3.

This study discusses material design and quality control for recycled aggregate concrete via a large-scale case study of the scrapping and rebuilding of an actual thermal power plant. This plant has almost the same scale as the simulation model; Table 4 presents its dimensions.

4.1 Manufacturing system for recycled materials

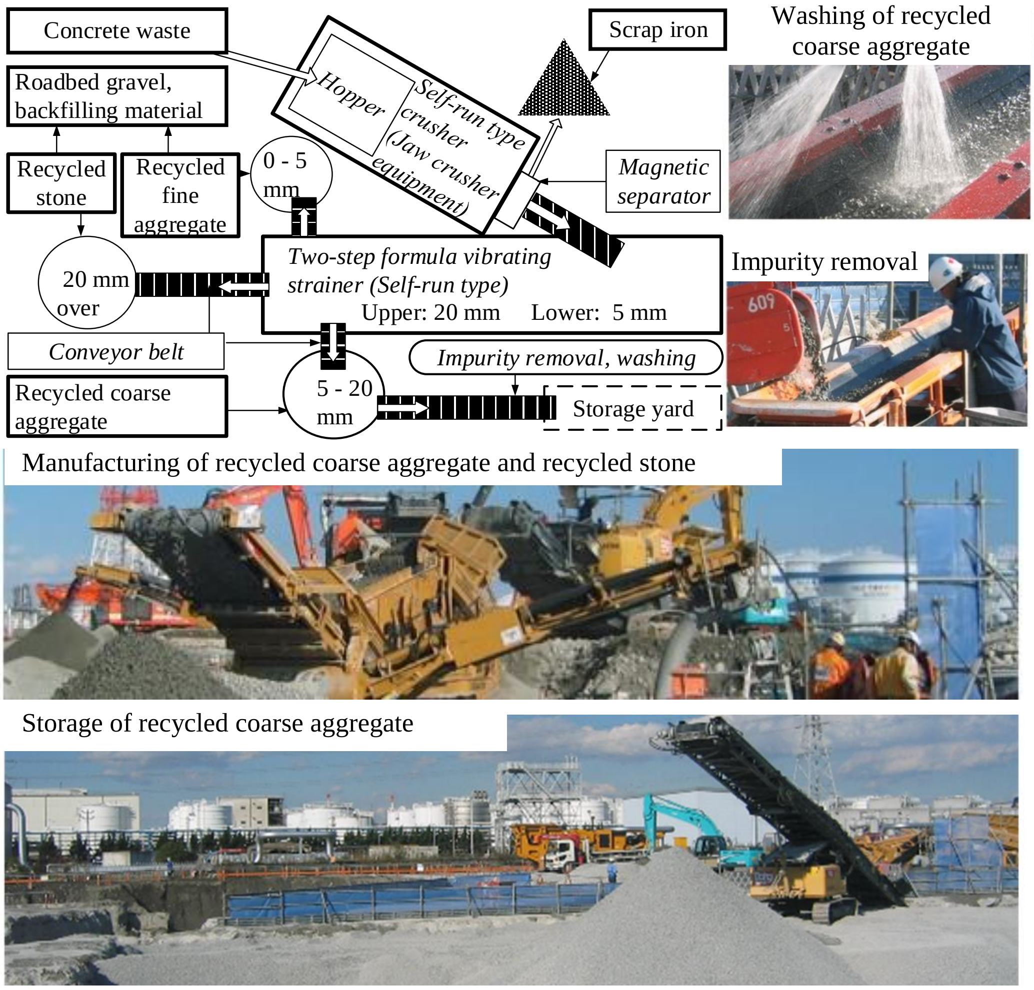


Fig. 7 – Manufacturing system for recycled materials [7].

This manufacturing system is simple and compatible with general-purpose equipment. Figure 7 shows the samples of the actual recycled coarse aggregate and recycled stone. Using this method, 33% of the total concrete waste can be used in structural concrete as recycled coarse aggregate. The remaining 67% can be used as fine aggregate and stone for manufacturing precast concrete products and as roadbed gravel.

4.2 Quality appraisal method

The relative quality index is used for assessing the aggregate quality and is expressed in Equation (3). The relative quality value and the main properties of the recycled aggregate concrete, such as the compressive strength, Young's modulus, and drying shrinkage-accelerated carbonation depth, are clearly correlated. Therefore, in the case of recycled aggregate concrete manufactured using the aggregate replacement method, the concrete mixture can be designed using this index to ensure compliance with the quality specifications [8]. The selection of the normal aggregate is significantly constrained by this value. For example, the drying shrinkage decreases the number of uses of crushed limestone [26].

$$QCt = \frac{QC_V G \cdot a + QC_V S \cdot b + QC_r G \cdot c + QC_r S \cdot d}{a+b+c+d} \quad (3)\ [8]$$

where,

$QCt\left(\%\right)$: relative absorption index;

$QC_V G\left(\%\right)$: absorption of normal coarse aggregates in recycled aggregate concrete;

$QC_V S\left(\%\right)$: absorption of normal fine aggregates (river sand, pit sand, crushed sand, etc.) in recycled aggregate concrete;

$QC_r G\left(\%\right)$: absorption of recycled coarse aggregate in recycled aggregate concrete;

$QC_r S\left(\%\right)$: absorption of recycled fine aggregate in recycled aggregate concrete; and a, b, c, and $d\left(L/m^3\right)$: absolute volumes of normal coarse aggregate, normal fine aggregate, recycled coarse aggregate, and recycled fine aggregate, respectively.

4.3 Approval of MLIT and actual application

Table 8 lists the specifications of the recycled aggregate concrete approved by MLIT for the aggregate replacement method. Based on advanced mixing design and quality control, this method was applied to 11,000 m^3 of structural concrete in the scrapping and rebuilding of the thermal power plant shown in Table 9 and Figure 8.

Table 8 - Outline of approval by MLIT.

Item	**Content**
Approval by MLIT	No. MCON-2090, 9 June 2009
Applicants	T Co. Ltd. S Co. Ltd. TK Co. Ltd. TS Co. Ltd
Authorization classification	Approval, All components in T Co. Ltd.'s owning buildings
Ready-mixed concrete factory	Tokyo: 9 factories, Kanagawa pre.: 5 factories, Chiba pre.: 2 factories
Specifications for recycled aggregate concrete	OPC[*1]: Fc = 21–33 N/mm^2 Slump = 15 and 18 cm LPC[*2]: Fc = 21–30 N/mm^2, Slump = 15 and 18 cm BB[*3]: Fc = 21–33 N/mm^2, Slump = 15 and 18 cm
Replacement ratio of recycled aggregate	Coarse aggregate: 50% (maximum), 30% (maximum)[*4] Fine aggregate: 30% (maximum)

*1 OPC: Ordinary Portland cement; used fly-ash type II(FAII) as admixture, FAII/(OPC+FAII) ≥20 mass% and/or ≥80 kg/m^3,
*2 LPC: Low-heat Portland cement, *3 BB: Portland blast-furnace slag cement type B. Only in an underground structure, *4 The case of using both the coarse and fine aggregates.

The specified slump is in the range of 15–18 cm, and the replacement ratio, which is the volume ratio to be replaced by recycled aggregate, is under 50%. The replacement ratio for recycled fine aggregate is under 30%, and when both are used together, the replacement ratio is under 30%. In addition to the ordinary Portland cement, type B slag cement and low-heat Portland cement, which can be used for mass-produced concrete, are included in the study. In addition, fly-ash JIS type II (FAII) is included as the admixture, which can be used to facilitate the anti-alkali–silica reaction [27].

Table 9 – Outline of concrete structures.

Item	**Content**
Place	Kanagawa Pre.
Date of concrete placement	December 2009 to May 2010
Volume of concrete waste	About 9,700 m^3
Volume of recycled aggregate	Coarse aggregate: about 3,200 m^3
Volume of concrete placement	Total: about 11,000 m^3; turbine building foundation of a thermal power plant: about 8,000 m^3, machine foundation of a thermal power plant*: about 3,000 m^3
Used volume of recycled stone in site	RC-40: about 6,500 m^3
Ready-mixed concrete factories	A, B and C (Kanagawa Pre.)
Specifications for recycled aggregate concrete	LPC: Fc = 21N/mm^2, Slump = 15 cm
Replacement ratio of recycled aggregate	Coarse aggregate: 50%

* Because the Building Standards Law did not apply to this structure, MLIT approval was not required; nevertheless, quality control was performed as per the MLIT approval requirements.

Fig. 8 – Appearance of concrete structures prepared using recycled aggregates [7].

4.3.1 Design and quality

When using the aggregate replacement method, the quality required for structural concrete can be ensured by choosing materials in accordance with the appropriate indices such as the relative absorption index and replacement ratio.

The replacement ratio can be determined by the relative quality value. Figure 9 shows the correlation between the relative absorption index and the main properties of the recycled aggregate concrete. These properties include the compressive strength, Young's modulus, drying shrinkage, and carbonation resistance.

4.3.1.1 Mix proportion

The mix proportion for the recycled aggregate concrete is based on JASS 5 (2009) [28]. From Table 10, we find that the strength of proportioning (F) is determined using Equations (4) and (5).

$$F \geq F_m + 1.73 \cdot \sigma = F_C + {}_mS_n + 1.73 \cdot \sigma \tag{4}$$

$$F \geq 0.85F_m + 3 \cdot \sigma = 0.85 \cdot \left(F_C + {}_mS_n\right) + 3 \cdot \sigma \tag{5}$$

where: F : strength of proportioning (N/mm^2); F_m : strength of proportioning control (N/mm^2); F_C : design strength (N/mm^2); ${}_mS_n$: in-situ strength correlation factor (N/mm^2) m = 28, n = 91; ${}_{28}S_{91}$ values were checked by experiment [29] (See Table 11); σ : standard deviation of the compressive strength for the use of concrete (N/mm^2). 4σ is assigned a high value of 2.5 or $0.1\cdot F_m$

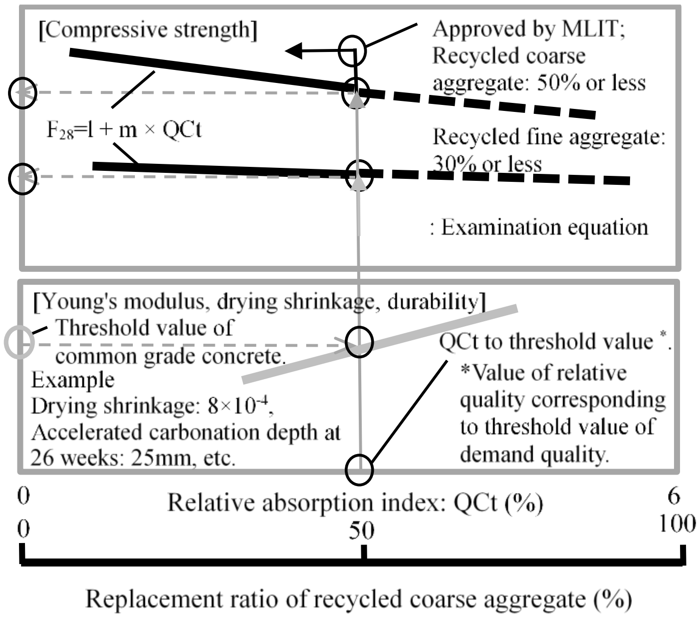


Fig. 9 – Example of the correlation between the relative absorption index and main properties of the recycled aggregate concrete.

Table 10 – Adopted strength of proportioning.

Type of cement	**Range of θ^*(°C)**	**Fc (N/mm^2)**	**$_{28}S_{91}$ (N/mm^2)**	**$F_m=F_c+{}_{28}S_{91}$ (N/mm^2)**	**σ (N/mm^2)**				**F (N/mm^2)**		
					Factory A	**Factory B**	**Factory C**	**Adoption value**	**Equation (2)**	**Equation (3)**	**Adoption value**
LPC	$14 \le \theta$	21	3	24	2.0	2.5	2.0	3.0	$F \ge 29.2$	$F \ge 29.4$	29.4
	$0 \le \theta < 14$		6	27	2.2	3.0	2.5		$F \ge 32.2$	$F \ge 32.0$	32.2

* Included use of fly-ash (FAII) as admixture.

Equation (6) shows the presumed cement-to-water ratio that satisfies the nominal strength for the relative absorption index in accordance with the ratio of the compressive strength reduction (R) from Equation (7) using concrete replacement ratios of 0% and 50%. Following Equation (7), Table 12 lists the relationships between the average strength required (F_{28}) and the cement-to-water ratio for the three actual plants.

$$F_{28} = l + m \cdot QC_t \qquad (6)\ [30]$$

where, F_{28} : average strength required at 28 days; QC_t (%): relative absorption index; l, m : experimental constant.

$W/C = 40\% : l = 43.79; m = -2.77$; $W/C = 50\% : l = 31.62; m = -1.94$

$$R = RG50F_{28} / RG0F_{28} \qquad (7)\ [30]$$

where, R : decreasing ratio of the compressive strength; $RG50F_{28}$: compressive strength of the recycled aggregate concrete for a replacement ratio of 50%; $RG0F_{28}$: compressive strength of the normal aggregate concrete.

Ready-mixed concrete factory A:
$W/C = 45\%$ and $R = 0.87$; $W/C = 55\%$ and $R = 0.87$
Ready-mixed concrete factory B:
$W/C = 45\%$ and $R = 0.88$; $W/C = 55\%$ and $R = 0.88$
Ready-mixed concrete factory C:
$W/C = 45\%$ and $R = 0.87$; $W/C = 55\%$ and $R = 0.88$

Table 11 – In-situ strength correlation factor of concrete.

Type of cement	Range of anticipated average temperatures of term until 28 days from concrete placement (°C)		
OPC*	Hottest season	$8 \le \theta$	$0 \le \theta < 8$
BB	Hottest season	$13 \le \theta$	$0 \le \theta < 13$
LPC	Hottest season	$14 \le \theta$	$0 \le \theta < 14$
$_{28}S_{91}$ (N/mm^2)	6	3	6

*Included used fly-ash (FAII) as admixture.

4.3.1.2 Quality control

Figure 10 shows the quality control process from the investigation of the original concrete to the application of the recycled aggregate concrete (Note 3). Quality control is performed according to construction specifications and manufacturing guidelines for the recycled aggregate concrete based on studies and experience. Quality control covers the processes for producing three materials: (a) original concrete, (b) recycled aggregate, and (c) recycled aggregate concrete. Any material that does not satisfy the quality specifications and/or manufacturing guidelines is precluded from use.

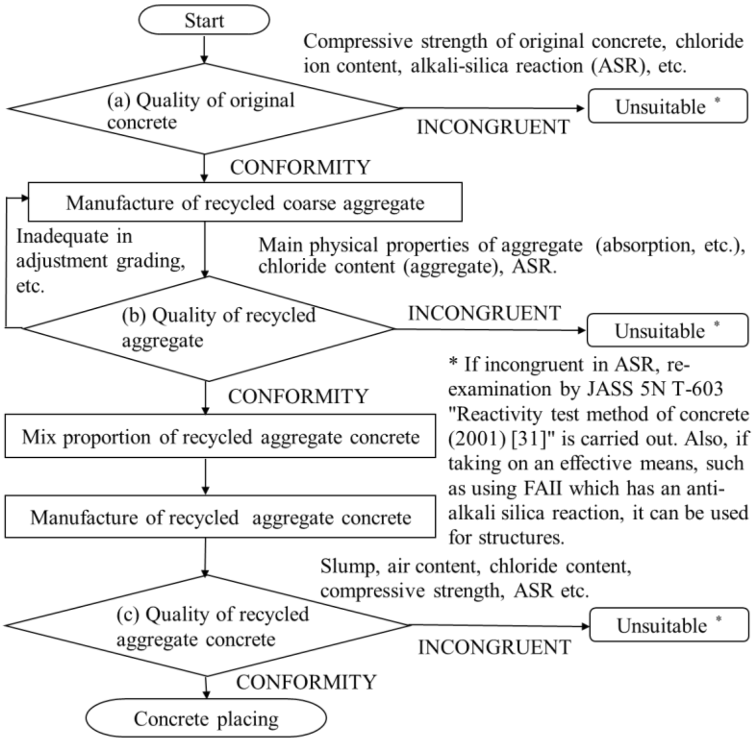
We noted some impact of unidentified alkali–silica reactions in the crushed stone coarse aggregate produced before 1986. Countermeasures against such alkali–silica reactions are important, and double or triple measures are recommended. In particular, the reactions must be tested for each process and if incongruent in ASR, a re-examination by adhering to JASS 5N T-603 “Reactivity test method of concrete (2001)” [31] is required. The restrictions on the total alkali content in concrete and the use of FAII for the admixture are specified.

Table 12 – Estimation equation of compressive strength.

Factory	Nominal strength	Estimation equation of compressive strength at 28 days (LPC,AE and water-reducing admixture)	
		Popular concrete: F_{28}	Compressive strength of recycled aggregate concrete for replacement ratio 50%: $F'_{28} = F_{28} \cdot R$
A	21 – 33	$F_{28} = -29.2 + 30.4 \cdot C/W$	$F'_{28} = -25.4 + 26.4 \cdot C/W$
B	21 – 24	$F_{28} = -18.7 + 24.8 \cdot C/W$	$F'_{28} = -16.5 + 21.9 \cdot C/W$
	27 – 33	$F_{28} = -4.73 + 18.1 \cdot C/W$	$F'_{28} = -4.16 + 16.0 \cdot C/W$
C	21 – 33	$F_{28} = -22.6 + 26.8 \cdot C/W$	$F'_{28} = -19.7 + 23.3 \cdot C/W$

4.3.1 Original concrete

As listed in Table 13, the main quality control parameters for the original concrete comprise the compressive strength (core) as specified by JIS A 1107 [32], chloride ion content in JIS A 1154 [33], and alkali–silica reaction in JIS A 1804 [34]. If the necessary data are available, such as from the construction records, and if the data indicate the production source and quality of the aggregate, design strength of the original concrete, and other necessary indicators, the inspection frequency can be reduced. When the construction records are unavailable, inspection must be conducted for one unit per 500 m^3 of the original concrete used. When the construction records are available, inspection must be conducted for one unit per 1,000 m^3.



- Construction specifications and manufacturing guidelines -

Standard for use of recycled aggregate concrete
- Recommendations for material design of recycled aggregate concrete
- Recommendations for character survey of original concrete
- Recommendations for manufacture of recycled aggregate
- Recommendations for manufacture of recycled aggregate concrete
  - Guidelines for designing concrete mixture
  - Guideline for selecting ready-mixed concrete factories
- Recommendations for acceptance and construction practices for recycled aggregate concrete

Fig. 10 – Quality control flow for recycled aggregate concrete.

Table 13 – Main quality control items for original concrete.

Item		Content		
Number of years elapsed		Approximately 49 years		
Use of the original structure		Turbine building foundation of a thermal power plant		
Fc (N/mm^2)		Unknown		
Main quality control items		Value of quality standard	Measurement result	
Compressive strength (N/mm^2)	JIS A 1107 [32]	18 or more	27.7 – 44.8	$\sigma = 6.6, n = 30$
Chloride ion content (kg/m^3)	JIS A 1154 [33]	0.3 or less	0.05 – 0.17	$\sigma = 0.04, n = 30$
Alkali–silica reaction	JIS A 1804 [34]	Harmless	Harmless, $n = 10$	

4.3.2 Recycled aggregate

Table 14 lists the quality values and standards related to the recycled coarse aggregate. When conducting manufacturing tests, investigations are performed on one unit per 1,000 tons of recycled coarse aggregate used. In addition, when acceptance tests are conducted at the ready-mixed concrete factory, investigations are performed on one unit per 500 *tons*.

4.3.2.1 Aggregate quality

The main quality control parameters for the recycled coarse aggregate are the density under oven-dry conditions (JIS A 1110 [35]), absorption (JIS A 1110 [35]), fineness modulus (JIS A 1102 [36]), content of materials finer than 75-μm sieve (JIS A 1103 [37]), chloride content (JIS A 5023 [6]), and alkali–silica reactions (JIS A 1804 [34], ZKT-206 [38]). The recycled coarse aggregate used under the approval of MLIT was manufactured from concrete waste from a demolished turbine building foundation of a thermal power plant, which is approximately 49 years old.

4.3.2.2 Impurities

The impurities due to finished building materials cause fluctuations in the quality of the recycled aggregate concrete. Paper and wood chips have a particularly considerable influence. To ensure that the minimum amount of finishing material is used in thermal power plant structures, the quantity of the impurities was kept to approximately one-hundredth or one-tenth of the rated value. This was because the finishing material was carefully removed before the demolition of the structure. In case of thermal power plants, very few impurities will be present compared with ordinary buildings because the main RC components are not covered with a finishing material. Dirt was removed by washing with water and screening, and other impurities were removed by hand.

Table 14 – Quality of recycled aggregate.

Content of test			**Examination item**	**Density in oven-dry condition (g/cm^3)**		**Absorption (%)**	**Fineness modulus (*F.M.*)**	**Content of materials finer than 75 μm sieve (%)**	**Amount of contained impurities (*mass%*)**	**Chloride content (%)**	**Alkali–silica reaction**	
			Measurement method	**JIS A1110 [35]**			**JIS A1102 [36]**	**JIS A1103 [37]**	**JIS A5021 [4]**	**JIS A5023 [6]**	**JIS A1804 [34]**	**ZKT-206 [38]**
Type of test	Factory	Test volume range (tons)	Value of quality standard	≥2.2	≤8.0	6.60±0.50*1	≤3.0	Total; ≤1.0	Paper, wood chip; ≤0.1	≤0.04	H	NA
Manufacture test	Lab.	0 – 1,000	Measurement result	2.25	7.29	6.78	2.68	0	0	0	H	-
		1,000 – 2,000		2.33	4.60	6.74	1.90	0	0	0.001	H	
		2,000 – 3,000		2.22	7.63	6.65	0.50	0.02	0	0	H	
		3,000 – 4,000		2.25	6.83	6.69	0.40	0	0	0.001	H	
		4,000 – 5,000		2.28	6.60	6.74	0.40	0	0	0	H	
Acceptance test	A	0 – 500		2.28	6.15	6.52	1.2	0.01	0	0.012	H*2	NA
		500 – 1,000		2.30	5.93	6.50	2.7	0.01	0	0.020	H*2	
		1,000 – 1,500		2.24	7.53	6.73	2.7	0.01	0	0.016	H*2	
		1,500 – 2,000		2.28	6.47	6.50	2.9	0.01	0	0.024	H*2	
		2,000 – 2,500		2.31	6.03	6.49	2.5	0.01	0	0.020	H*2	
		2,500 – 3,000		2.27	5.84	6.51	2.4	0.01	0	0.020	H*2	
	B	0 – 500		2.25	7.9	6.50	1.4	0.13	0	0.020	H*2	NA
		500 – 1,000		2.27	7.6	6.66	1.2	0.06	0	0.016	H*2	
		1,000 – 1,500		2.30	6.5	6.59	0.9	0.04	0	0.028	H*2	
		1,500 – 2,000		2.27	7.8	6.50	3.0	0.01	0	0.016	H*2	
	C	0 – 500		2.28	6.81	6.56	2.75	0.02	0	0.012	H*2	NA
		500 – 1,000		2.28	6.74	6.52	2.70	0.02	0	0.020	H*2	

H: Harmless; *1 Maximum size: 20 *mm*, *2 Check from test records. NA: No reactivity (A)

4.3.3 Recycled aggregate concrete

4.3.3.1 Quality control method

For proposing a mix design method for recycled aggregate concrete, the quality control parameters, including the compressive strength, drying shrinkage, and carbonation depth, were specified to ensure the target quality. Although the quality control during manufacturing and delivery was performed according to JIS A 5308 [39] in principle, a strict value is assumed for chloride content in consideration of the salt elution from the original mortar (JIS A 5023 [6]). Moreover, it must be confirmed that the recycled aggregate concrete is free from any alkali–silica reaction by examination using JIS A 1804 [34] and ZKT-206 [38] prior to construction. The alkali–silica reaction is considered the strictest quality control parameter for all the processes relevant to the recycled aggregate concrete and must be frequently inspected.

4.3.3.2 Quality control system

A quality control committee comprising the construction supervisor, building designer, builders (general contractors), and manufacturers (recycled aggregate manufacturing factory and ready-mixed concrete factories) collaborates on the quality and schedule controls.

Table 15 – Mix proportions of concrete.

Notation^{*1}	**F**	**NS**	**TC**	**Rca**	**QCt (%)**	**TS**	**TAC (%)**	**W/C (%)**	**s/a (%)**	**W**	**Content per unit of concrete (*kg/m*^{3})**						**CC**	**AV**
											C	**Aggregate**^{*2}				**Ad.**^{*3}	**≤0.3**^{*4}	**≤3.0**^{*4}
												G	**RG**	**S1**	**S2**			
A-24-L-NG^{*5}	A	224	LPC	50	0.88	15 ± 2.5	4.5 ± 1.5	51.9	44.8	169	326	1021	0	473	330	3.52		
A-24-L-RG0^{*6}					0.88			51.9	44.8	169	326	1020	0	476	331	3.53		
A-24-L-RG50					2.81			48.2	43.6	175	363	508	463	450	311	3.92	0.041	1.89
A-27-L-RG0^{*6}		227			2.87			49.5	44.2	171	345	1020	0	464	322	3.67		
A-27-L-RG50					2.83			45.9	42.7	175	381	513	463	437	303	4.11	0.043	1.99
B-24-L-RG0^{*6}	B	224			1.16			51.6	45.9	166	322	1006	0	494	334	2.90		
B-24-L-RG50					2.94			47.3	45.1	168	355	502	456	476	322	3.20	0.021	1.44
B-27-L-RG0^{*6}		227			1.15			49.1	45.3	166	338	1009	0	484	327	3.04		
B-27-L-RG50					2.95			43.4	43.8	171	394	502	456	452	306	3.55	0.022	1.59
C-24-L-RG0^{*6}	C	224			1.02			51.5	46.1	169	329	996	0	822	-	3.29		
C-24-L-RG50					2.88			47.5	44.9	171	360	500	453	788	-	3.60	0.025	1.44
C-27-L-RG0^{*6}		227			1.01			48.9	45.3	171	350	994	0	795	-	3.50		
C-27-L-RG50					2.90			45.0	44.9	175	390	500	453	754	-	3.90	0.026	1.55

*1 Ready-mixed concrete: factory - nominal strength - cement – aggregate (replacement ratio in case of recycled aggregate concrete, *2 G: Crushed limestone (absorption: 0.33%–0.70%), RG: Recycled coarse aggregate, S1: Pit sand (absorption: 1.72%–2.14%), S2: Crushed lime sand (absorption: 1.03%–1.32%), *3 Ad.: AE and water-reducing admixture, *4 Value calculated as per JIS A 5023 [6]. *5 Only the sample for concrete properties, *6 Standard mixing design for concrete with a replacement ratio of 0% to calculate R. **F**: Factory; **NS**: Nominal strength; **TC**: Type of cement; **Rca**: Replacement ratio of recycled coarse aggregate (%); **TS**: Target slump (*cm*); **TAC**: Target air content (%); **W**: Water (*kg/m*^{3}); **CC**: Chloride content (*kg/m*^{3}); **AV**: Alkali volume (*kg/m*^{3})

4.3.3.3 Quality control results

To ensure that all the quality requirements are satisfied, the validity of the material design was confirmed using the relative quality index. Table 15 lists the mix proportions of the recycled aggregate concrete used in the actual structures. Table 16 lists the typical examples of the quality control results. In terms of the surface moisture (JIS A 1803 [40]), the appearance of fresh concrete, slump (JIS A 1101 [41]), air content (JIS A1128 [42]), concrete temperature (JIS A 1156 [43]), chloride content (JIS A 5308 9.6 [39], JIS A 5023 [6]), and compressive strength (JIS A 1108 [44] and JIS A 1132 [45]), all the specimens satisfied the requirements. As shown in Figure 11 [46], the recycled aggregate concrete was manufactured at general-purpose facilities using the same processes as those employed for the normal aggregate concrete [39]. Over a range of demand quality, it is impossible to mix the concrete using the same proportions as with ready-mixed concrete under JIS A 5308 [39].

Furthermore, to ensure that all the quality requirements were satisfied, the validity of the material choice was confirmed using the relative quality index.

4.3.3.4 Concrete performance

Table 17 lists the main properties of the concrete used in this study. The main properties of the concrete manufactured by factory A were tested, and the results were used to check for any deterioration in the performance compared with that of the normal aggregate concrete.

Table 16 – Quality control result of the recycled aggregate concrete.

T_i	**T_m**	**T_f**	**C_v**		**A-24-L-RG50**	**A-27-L-RG50**	**B-24-L-RG50**	**B-27-L-RG50**	**C-24-L-RG50**	**C-27-L-RG50**
S_m	JIS A 1803 [40]	Oper W	Nav		0.7 – 1.1		0.5 – 1.0		0.5 – 1.5	
Cfc	Vc	All ac	GC		All g	All g	All g	All g	All g	All g
Su	JIS A 1101 [41]	UrUa Oper 150 m^3	15.0 ± 2.5		13.0–17.5	14.0–17.5	14.0–16.5	13.5–17.0	15.5–17.0	16.0–17.0
					14.0–17.0	14.0–17.0	15.5–16.5	14.5–17.5	16.0–16.5	15.5–17.0
Ac[*1]	JIS A 1128 [42]		4.5 ± 1.5		3.1–5.5	3.1–4.6	3.2–5.1	3.0–4.4	3.6–4.5	3.5–4.1
					3.7–5.5	3.3–4.5	3.2–4.2	3.1–3.9	4.0–4.2	3.7–4.3
Ct	JIS A 1156 [43]		5〜35		11.0–24.0	10.0–16.0	12.0–23.0	9.0–20.0	19.0–24.0	13.0–16.0
					11.3–23.3	10.0–17.0	12.0–26.3	9.0–19.3	19.7–24.7	13.3–16.0
Cc	JIS A 5308 9.6 38 [39]	UrUa Oper day	0.30 or less		0.03–0.04	0.02–0.04	0.03–0.07	0.02–0.05	0.02	0.03
					0.03–0.08	0.02–0.09	0.03–0.07	0.02–0.05	0.04–0.06	0.02–0.03
	JIS A 5023 [6]				0.06[*2]	0.06[*2]	0.09–0.25	0.04–0.16	0.06	0.08
					0.22[*2]	0.26[*2]	0.09–0.25	0.04–0.16	0.13–0.21	0.04–0.08
Cs[*3]	JIS A 1108 [44] JIS A 1132 [45]	UrUa Oper 150 m^3	$X \geq 24.0, 27.0$ $X_{min} \geq 20.4, 23.0$	X	30.3–38.7	30.0–43.4	33.9–44.0	37.1–48.1	37.3–41.8	40.5–46.0
				X_{min}	29.9	29.0	33.6	36.8	36.8	40.0
				X	31.6–35.6	34.4–43.9	32.7–42.6	37.6–46.2	35.4–39.5	35.5–38.6
				X_{min}	30.7	32.2	30.7	35.9	35.0	34.9

*1 Aggregate correction factor: 0.2%, *2 Maximum value, *3 Test lot is constituted by concrete placement area and day. $X \geq F_c + {}_mS_n$; X is the average test value from three tests per lot. $X_{min} \geq 0.85 \times (F_c + {}_mS_n)$; X_{min} is the minimum value from one test (average test value for three examination samples) in the test lot.

T_i: Test item; **T_m**: Test method; **T_f**: Test frequency; **C_v**: Control value; **S_m**: Surface moisture (%); **Cfc**: Condition of fresh concrete; **Su**: Slump (cm); **Ac**[*1]: Air content (%)[*1]; **Ct**: Concrete temperature (°C); **Cc**: Chloride content (kg/m^3); **Cs**[*3]: Compressive strength[*3] (N/mm^2); UrUa Oper 150 m^3: Upper; Result of manufacture test, Under; Acceptance test, Once per 150 m^3; UrUa Oper day: Upper; Result of manufacture test, Under; Acceptance test, Once per day; Vc: Visual confirmation; Nav: No abnormal value; GC: Good condition; Oper W: Once per week; All ac: All agitator car; All g: All good

An examination object for core samples of the recycled aggregate concrete was installed near the structures in question and was monitored to confirm the main quality criteria (compressive strength JIS A 1107 [32], Young's modulus JIS A 1149 [47], carbonation depth JIS A 1107 [32], JIS A 1152 [48], and salt osmosis depth JIS A 1154 [33]). In the acceptable range for slump (JIS A 1101 [41]) at 15 ± 2.5 cm and air content (JIS A 1128 [42]) at 4.5 ± 1.5%, it is possible to mix the concrete using the same proportions as the normal aggregate concrete.

The density (JIS A 1116 [49]) of the recycled aggregate concrete is less than that of the normal aggregate concrete. The test results for chloride content (JIS A 5308 9.6 [39]), compressive strength (JIS A 1108 [44]), Young's modulus (JIS A 1149 [47]), and accelerated carbonation depth (JIS A 1152 [48] and JIS A 1153 [50]) revealed no difference between the recycled aggregate and normal aggregate.

Fig. 11 – Construction status using recycled aggregate concrete [46].

Table 17 – Main properties of concrete.

Item	Test method	Age	Target value	Measurement result			
				A-24-L-NG		A-24-L-RG50	
				Standard curing or based on test method	Core[*1]	Standard curing or based on test method	Core[*1]
Slump (*cm*)	JIS A1101 [41]	-	15± 2.5	17.5		12.5	
Air content (%)	JIS A 1128 [42]	-	4.5 ± 1.5	5.2		4.9 (0.2[*3])	
Density (*kg*/*m*^{3})	JIS A1116 [49]	-	-	2304		2250	
Chloride content (*kg*/*m*^{3})	JIS A 5308 9.6 [39] (Mohr Method)	-	≤0.30	0.040		0.036	
Compressive strength (*N/mm*^{2})	JIS A 1107 [32] JIS A 1108 [44]	28 days	≥27	27.2	-	29.5	-
		91 days	-	42.3	(46.5)[*4]	42.4	(46.4)[*4]
		182 days	-	-	51.1	-	50.9
Young's modulus (*kN*/*mm*^{2})	JIS A 1149 [47]	28 days	-	26.8	-	25.5	-
		91 days	-	30.8	(30.6)[*4]	29.8	(28.0)[*4]
		182 days	-	-	33.0	-	29.9
Drying shrinkage (10^{-4})	JIS A 1129-3 [51]	182 days	≤8	6	-	8	-
Carbonation depth (*mm*)	JIS A 1107 [32] JIS A 1152 [48]	182 days	-	-	0.8	-	0.4
Accelerated carbonation depth (*mm*)	JIS A 1152 [48] JIS A 1153 [50]	182 days	≤25	24.5	-	21.5	-
Chloride ion content in 30-45 *mm*[*2] (*kg*/*m*^{3})	JIS A 1154 [33]	182 days	-	-	0.046	-	0.091
Dynamic modulus of elasticity (%)	JIS A 1148 [52] (Method A)	300 cycles	≥60	91	-	71	-

*1 Based on JIS A 1107 [32], *2 Chloride ion content 30–45 mm from the concrete surface, *3 Aggregate correction factor, *4 For reference as these values were tested at 98 days.

The chloride ion content in the recycled aggregate concrete at a depth of 30 to 45 *mm* was somewhat higher than that of the normal aggregate concrete. However, this slight difference is of little significance in most practical applications.

The drying shrinkage (JIS A 1129-3 [51]) of the recycled aggregate concrete was 8×10^{-4}, which was 2×10^{-4} higher than that of the normal aggregate concrete. Nevertheless, the target value of the drying shrinkage of 8×10^{-4} or less was satisfied. The relative dynamic modulus of elasticity (JIS A 1148 [52]) of the recycled aggregate concrete after 300 cycles was 71%, which was 20% lower than that of the normal aggregate concrete. Nevertheless, the target value of the relative dynamic modulus of elasticity of 60% or more was satisfied.

These results confirmed that the performance does not deteriorate compared with that of the normal aggregate concrete; if it deteriorates, the target values are satisfied. This confirms that the material design process using the relative quality index is valid for planning the use of recycled concrete aggregate.

5 Conclusions

This study confirmed the feasibility of using low-quality recycled aggregate by conducting a LIME analysis. The study results are summarized as follows:

(1) The impacts of resource cycles, such as the crude oil consumption, land use for waste disposal, and use of normal aggregate, on the environment were evaluated using an integrated EI. This evaluation showed that a recycling system using recycled aggregate for aggregate replacement generates less fine powder waste, which had a better environmental impact reduction than the aggregate refinement method.

(2) Concrete prepared using the aggregate replacement method can be used as structural concrete when the raw materials selected adhere to the related quality standards. This system effectively recycles concrete waste after demolition while reducing the environmental burden. With suitable material design and quality controls, aggregate replacement can be generally applied to the scrapping and rebuilding of structures (Note 4).

(3) The results of this study provide evidence for the effectiveness of using low-quality recycled aggregate concrete such as Class L specified in JIS A 5023.

Notes

Note 1) According to the Architectural Institute of Japan (AIJ) [7], all aggregates, except for the recycled aggregate, are defined as normal aggregates.

Note 2) According to the AIJ [7], concrete, except for recycled aggregate concrete, is defined as normal aggregate concrete.

Note 3) For the approval of MLIT on September 15, 2004 (MCON-0979) [8], MCON-2090 was mainly made to be substantial as a countermeasure against the alkali–silica reactions.

Note 4) The aggregate replacement method obtained as a result of this study was reflected in JIS A 5022 [53] and JASS 5 [54] that were revised in 2018.

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REFERENCES

[1]- H. Klee, The cement sustainability initiative: recycling concrete. World Business Council for Sustainable Development (WBCSD): Geneva, Switzerland, 2009.
[2]- Result of actual status investigation into construction waste in fiscal 2018 (census). Ministry of Land, Infrastructure, Transport and Tourism, 2020.
[3]- Leaching of Minor Elements from Concrete. Concrete Library 111, Japan Society of Civil Engineers, 2003.
[4]- J.S. Association, JIS A 5021: Recycled aggregate for concrete, class H. Japanese Standards Association Tokyo, Japan, 2005.
[5]- J.S. Association, JIS A 5022: Recycled aggregate for concrete, class M. Japanese Standards Association Tokyo, Japan, 2007.
[6]- J.S. Association, JIS A 5023: Recycled concrete using recycled aggregate class L. Japanese Standards Association Tokyo, Japan, 2006.
[7]- Recommendation for mix design, production and construction practice of concrete with recycled concrete aggregate.

Architectural Institute of Japan, 2014

[8]- Y. Dosho, Development of a sustainable concrete waste recycling system. J. Adv. Concrete Technol. 5(1) (2007) 27-42. doi:10.3151/jact.5.27.

[9]- H. Tachi, N. Mizoguchi, H. Okamoto, Y. Dosho, Application to actual structure of recycled aggregate concrete by aggregate replacing. Proc Jpn. Concr. Inst. 32(1) (2010) 1463-1468.

[10]- Y. Dosho, Various performance of concrete replaced to low quality recycled aggregate. Proc Jpn. Concr. Inst. 37(1) (2015) 1393-1396.

[11]- Y. Dosho, A Use to Precast Concrete Products of Recycled Aggregate Concrete produced by Aggregate Replacing. Concrete Research and Technology, 20(2) (2009) 2-13 - 2_26. doi:10.3151/crt.20.2_13.

[12]- The Development of Assessment Technology for Life Cycle Environment Impacts of Products and so forth. Results Report. Japan Environmental Management Association for Industry, 2003.

[13]- M. Goedkoop, De Eco-indicator 95, Eindrapportage (Final report in Dutch); NOH report 9514; PRé consultants; Amersfoort (NL), 1995.

[14]- M. Goedkoop, R. Spriensma, The Eco-indicator 99: a damage oriented method for life cycle assessment, methodology report. PreConsultans BV, The Netherlands, 12 (2000).

[15]- Japan Society of Civil Engineers , Recommendation of environmental performance verification for concrete structures (Draft). Concrete Library 125 (2005).

[16]- New Energy and Industrial Technologies Development Organization (NEDO), Development of Technology to Assess and Verify Product Life Cycle Carbon Dioxide Emissions - Development of Assessment Methods for Efficient Progress of Environmental Technology - Development of Life Cycle Assessment (LCA) Method for Products and Systems. Results Report. 2006.

[17]- Ministry of Economy, Trade and Industry and Ministry of the Environment, Ministerial Ordinance regarding the Calculation of Greenhouse Gas Emission concerning the Business Activities of Specific Emitters. Ministerial Ordinance No. 3, 2006.

[18]- J.S. Association, JIS A 5372: Precast Reinforced Concrete Products. Japanese Standards Association Tokyo, Japan, 2004.

[19]- J.S. Association, JIS A 5371: Precast Unreinforced Concrete Products. Japanese Standards Association Tokyo, Japan, 2004.

[20]- K. Yanagibashi, A study on utilization of quality improvement technology of recycled aggregates using an eccentric rotor mill. Osaka City University, 2005.

[21]- Y. Kuroda, H. Hashida, N. Uchiyama, Y. Nachi, N. Yamazaki, Y. Miyachi. A closed-loop concrete system on a construction site. in Proceeding of international symposium on sustainable development of cement, concrete and concrete structures. Toronto, Canada. (2005) 371-388.

[22]- Y. Dosho, M. Kikuchi, M. Narikawa, A. Ohshima, A. Koyama, T. Miura, Application of Recycled Concrete for Structural Concrete- Experimental Study on the Quality of Recycled Aggregate and Recycled Aggregate Concrete. ACI Symposium Publication, 179(1998) 1073-1101.

[23]- A.I. Japan, Guidelines for Life Cycle Assessment of Buildings, Architectural Institute of Japan, Japanese Architectural Standard Specification, 2006.

[24]- K. Kobayashi, T. Mamiya, T. Inoue, Issues and evaluation of environmental load of building demolition waste disposal : Clarificaiton of issues an quantitive influence evaluation based on field survey. J. Environ. Eng. Trans-AIJ. 69(582) (2004) 115-121. doi:10.3130/aije.69.115.

[25]- Y. Dosho, Y. Mura, Recycling system of concrete waste incurred from building demolition - Evaluation of recycling concrete waste using “Life-cycle Impact assessment Method based on Endpoint modeling ; LIME&rdquo. AIJ J. Technol. Des. 14(28) (2008) 393-398. doi:10.3130/aijt.14.393.

[26]- Y. Dosho, Improvement in quality of concrete using recycled coarse aggregate class L. Proc Jpn. Concr. Inst. 39(1) (2017) 1525-1530.

[27]- N. Mizoguchi, H. Tachi, Y. Kaneko, Y. Dosho, Effect of controlling for alkali silica reaction due to fly ash mixing in recycled aggregate concrete. Proc Jpn. Concr. Inst. 33(1) (2011) 1553-1558.

[28]- A.I. Japan, JASS 5 Reinforced Concrete Work, Architectural Institute of Japan, Japanese Architectural Standard Specification. 2009.

[29]- Y. Dosho, In-situ strength correlation factor of concrete replaced to low quality recycled aggregate. Proc Jpn. Concr. Inst. 38(1) (2016) 1779-1784.

[30]- Y. Dosho, Y. Mura, Mixing design and quality control of recycled aggregate concrete used in large-scale applications - Recycling system of concrete waste incurred from building demolition. AIJ J. Technol. Des. 20(44) (2014) 19-24. doi:10.3130/aijt.20.19.

[31]- A.I. Japan, JASS 5N Reinforced Concrete Work at Nuclear Power Plants, Architectural Institute of Japan, Japanese Architectural Standard Specification. 2001.

[32]- J.S. Association, JIS A 1107: Method of sampling and testing compressive strength of drilled cores of concrete. Japanese Standards Association Tokyo, Japan, 2002.

[33]- J.S. Association, JIS A 1154: Method of test for chloride ion content in hardened concrete. Japanese Standards Association Tokyo, Japan, 2003.

[34]- J.S. Association, JIS A 1804: Methods of test for production control of concrete - Method of rapid test for identification of alkali-silica reactivity of aggregate. Japanese Standards Association Tokyo, Japan, 2001.

[35]- J.S. Association, JIS A 1110: Methods of test for density and water absorption of coarse aggregate. Japanese Standards Association Tokyo, Japan, 2006.

[36]- J.S. Association, JIS A 1102: Method of test for sieve analysis of aggregate. Japanese Standards Association Tokyo, Japan, 2006.

[37]- J.S. Association, JIS A 1103: Method of test for amount of material passing sieve 75 μm in aggregate. Japanese Standards Association Tokyo, Japan, 2006.

[38]- ZKT-206.: Rapid test method for alkali-silica reactivity of concrete. National Federation Ready-mixed Concrete Industrial Association (ZENNAMA), 2007.

[39]- J.S. Association, JIS A 5308: Ready-mixed concrete. Japanese Standards Association Tokyo, Japan, 2003.

[40]- J.S. Association, JIS A 1803: Methods of test for production control of concrete - Method of rapid test for surface moisture in coarse aggregate. Japanese Standards Association Tokyo, Japan, 2009.

[41]- J.S. Association, JIS A 1101: Method of test for slump of concrete. Japanese Standards Association Tokyo, Japan, 2005.

[42]- J.S. Association, JIS A 1128: Method of test for air content of fresh concrete by pressure method. Japanese Standards Association Tokyo, Japan, 2005.

[43]- J.S. Association, JIS A 1156: Method of measurement for temperature of fresh concrete. Japanese Standards Association Tokyo, Japan, 2006.

[44]- J.S. Association, JIS A 1108: Method of test for compressive strength of concrete. Japanese Standards Association Tokyo, Japan, 2006.

[45]- J.S. Association, JIS A 1132: Method of making and curing concrete specimens. Japanese Standards Association Tokyo, Japan, 2006.

[46]- Y. Dosho, Sustainable concrete waste recycling system - Use of low-quality recycled aggregate for structural concrete. J. Concrete Technol. 33(11) (2014) 74-80.

[47]- J.S. Association, JIS A 1149: Method of test for static modulus of elasticity of concrete. Japanese Standards Association Tokyo, Japan, 2010.

[48]- J.S. Association, JIS A 1152. Method for measuring carbonation depth of concrete. Japanese Standards Association Tokyo, Japan, 2002.

[49]- J.S. Association, JIS A 1116: Method of test for unit mass and air content of fresh concrete by mass method. Japanese Standards Association Tokyo, Japan, 2005.

[50]- J.S. Association, JIS A 1153: Method of accelerated carbonation test for concrete. Japanese Standards Association Tokyo, Japan, 2003.

[51]- J.S. Association, JIS A 1129-3: Method of measurement for length change of mortar and concrete–Part 3. Method with dial gauge. Japanese Standards Association Tokyo, Japan, 2010.

[52]- J.S. Association, JIS A 1148: Method of test for resistance of concrete to freezing and thawing. Japanese Standards Association Tokyo, Japan, 2010.

[53]- J.S. Association, JIS A 5022: Recycled aggregate concrete - Class M. Japanese Standards Association Tokyo, Japan, 2018.

[54]- A.I. Japan, JASS 5 Reinforced Concrete Work, Architectural Institute of Japan, Japanese Architectural Standard Specification, 2018.