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Scientific paper

Improving the Quality of Recycled Fine Aggregate by Selective Removal of Brittle Defects

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Abstract

Crushed recycled aggregate contains particles with brittle defects such as cracks, pores, and voids. This study presents a method for improving the quality of recycled fine aggregate by selectively removing these defects. Fourteen recycled fine aggregates were manufactured by three types of processors including a jaw crusher, ball mill, and granulator. The influence of the recycled fine aggregate on the flowability and strength of the mortar was evaluated by multivariate analysis. The results showed that flowability was mainly affected by the filling fraction of the recycled fine aggregate and the content of components passing through a 0.075-mm sieve. Both the compressive and flexural strengths of the recycled mortars were unaffected by the filling fraction, but they were affected by the fraction of defects in the aggregate and its surface smoothness. In addition, the results clearly showed that polishing involved in ball mill or granulator processing is effective both for increasing the filling fraction of recycled fine aggregate and reducing the fraction of defects in the aggregate. Moreover, it was determined that the grain surface of grains was more irregular with the granulator than that with the ball mill, resulting in higher strength of the mortar subjected to the granulator. The fracture configuration resulting from flexural stress on the recycled fine aggregate in the mortar differed according to the type of aggregate. Furthermore, the calculated amounts of emitted CO_2 and the compressive strength of the recycled mortar showed that the recycled fine aggregate should not be polished excessively.

1. Introduction

Large volumes of aggregate are produced and consumed in the production of concrete and roads. **Figure 1** shows the volumes of aggregate used in Japan according to statistics provided by the Ministry of Economy, Trade and Industry (METI). In 2009, approximately 278 million tons of aggregate were used for concrete and approximately 112 million tons were developed into roads. (METI 2009). This aggregate is used in general construction and to improve the infrastructure. However, issues related to the destruction of nature and the depletion of resources during the mining of the aggregate should be considered.

The demolition of concrete structures generates large volumes of concrete waste, equivalent to approximately 35 million tons per year in Japan and comprising approximately 40-% of all construction waste (MOE 2010). Most of this concrete waste is recycled as roadbed gravel. Aqil *et al*. reported that well-compacted crushed concrete is considered as the highest class of roadbed gravel when it is well compacted. However, demand for aggregate for road construction has declined since 1990, as suggested in **Fig. 1**, because of a decrease in public works projects (Shibuya *et al.* 2008). Calculations show that the discharged amounts of concrete waste will reach twice the volume of the recycled concrete in 2020 in some prefectures (Fujikawa *et al.* 2006). As a result, there is a growing awareness of other uses of concrete waste in Japan.

An additional problem is insufficient space for landfills. The annual volume of industrial waste dumped is approximately 40 million m^3 per year, and the available landfill capacity is only 180 million m^3, and is steadily decreasing. The provision of new landfill sites is extremely difficult due to protests by the neighboring communities. Moreover, dumping concrete waste in landfills is undesirable.

In view of the above considerations, the use of recy-

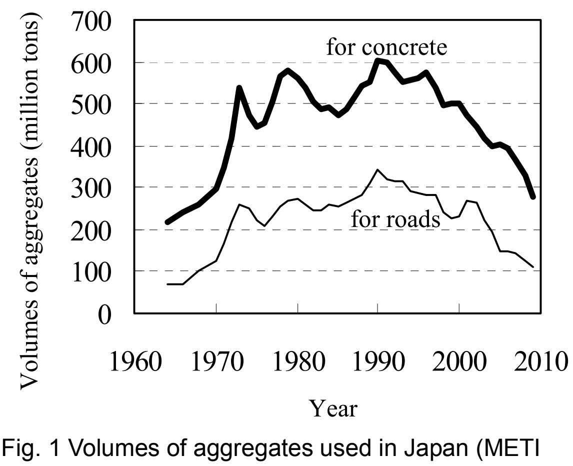

Fig. 1 Volumes of aggregates used in Japan (METI 2009).

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cled aggregate is one way to alleviate the various problems, in that it helps reduce the consumption of natural aggregate, promotes the effective use of concrete waste and reduces the problems related to the lack of landfill sites. Recycled aggregate made from concrete waste would be an attractive alternative to virgin aggregate in new concrete. However, most of the concrete waste worldwide is either dumped in landfills or used as roadbed gravel; few countries use recycled aggregate in concrete. Although standards for recycled aggregate in concrete exist in Japan (JIS A 5021, JIS A 5022, JIS A 5023), the U.K. (BS8500), and Germany (DIN 4226-100), no such standards have been established by the American Society for Testing and Materials (ASTM).

Figure 2 shows the concept guiding the present study, which involves the relationship between adhered cement paste rates of the recycled aggregate and the performance of the recycled concrete. When used as an aggregate for new concrete, the recycled crushed concrete alone does not perform as well as the commonly used aggregate, as suggested by point [a] in **Fig. 2** (Limbachiya *et al.* 2004; Konin 2011; Matsushita *et al.* 2006). Other studies have reported the possibility of improving the performance of the recycled concrete by reducing the adhered cement paste rate of the recycled aggregate (Fumoto *et al.* 2002; Kiji *et al.* 2003). As suggested by point [b] in **Fig. 2**, if this rate is reduced further, a concrete with performance similar to that of commonly used virgin aggregate can be obtained(Abe 1997; Shima *et al.* 2005; Ishikura *et al.* 2004; Hayakawa *et al.* 2003). For a class H (JIS A 5021) recycled aggregate, the paste adheres slightly to the aggregate to yield a concrete identical to that obtained using commonly available aggregate. A waste-concrete-recycling method that uses recycled class H aggregate manufactured by heating and rubbing has been proposed (Tateyashiki *et al.* 2001). In addition, recycled aggregate H was used in actual structures (Kuroda *et al.* 2004), and good-quality recycled concrete can be manufactured by using different manufacturing equipment (Shintani *et al.* 2006). One study has presented the results of 17 cases from 1999 to 2005 in which recycled aggregate H was used in actual structures (Yanagibashi 2008).

Alternatively, a method for manufacturing aggregate in which most of the paste is not separated from the recycled aggregate has been investigated, removing only the brittle parts of the recycled aggregate particles (Nawa *et al.* 2006a). This study mainly used an attrition mill, which is a type of autogenous mill (Nawa 2005; Nishida *et al.* 2005; Nawa *et al.* 2006b), to manufacture recycled coarse aggregate and to examine the relationship between aggregate quality and concrete characteristics. As suggested by point [c] in **Fig. 2**, a performance similar to that of concrete was possible with the commonly used aggregate although the adhered cement paste rate of the recycled coarse aggregate was high. Specifically, the mechanical properties and chloride permeability of the recycled concrete were equal or superior to those of the concrete with virgin natural gravel.

Figure 3 shows the relationship between the adhered cement paste rate of recycled aggregate and (a) economy, (b) amount of by-product produced, and (c) environmental impact expressed as the amount of emitted CO_2. Separating a larger amount of adhered paste increases the manufacturing cost (Morales *et al.* 2011), the volume of the generated by-product powder, and environmental impact (Ogawa *et al.* 2011). Therefore, retaining the cement paste adhered to the original aggregate instead of separating it during the production of recycled aggregate carries substantial advantages.

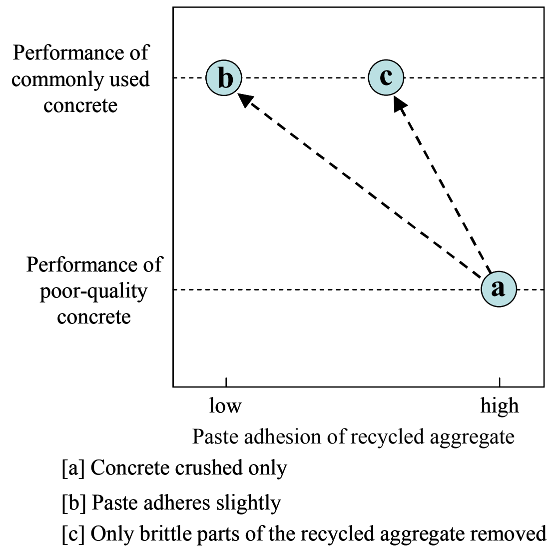


Fig. 2 Concept of the relationship betweem adhered cement paste rates of the recycled aggregate and the performance of recycled concrete.

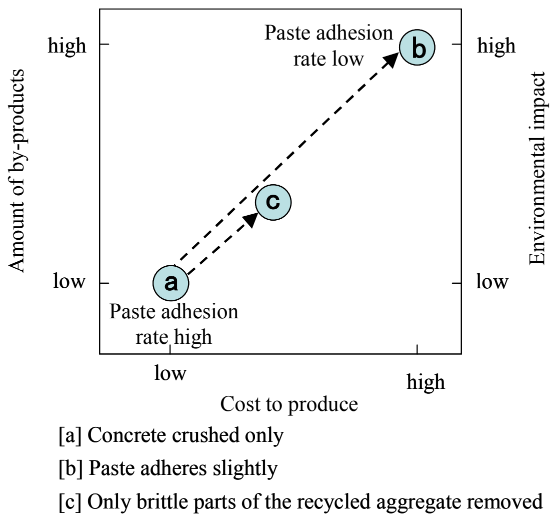


Fig. 3 Concept of the relationship between the adhered cement paste rate of recycled aggregate and economy, amount of by-product produced, and environmental impact expressed as the amount of emitted CO_2.

The method advocated by Nawa, *et al.* was tentatively termed as the defect-removal (DR) method. The researchers have conducted further studies to improve the quality of the recycled fine aggregate to clarify the theoretical aspects of its production methods. The DR method can selectively remove a portion of the brittle parts from the original paste of the recycled aggregate grains having cracks, pores, and voids without creating new defects. Thus, recycled aggregate can be manufactured practically.

Figure 4 shows photographs of the sections of recycled fine-aggregate grains crushed by a jaw crusher with brittle defects such as cracks, pores, and voids as found in the original paste. Similar cracks appear in the photographs of the original aggregate (Etxeberria *et al.* 2006) and are considered to be weak points. **Figure 5** shows examples of recycled fine-aggregate grains produced by the DR method. In **Fig. 5 (a)**, the paste penetrates into the concave portions of the original aggregate, and the original aggregate and paste coalesce. In **Fig. 5 (b)**, the paste forms round and bulbous parts. Thus, brittle parts within the recycled fine aggregate are absent, whereas a large volume of paste remains on the aggregate surface. Hence, it is possible to manufacture recycled aggregate and accurately determine the relationship between the processor effects and the defective portions in recycled fine aggregate (Ogawa *et al.* 2010). In addition, the characteristics of the mortar with the recycled fine aggregate were evaluated to confirm that the performance of the mortar in which the defective parts of the recycled fine aggregate were removed was equal to that of the commonly used fine aggregate mortar (Ogawa *et al.* 2007a; Ogawa *et al.* 2011).

In this study, the recycled fine aggregate is further examined because its use is understood less than that of the recycled coarse aggregate (Press *et al.* 2012). The separation of the original paste from the recycled fine aggregate is more difficult than that from the coarse

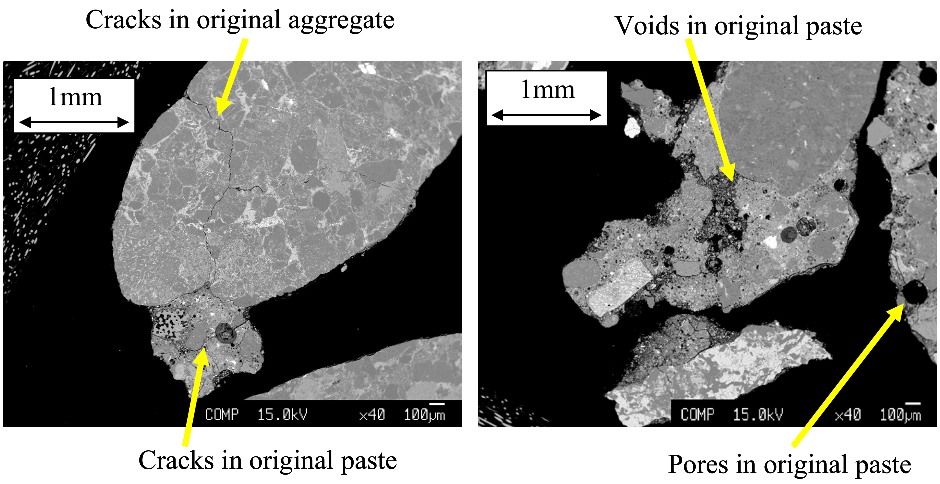


Fig.4 Grains of recycled fine aggregate crushed by a jaw crusher.

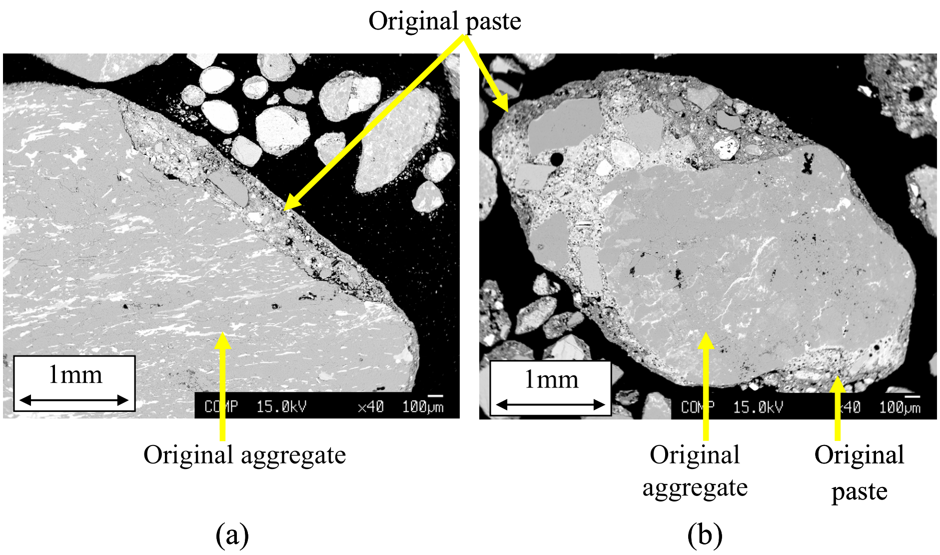


Fig. 5 Grains of the recycled fine aggregate with brittle parts removed.

aggregate. In addition, the removal of foreign substances is important to expand the range of usage of the recycled fine aggregate (Shibatani 2004). Similarly, according to BS 8500 (BS8500-2 2006) and JIS A 5021 (recycled class H aggregate), the recycled fine aggregate must be used carefully because foreign components such as gypsum plaster and asphalt negatively affect the performance of the recycled concrete.

2. Materials and methods

2.1 Recycled fine aggregate

Many types of processors such as crushing and polishing processors are used to manufacture recycled aggregate. Crushing, which involves breaking an object by applying external force, was further defined by Taggar (1953) and Lynch (1977) to include two types: the compression type in which a compressive force is applied, and the impact type, in which objects are hit by a metal body revolving at a high speed. Polishing involves breaking or shaping objects by friction such as that produced when grains brush against each other.

In this study, three types of processors with various types of processing actions, namely a jaw crusher, a ball mill, and a granulator, were used. The ball mill and granulator were selected to verify the validity of the production theory and concepts of the previously outlined DR method. The jaw crusher is commonly used and was employed for comparison between the other two processors. **Table 1** lists the relevant actions of these three processor types. The jaw crusher excels in the crushing action (JCMA 1975; Chemical industry company 2000) as suggested by **Fig. 6**. When the recycled fine aggregate is crushed by a jaw crusher, the grain sizes were reduced to a fraction of the original sizes. The granulator excels in polishing (Ogawa *et al.* 2007b). As indicated by **Fig. 7**, grains rub against each other between the roller and the drum, and the grains are broken by the generated friction. The principle for the operation of the granulator is similar to that of the eccentric rotor type of the grinder (Yanagibashi *et al.* 1999; Yanagibashi 2003). However, the granulator power can be easily controlled within the range of the weak force. As mentioned in **Fig. 8**, this study assumed that the brittle parts and corners of aggregate grains are selectively broken off when the aggregate is polished in a granulator. **Figure 9** shows the action mechanisms of a ball mill, which includes polishing by the rotation of the balls inside the mill and the impact fracturing between ball particles. **Table 2** lists the specifications of each processor used in this study.

The original concrete was produced using an ordinary portland cement and ordinary aggregate. The fine aggregate in the original concrete was land sand with a dry density of 2.65g/cm^3 and a water absorption of 1.47%. It was manufactured at a water/cement ratio of 0.55, and the compressive strength at 28 days was 24 N/mm^2. The concrete was kept outside for two years from the manufacture date until its use in the experiments.

Table 1 Actions of processors.

	Jaw crusher	Ball mill	Granulator
Crushing action	strong	mid	weak
Polishing action	weak	mid	strong

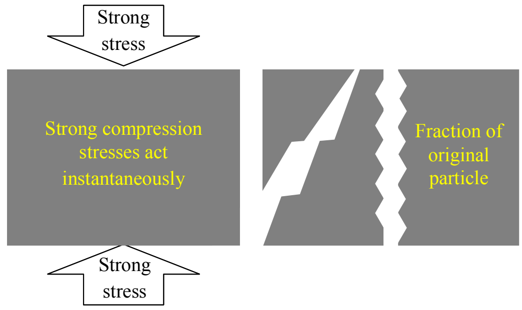


Fig. 6 Crushing mechanism.

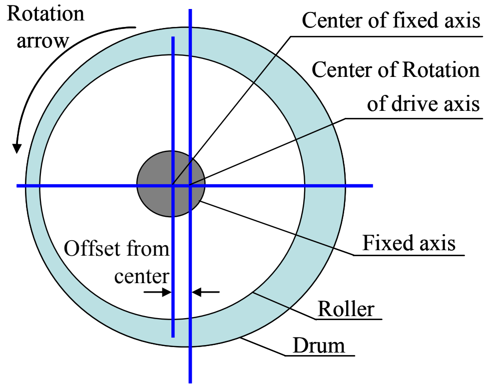


Fig. 7 Structure of the granulator.

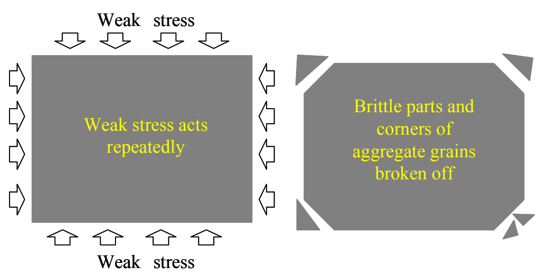


Fig. 8 Polishing mechanism.

Initially, the original concrete was crushed by a large jaw crusher to grains sized 40 mm or less. The crushed material was passed through a 5-mm sieve, and fine powder not larger than approximately 0.15 mm was removed by an air separator. The resulting recycled fine aggregate was labeled as starting material R_1. Next, the recycled coarse aggregate was produced by screw grinding (Kimura *et al.* 2006) the 5 to 40-mm crushed material remaining on the 5-mm sieve. The fine powder of

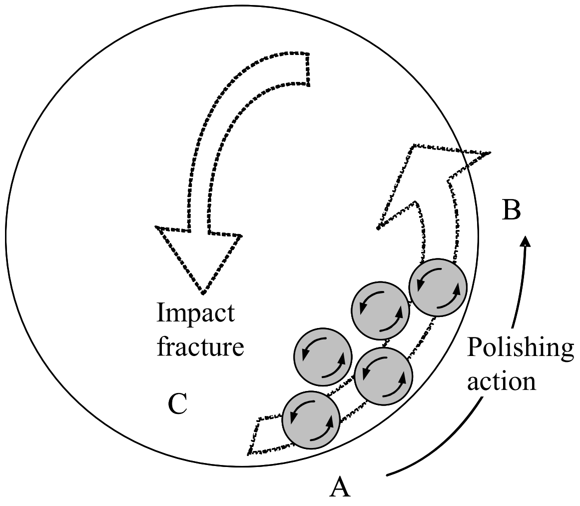


Fig. 9 Action mechanisms of a ball mill.

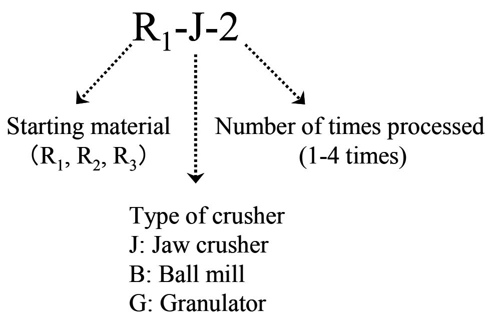


Fig. 10 Notation of samples of recycled fine aggregate.

Table 2 Specifications of processors.

Type	Specification	
Jaw crusher	Width of board	8 cm
	Frequency	260 rpm
Ball mill	Size of iron ball	Diameter 15 mm
	Size of mill	Diameter 46 cm ; width 60 cm
	Frequency	30 rpm
Granulator	Size of drum	Diameter 70 cm ; width 30 cm
	Frequency	200 rpm

Table 3 Symbols for recycled fine aggregate.

Starting material	Type	Number of times processed			
		1	2	3	4
R_1	Jaw crusher	R_1-J-1	R_1-J-2	-	-
	Ball mill	R_1-B-1	R_1-B-2	-	-
	Granulator	R_1-G-1	R_1-G-2	-	-
R_2	Ball mill	R_2-B-1	R_2-B-2	-	-
	Granulator	R_2-G-1	R_2-G-2	-	-
R_3	Granulator	R_3-G-1	R_3-G-2	R_3-G-3	R_3-G-4

R_1: Fraction(5 mm or less) from crushed concrete by large jaw crusher
R_2: Fraction(5 mm or less) from crushed material remaining after manufacture of recycled coarse aggregate
R_3: After one year, R_3 manufacture similar to R_1

the fine fraction (5 mm or less) was removed after the manufacture of the recycled coarse aggregate, and this resulting fine fraction was labeled as the starting material R_2. It was believed that R_2 was subjected to partial polishing when the recycled coarse aggregate was produced. Subsequently, R_1 and R_2 were processed twice by the small-sized jaw crusher (J), ball mill (B), and granulator (G) listed in **Table 2**, and the powder generated by these processes was removed. One year after the original concrete was manufactured, a starting material, R_3, was produced in the same manner as that for R_1. The various types of recycled fine aggregates were then processed one through four times in the granulator to generate four types of recycled fine aggregate with various amounts of adhesive paste. **Figure 10** shows the notation of the samples of the recycled fine aggregate samples, and **Table 3** lists the sample symbols for the starting material (R_1, R_2, and R_3), the type of processor (J, B, and G), and the number of times processed (one through four times).

2.2 Characterization of the recycled fine aggregate

The characterization of the recycled fine aggregate is determined by the fraction of defects in the aggregate, filling fraction, and grain geometrical characteristics, as well as water absorption, dry density, content of materials finer than the 0.075 mm sieve, and grain size distribution, which are all conventionally considered evaluation indexes.

The fraction of defects in the aggregate is an index expressing the content of brittle defective parts, such as cracks, pores, and voids in the recycled fine aggregate. During the measurement, the recycled fine aggregate grains were first impregnated with fluorescent resin. After the resin had hardened, 20 to 30 grains of each sample were cut, and the areas of the resin and paste in the aggregate cross section were measured using image processing software. **Figure 11** shows examples of these grain cross sections. It was confirmed that the resin had entered into pores and voids in the original paste. The area ratio of the resin to the paste in the aggregate cross section was defined as the fraction of defects in the original paste, calculated by Equation (1). The ratio of decrease in mass was defined as the adhered cement paste rate when the recycled fine aggregate was dissolved in hydrochloric acid after being crushed. Then, the fraction of defects in the aggregate was calculated by Equation (2).

$$Dp = Ar/Ap \times 100, \quad (1)$$

where Dp is the fraction of defects in the original paste (%), Ar is the area of resin in the aggregate cross section, and Ap is the area of paste in the aggregate cross section.

$$Da = P \times Dp/100, \quad (2)$$

where Da is the fraction of defects in the aggregate (%),

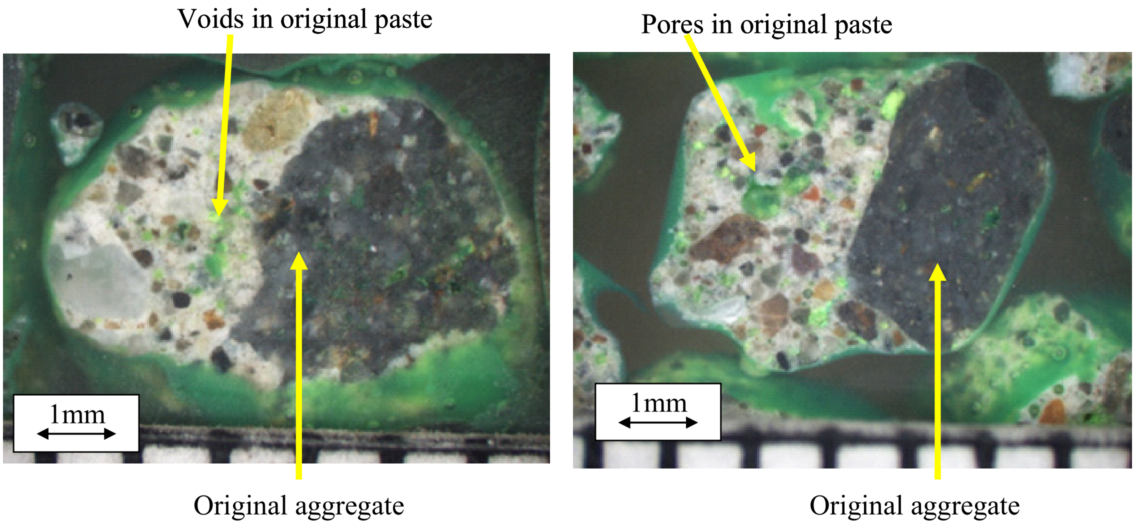


Fig. 11 Cross sections of recycled fine aggregate grains impregnated with fluorescent resin.

P is the adhered cement paste rate(%), and *Dp* is the fraction of defects in the original paste (%).

The grain shapes of crushed minerals vary with the types of rock and crusher. The macro shape and surface roughness are frequently used in quantifications (SPTJ 2005). For example, Medaria (1970) demonstrated that the degree of flatness comprehensively expresses the shape of grains while using the ratio of the major axis to the width. Pons *et al.* (1999) demonstrated that the surface smoothness of grains expresses the degree of surface irregularity. Sims *et al.* (1998) made visual assessments of the shape on the basis of morphological observations, and Graboczi(2002) analyzed the three-dimensions of the shape by using X-ray tomography and spherical harmonics . All of these studies targeted the commonly used aggregate for concrete. Regarding the recycled aggregate, Chidiroglou *et al.* (2006) reported the shape of the crushed concrete. On the basis of the results of these studies, the geometric characteristics of the recycled fine-aggregate grains were explored. For performing measurements, representative grains with diameters of 2.5 to 5.0 mm were initially photographed under an optical microscope. These grains were selected at random, and the number of grains in the photographs was between approximately 20 and 30 in each sample.

Next, digital image processing was used to measure the length of the major axis (L), width (W), area of the peripheral envelope (A_e), and area of the grain image (A_g). The degree of flatness and surface smoothness of the grains were calculated by using Equations (3) and (4), respectively.

$$Fd = L/W, \tag{3}$$

where *Fd* is the degree of flatness, Fd $\geqq$ 1; *L* is the length of the major axis in the grain image, and *W* is the width of the grain image (orthogonal to L).

$$S = A_g/A_e, \tag{4}$$

where *S* is the surface smoothness of the grain, A_g is the area of the grain image, and A_e is the area of the peripheral envelope of the grain image.

A larger degree of flatness indicates a more slender grain. The surface smoothness of a circular body is 1; smaller surface smoothness indicates a more irregular surface.

2.3 Tests of the recycled mortar

Ordinary portland cement was used in the recycled mortar. The density of the cement was 3.16 g/cm^3, and its specific surface area was 3,300 cm^2/g. The fine aggregate consisted of the recycled fine aggregate prepared as explained in section (2.2); samples prepared with land sand were used for comparison. The land sand used was the same as that used in the fine aggregate of the original concrete. The recycled mortar consisted of mixed cement, fine aggregate, and water in the weight ratio 1:3:0.5, produced at a water/cement ratio of 0.50.

The test specimens of recycled mortar were prisms with cross sections of 40 × 40 mm and lengths of 160 mm. The flow value, compressive strength, and flexural strength of the mortar were measured according to JIS R 5201, which outlines the physical-testing methods for cement. The forms of the fractures of the recycled fine aggregate grains at the fracture plane in the recycled mortar due to flexural stress were also observed.

3. Results and discussions

3.1 Recovery rates of the recycled aggregate

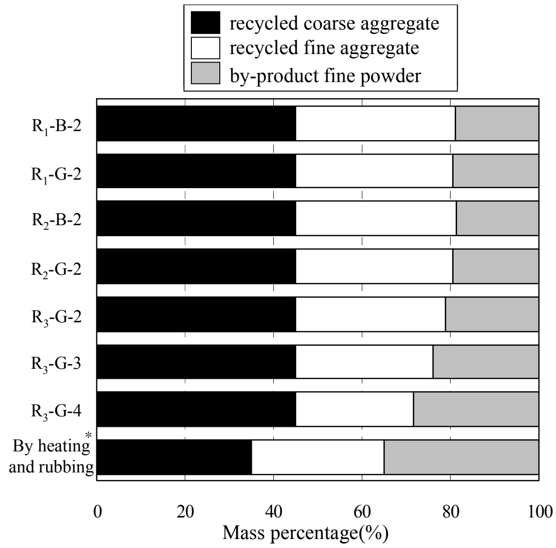
Figure 12 shows the recovery rates of the recycled aggregate for samples processed two or more times with the ball mill or granulator. The recovery rate obtained by heating and rubbing (Tateyashiki *et al.* 2001) is added as a reference value, also shown in the figure. These recovery rates indicate the mass percentages of the manufactured aggregate and by-product powder to original concrete.

The total recovery rate of the recycled coarse aggregate and fine aggregate with a quality similar to the ordinary aggregate obtained by heating and rubbing is approximately 65% (Tateyashiki *et al.* 2001). On the other hand, the total recovery rates of samples after processing twice with the granulator and ball mill on the basis of the DR method are approximately 80%. Although these values cannot be easily compared because the recovery rates include the coarse aggregate, the recovery rate by the DR method has the possibility of growing more than that of the heating and rubbing method.

3.2 Quality of the recycled fine aggregate

Table 4 lists the quality parameters for the recycled fine aggregate; the relationship between dry density and water absorption listed in the table are shown in **Fig. 13**. The quality of the recycled aggregate is generally classified on the basis of dry density and water absorption. However, the results showed no obvious correlation between these parameters even though the samples were manufactured from the same original concrete.

Figure 14 shows the mass percentages of the coarse (1.2 to 5 mm), intermediate (0.3 to 1.2 mm), and finer (0.3 mm or less) grains of the recycled fine aggregates in this study. The R_1-J-2 crushed by the jaw crusher had a higher ratio of intermediate grains than that observed in R_1, i.e., the starting material. However, the ratio of the fine grain component did not change. These results indicate that the coarse grains were crushed and that a large number of grains were produced at a fraction of



∗ Reference value (The kind of original concrete was different)

Fig. 12 Recovery rates of the recycled aggregate.

Table 4 Characteristics of recycled fine aggregate.

	Aggregate test					Defect rate			Geometric characteristics	
	Dry density (g/cm^3)	Water absorption (%)	Fineness modulus (F.M.)	Content of components passing 0.075-mm sieve (%)	Filling fraction (%)	Adhered cement paste rate (%)	Fraction of defects in original paste (%)	Fraction of defects in aggregate (%)	Degree of flatness	Surface smoothness (%)
Test method or equation for calculation	JIS A 1110	JIS A 1110	JIS A 1102	JIS A 1103	JIS A 1104	Loss of mass in hydrochloric acid	Impregnation resin area/paste area	Equation (1)	Equation (2)	Equation (3)
R_1	2.39	5.75	3.57	5.07	59.0	31.1	13.73	4.27	1.41	95.0
R_1-J-1	2.41	5.77	3.48	0.66	59.1	28.8	14.00	4.03	1.41	95.6
R_1-J-2	2.45	4.55	3.38	0.83	60.9	31.0	14.41	4.47	1.43	94.8
R_1-B-1	2.43	5.91	3.40	1.83	62.4	32.4	9.10	2.95	1.33	97.2
R_1-B-2	2.47	4.47	3.07	2.44	68.0	27.5	4.57	1.26	1.34	97.6
R_1-G-1	2.41	5.41	3.32	4.75	60.6	30.9	10.50	3.24	1.36	94.4
R_1-G-2	2.43	5.65	3.04	5.15	63.0	24.4	5.84	1.42	1.34	95.7
R_2	2.42	6.63	2.89	6.20	70.3	32.2	11.71	3.77	1.43	95.2
R_2-B-1	2.46	5.63	2.93	1.61	69.9	28.8	7.20	2.07	1.35	96.7
R_2-B-2	2.48	3.99	2.81	2.67	70.6	21.6	4.19	0.91	1.26	97.4
R_2-G-1	2.43	6.02	2.60	5.82	70.0	31.0	10.10	3.13	1.31	96.3
R_2-G-2	2.52	4.18	2.59	4.32	70.3	19.6	5.34	1.05	1.32	96.4
R_3	2.20	7.46	3.36	7.81	58.8	30.6	12.21	3.74	1.40	95.4
R_3-G-1	2.37	4.89	3.14	7.71	62.0	26.9	10.41	2.80	1.36	94.9
R_3-G-2	2.38	5.43	2.74	10.21	64.5	23.1	6.35	1.47	1.32	96.1
R_3-G-3	2.44	4.36	2.53	8.84	67.5	20.6	7.24	1.49	1.26	96.3
R_3-G-4	2.50	3.39	2.54	9.30	68.7	16.7	6.30	1.05	1.24	96.7
Natural fine aggregate*1	2.65	1.47	2.74	0.40	69.1	-	-	-	-	-

*1 Land sand used for comparison, the same as the fine aggregate in the original concrete.

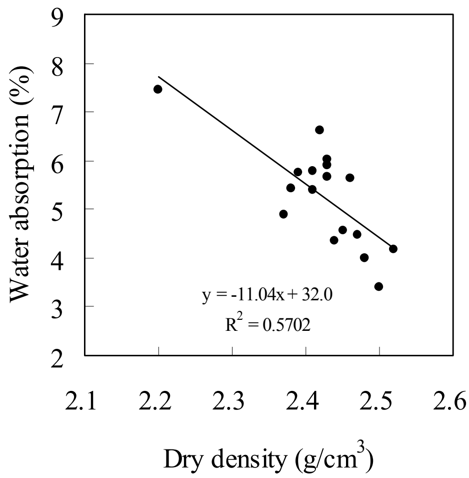


Fig. 13 Relationship between dry density and waterabsorption.

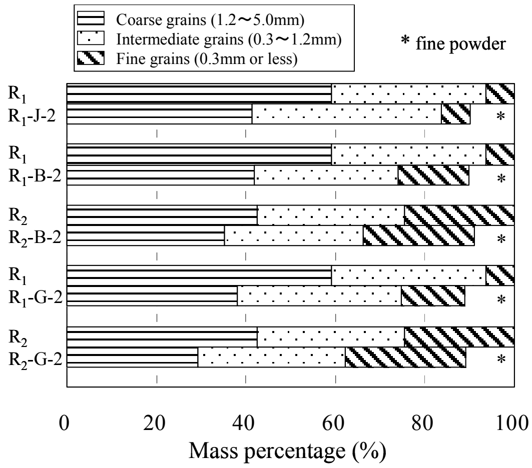


Fig. 14 Grain size distributions of the recycled fine aggregate.

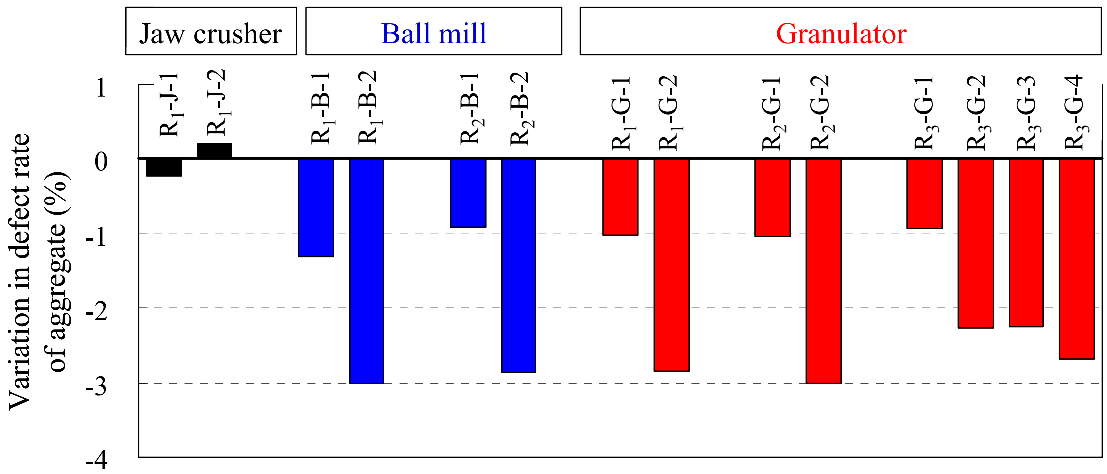


Fig. 15 Variations in the fraction of defects in the aggregate.

the original size. In the R_1-B-2 sample polished by the ball mill and the R_1-G-2 sample polished by the granulator, the fine-grain ratio increased substantially, which was attributed to polishing rough and intermediate grains. On the other hand, the R_2 sample originally comprised a larger percentage of fine grains than that observed in the R_1 sample, which was possibly due to polishing while producing the recycled coarse aggregate.

Figure 15 shows the variations in the fraction of defects in the aggregate samples. The fraction of defects in the aggregate of the R_1-J-2 sample crushed by the jaw crusher changed only slightly, suggesting that the brittle parts were not selectively removed by the crushing. When the R_1 and R_2 samples were polished once by the ball mill or the granulator, the fraction of defects decreased by approximately 1%; when processed twice, the defects decreased by approximately 3%. These results indicate that the fraction of defects in the aggregate decreases by using a processor such as the ball mill and granulator for polishing.

Figure 16 shows the changes in the adhered cement paste rate versus the fraction of defects in the original

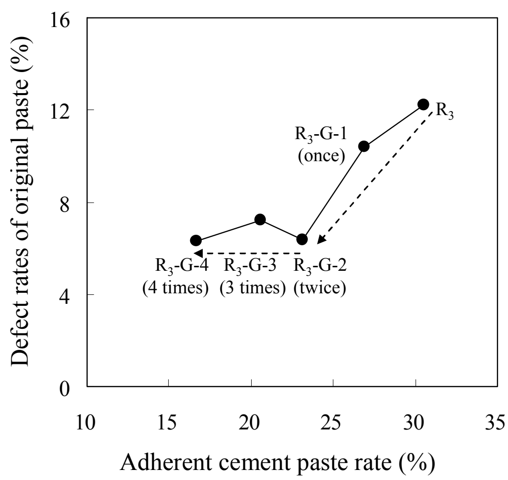


Fig. 16 Changes in the adhered cement paste rates and the fractions of defects in the original paste.

paste when the R_3 sample was polished by the granulator. This plot shows that it is necessary to selectively remove brittle, defective parts from the sample by polishing. Both the paste-adhesion rate and fraction of defects of the original paste decreased after processing once and twice, respectively. However, while processing three or four times, the adhered cement paste rate decreased, but the fraction of defects in the original paste did not change further, suggesting that the brittle defective parts of the samples were selectively removed by polishing once or twice by using the granulator. However, some original paste parts with few defects could disintegrate if polished three or more times.

Figure 17 shows changes in flatness and surface smoothness of the recycled fine aggregate grains. The flatness of the R_1 sample, the starting material, was 1.41, which indicates the presence of numerous slender grains. The surface smoothness of the sample was 95%, indicating an irregular surface. The flatness and surface smoothness of the R_1-J-1 and R_1-J-2 samples, produced by crushing the R_1 sample, changed slightly. Therefore, the results suggest that the geometric characteristics of the grains changed minimally even if crushing was repeated in the jaw crusher. When the R_1 and R_2 samples were polished by the ball mill, flatness decreased and surface smoothness increased, which indicates that the grains became more round and the surfaces had fewer irregularities after polishing in the ball mill. When the R_1, R_2, and R_3 samples were polished in the granulator, flatness decreased in the same manner as that with the ball mill, but changes in surface smoothness were smaller than those with the ball mill. Overall, the grains became more round, but the surfaces remained irregular after treatment in the granulator. Tabata *et al.* (2005) reported the results of the experiment in which the crushed sand became more round and surface irregularities decreased because of polishing. Therefore, changes in the shape of the crushed sand and recycled fine aggregate tended to be similar.

3.3 Flowability of the recycled mortar

In addition, experiments evaluated the flowability of the recycled mortar and explored the relationship between the characteristics of the recycled fine aggregate (**Table 4**) and flowability by multivariate analysis. The variables used to explore flowability were the characteristic values that express the properties of the recycled fine aggregate, specifically the fineness modulus, the content of components passing the 0.075-mm sieve, filling fraction, the degree of flatness, and surface smoothness. The target variable was the flow value of the recycled mortar. Equation (5) shows the regression equation expressing the flowability of the mortar developed in this manner. The filling fraction and content of components passing the 0.075-mm sieve were included in the regression equation.

$$Mf = -21.0 + 3.24\,Ff - 0.867\,P, \tag{5}$$

where Mf is mortar flow value (mm), Ff is filling fraction (%), and P is the contents of components passing the 0.075-mm sieve (%).

Table 5 shows the influence of each of the variables on flowability. The rate of influence is expressed by the ratio of the regression coefficient to the standard error. It was determined that the filling fraction and content of components passing the 0.075-mm sieve influenced flowability. In particular, filling fraction had a strong influence on the rate of flowability at five times the absolute value of the content of finer than 0.075-mm sieve components.

Table 5 Rate of influence of each explanatory variable on flowability.

Explanatory variable		Rate
Filling fraction	(%)	7.14 *
Content of components passing 0.075-mm sieve	(%)	-1.28 *
Degree of flatness		0.92
Surface smoothness	(%)	0.28
Fineness modulus (F.M.)		0.30

*Explanatory variable included in the regression equation.

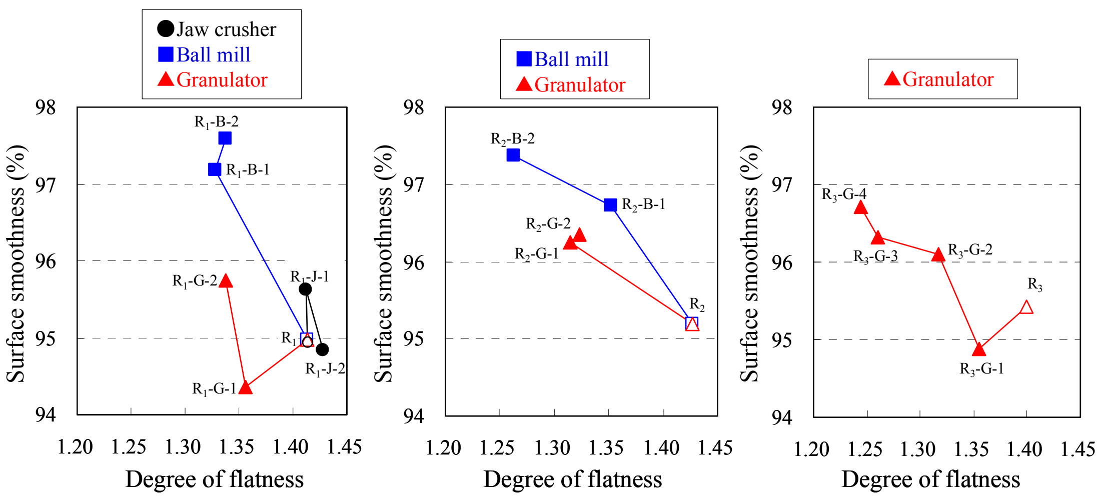


Fig. 17 Changes in flatness and surface smoothness of the recycled fine aggregate grains.

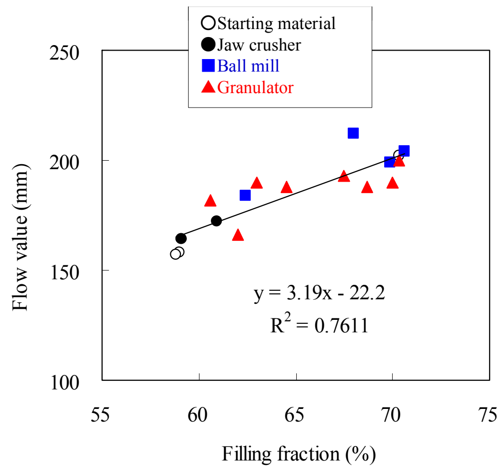


Fig. 18 Relationship between the filling fractions and flow values.

Figure 18 shows the relationship between the filling fraction and flow value of the recycled mortar. This figure strongly suggests that the filling fraction is a very good index for the flowability of the recycled mortar. The filling fraction of the recycled fine aggregate increased when it was processed by the ball mill and granulator; therefore, the flow value increased. However, when the fine aggregate was processed by the jaw crusher, the flow changed a little, and the filling fraction increased only slightly. Fujii *et al.* (1996) reported that an increase in the filling fraction by 1% has an effect equivalent to an increase in flow value of 10 mm. Considered together, these reports suggest that the relationship between filling fraction and flowability was similar for crushed sand and recycled fine aggregate.

3.4 Mechanical properties of the recycled mortar
3.4.1 Compressive strength
The compressive strength of the recycled mortar was measured, and the relationship between the characteristics of the recycled fine aggregate and compressive strength was examined through multivariate analysis. The variables included the fraction of defects in the aggregate, filling fraction, the degree of flatness, surface smoothness, water absorption, dry density, and the content of components passing the 0.075-mm sieve, which were conventionally considered as evaluation indices for the recycled aggregate.

The target variable was the compressive strength of the recycled mortar. Regression equations (6) and (7) are the equations for compressive strengths at 28 and 91 days, respectively. The fraction of defects in the aggregate as well as dry density and surface smoothness are included in these regression equations:

$$fc_{28} = 165.1 - 2.88\,Da + 17.2\,Den - 1.61S \qquad (6)$$

$$fc_{91} = 14.1 - 1.90\,Da + 16.7\,Den, \qquad (7)$$

where fc_{28} is compressive strength at 28 days (N/mm^2), fc_{91} is compressive strength at 91 days (N/mm^2), Da is the fraction of defects in the aggregate (%), Den is dry density (g/cm^3), and S is surface smoothness (%).

Table 6 lists the rate of influence of each of the explanatory variables on compressive strength. The fraction of defects in the aggregate had the strongest effect on compressive strength, indicating that the DR method for removing defective parts affected the mechanical properties of the recycled mortar.

Figure 19 shows the relationship between the rate of defects in the aggregate and compressive strength at 28 days. Overall, a negative correlation exists between the rate of defects and compressive strength. Furthermore, the figure clearly shows differences in tendency according to whether crushing occurred in the ball mill or granulator. When the regression line for the ball-mill treatment is extrapolated to a 0-% defect fraction in **Fig. 19**, the result is very similar to the compressive strength (48.7 N/mm^2) of the mortar of the ordinary fine aggregate (original fine aggregate). Presumably, this result suggests that the shape and surface characteristics of the

Table 6 Rate of influence of each explanatory variable on compressive strength.

Explanatory variable		Rate	
		28 days	91 days
Fraction of defects in aggregate	(%)	-4.99 *	-4.18 *
Surface smoothness	(%)	-2.19 *	-0.97
Dry density	(g/cm^3)	2.05 *	2.05 *
Degree of flatness		-0.15	-0.93
Filling fraction	(%)	-0.41	-0.07
Content of components passing 0.075-mm sieve	(%)	1.01	0.59
Absorbed water	(%)	1.11	1.13

*Explanatory variable included in the regression equation.

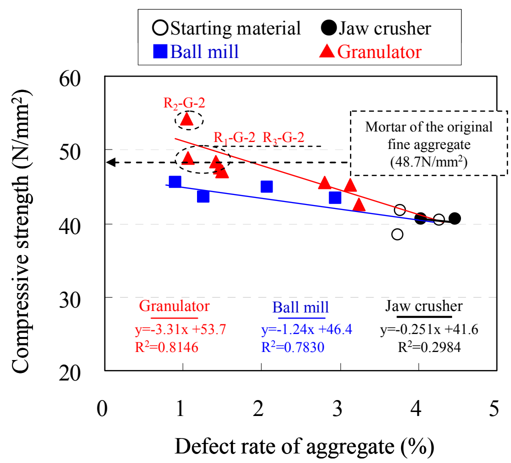


Fig. 19 Relationship between the defect rate of the aggregate and compressive strength.

recycled fine-aggregate grains became similar to those of the original fine aggregate when repeatedly polished by the ball mill. The compressive strength of the recycled mortar with the aggregate polished in the granulator was similar or superior to the strength of the mortar in the original fine aggregate, even with a 1% to 1.5% fraction of defects in the recycled aggregate. Such high compressive strength was possibly attained by irregularities in the grain surface. The strength of the recycled R_2-G-2 mortar was approximately 5 N/mm^2 greater than that of the R_1-G-2 and R_3-G-2 samples. Here the starting material for the R_2-G-2 sample was R_2, whose feed was polished once while manufacturing the recycled coarse aggregate. Thus, the effects of the two polishing processes were such that very fine brittle parts that did not contribute to the fraction of defects in the aggregate were completely removed.

Furthermore, the compressive strength of the mortar composed of the starting materials was approximately 14 to 21% lower than that of the mortar composed of the original fine aggregate. In addition, previous experiments reported a decrease in the compressive strength. For example, the compressive strength of the concrete with the recycled fine aggregate was approximately 40% lower than that of the concrete with the ordinary aggregate, according to Fukube *et al.* (1997). Overall, this study shows that the DR method is effective because the compressive strength of the mortar with the recycled fine aggregate manufactured by DR was equal or superior to that of the mortar with the original aggregate.

3.4.2 Flexural strength

In addition, the relationship between the characteristics of the recycled fine aggregate and the flexural strength of the recycled mortar was investigated by multivariate analysis. Regression equations (8) and (9) show the flexural strength at 28 and 91 days, respectively. The fraction of defects in the aggregate, dry density, surface smoothness and the degree of flatness were included in these regression equations.

$$fb_{28} = 41.7 - 0.392\,Da + 1.40\,Den - 0.379\,S \tag{8}$$

$$fb_{91} = 58.2 - 0.330\,Da - 0.467\,S - 3.28\,Fd, \tag{9}$$

where fb_{28} is flexural strength at 28 days (N/mm^2), fb_{91} is flexural strength at 91 days (N/mm^2), Da is the fraction of defects in aggregate (%), Den is dry density (g/cm^3), S is surface smoothness (%), and Fd is the degree of flatness.

Table 7 lists the rate of the influence of each of the explanatory variables aggregate characteristics on flexural strength, elucidating that the fraction of defects in the aggregate and surface smoothness considerably influenced flexural strength. These results suggest that the fraction of defects in the aggregate affects both the flexural and compressive strengths. The fraction of defects in the aggregate was the most important characteristic to express both compressive and flexural strengths of the recycled mortar, which substantiates the importance of removing defective parts of the aggregate, as considered in the DR method, as a valuable process for improving mortar strength.

Figure 20 shows the relationship between the fraction of defects in the aggregate and flexural strength. The flexural strength of the mortar with the starting materials was approximately 11% to 14% lower than that of the mortar with the original fine aggregate. Similarly, when recycled coarse aggregate was used, the flexural strength of the concrete was approximately 27% lower than that of the concrete with ordinary aggregate (Nassar *et al.* 2012). Moreover, when both coarse and fine recycled aggregates were used, the compressive strength of the concrete was approximately 20% lower than that of the concrete with the commonly used aggregate (Hansen 1986). Thus, the use of the recycled fine aggregate decreased the strength only when crushed concrete was used as the aggregate. Overall, these results confirm that flexural strength increases as the fraction of defects in the aggregate decreases similar to that observed in

Table 7 Rate of influence of each explanatory variable on flexural strength.

Explanatory variable		Rate	
		28 days	91 days
Fraction of defects in aggregate	(%)	-5.99 *	-3.14 *
Surface smoothness	(%)	-4.53 *	-4.80 *
Dry density	(g/cm^3)	1.48 *	1.04
Degree of flatness		-0.58	-1.50 *
Filling fraction	(%)	0.66	0.55
Content of components passing 0.075-mm sieve	(%)	0.45	0.01
Absorbed water	(%)	0.32	1.18

*Explanatory variable included in the regression equation.

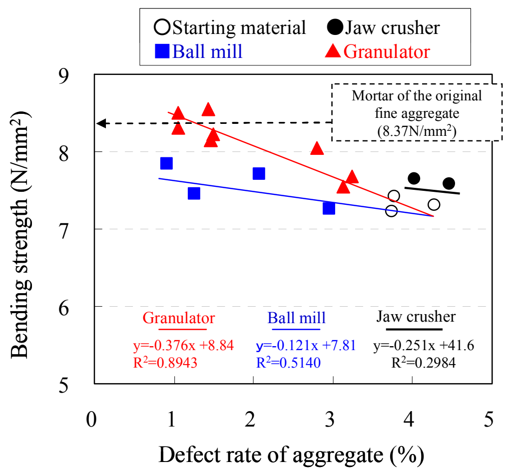


Fig. 20 Relationship between the defect rate of the aggregate and flexural strength.

compressive strength. The flexural strength of the recycled mortar with the aggregate polished by the granulator was greater than that treated by the ball mill, which implies that the geometric characteristics of the recycled fine aggregate grains influence the flexural strength. Surface smoothness had the strongest influence on flexural strength at 91 days. In addition, the degree of flatness was included in the regression equation, which highlights the importance of the geometric characteristics of the grains as the age of the concrete increases.

3.4.3 Fracture forms of recycled fine aggregate grains in the recycled mortar

Figure 21 shows the magnifications of the cross sections of the grains in the fracture plane of the recycled mortar fractured due to flexural stress. Grains that contain a significant amount of the original paste were selected for these photographs. The left-hand-side photographs in **Fig. 21** show the grains at 7 days as an early stage, and the right-hand-side photographs show grains at 28 days as an intermediate stage. In the grains crushed by the jaw crusher (R_1-J-2), many cracks penetrated through the interior of the grains at both 7 and 28 days. According to an analytical evaluation by Okuyama *et al*. (2003), cracks were initially produced in the paste-containing parts because the strength in this region is least. It is believed that many cracks penetrated through the interior of R_1-J-2 because the strength of the grains themselves was the lowest. R_1-J-2 showed a large fraction of defect in the aggregate in this region (**Table 4**); thus, it contained many brittle, defective parts. At 7 days, in the R_1-B-2 grains polished by the ball mill and the R_1-G-2 grains polished by the granulator, many cracks bypassed the recycled fine aggregate grains. Very few brittle defective parts were observed in these grains, which could become the starting points for fractures penetrating inside the grains of R_1-B-2 and R_1-G-2. This result suggests that the brittle defective parts were successfully removed by the ball mill and granulator in the DR method. At 28 days, a few cracks bypassed the

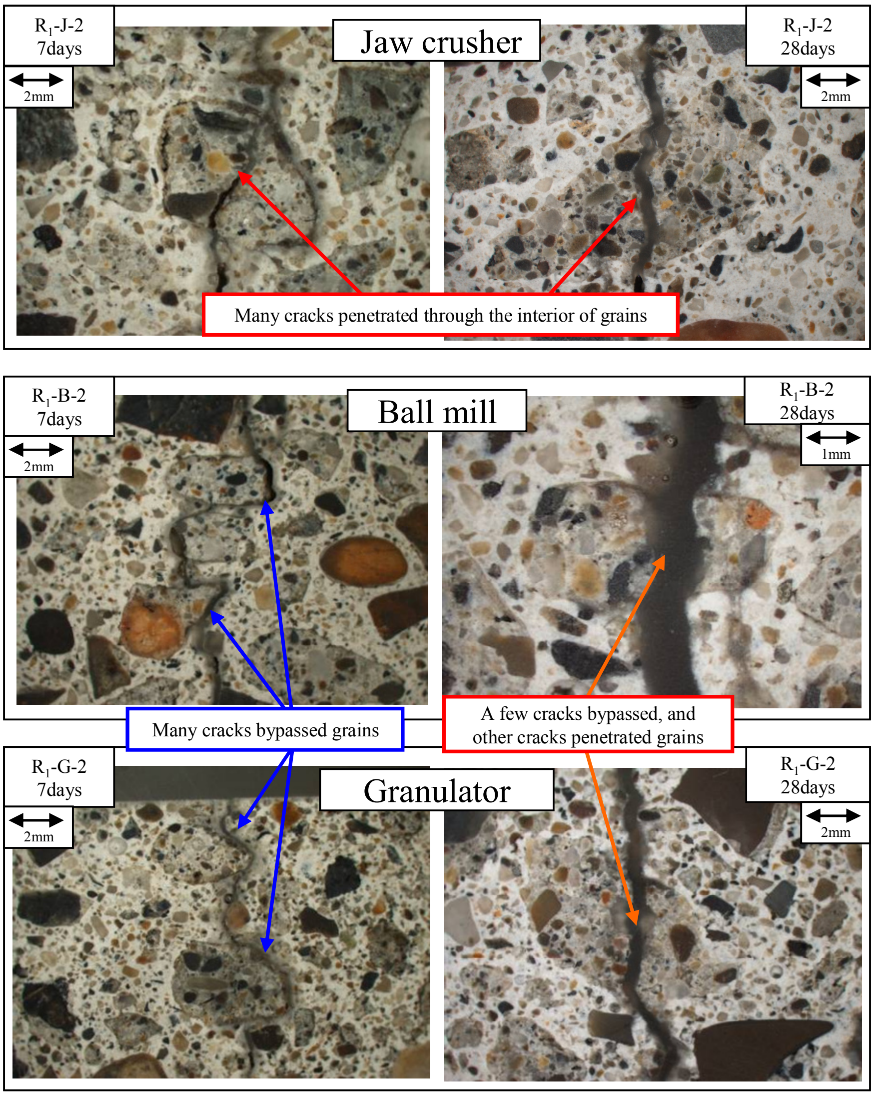


Fig. 21Cross sections of the grains in the fracture plane of the recycled mortar due to flexural stress.

grains, and other cracks penetrated through the R_1-B-2 and R_1-G-2 grains. This result is in accordance with the scenario that compressive and flexural strengths at 28 days were affected by the fraction of defects and geometric characteristics of the grains in the aggregate. It is believed that grain-penetrating cracks increased at 28 days because the strength of the surrounding new paste was approximately equal to that of the grains themselves.

3.5 Environmental impact

The recycled fine aggregate manufactured via the DR method by selectively removing defective parts could be treated as a commonly employed aggregate. In addition to aggregate quality, a report by Dosho (2007) stresses the need for ensuring an appropriate balance between quality, cost-effectiveness, and environmental impact. One merit of the DR method is the reduction in environmental impact. The environmental impact of the recycled fine aggregate was evaluated using the amount of emitted CO_2 according to the guidelines of the Japan Society for Civil Engineers (Concrete technical series 2004) in which the amount of emitted CO_2 changes depending on the manufacturing scale. For the present study, the process of manufacturing the recycled fine aggregate from 100 t of crushed concrete waste (0 to 5 mm) by granulator was selected, and the fine powder by-product was assumed to be transported to a cement plant 50 km away for use as a raw material for cement clinker. The total amount of emitted CO_2 was calculated using the power consumption of the granulator and the transportation of the fine powder by-product, and the amounts of emitted CO_2 were compared.

Table 8 lists the calculated amounts of emitted CO_2, indicating an approximately 300-kg increase in emitted CO_2 for every additional treatment by the granulator. **Figure 22** shows the calculated amounts of emitted CO_2 and the compression strength of the recycled mortar at 91 days. The calculated amounts of emitted CO_2 increased with additional treatments; however, the strength of the recycled mortar did not improve with added treatment cycles. Therefore, the number of polishing treatments by the granulator should be at most two because the strength of the recycled mortar did not improve with further treatment. In addition, when the number of polishing-treatment cycles was increased, the recovery rate of the recycled fine aggregate decreased, and the amount of the fine powder by-product increased. This simulation shows that polishing the recycled fine aggregate beyond a certain point (here, two cycles) should be avoided.

Therefore, the optimal number of polishing-treatment cycles for this granulator was determined to be two. Further treatment increased the dry density of the aggregate and decreased its water absorption; however, its strength did not improve, and the negative environmental impact increased. The optimal number of treatments may vary according to the type and scale of the processor employed; thus, this aspect must be verified by testing in each case.

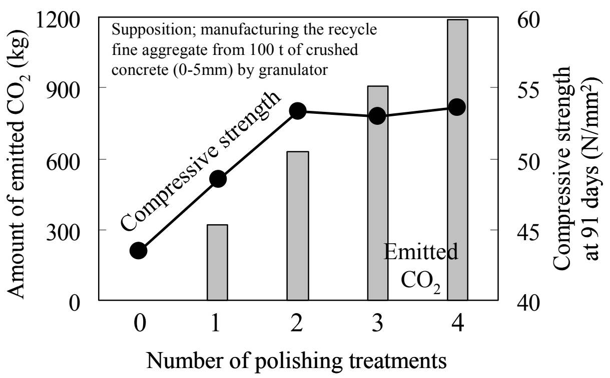


Fig. 22 Amounts of emitted CO_2 and compression strength of recycled mortar.

4. Conclusions

This study investigates the DR method for improving the quality of the recycled fine aggregate. In this method, the brittle defects of the recycled fine aggregate particles such as cracks, pores, and voids in the grains are selectively removed. This study uses recycled fine aggregates manufactured by three types of processors with various action mechanisms including a jaw crusher, ball mill, and granulator. The results are summarized below.

(1) The fraction of defects in the aggregate crushed by the jaw crusher changed slightly. The fraction of defects decreased by processing with the ball mill and granulator, which introduced a polishing action.
(2) The geometric characteristic of the grains changed slightly with repeated crushing by the jaw crusher.

Table 8 Amount of emitted CO_2 for concrete recycling.

Number of polishing treatments	Manufacturing of recycled fine aggregate: Amount of physical object (t)	Manufacturing of recycled fine aggregate: Amount of emitted CO_2 (total) (kg)	Transport of by-product fine powder: Amount of transport (t)	Transport of by-product fine powder: Transport distance (km)	Transport of by-product fine powder: Amount of emitted CO_2 (kg)	Total of emitted CO_2 (kg)
once	100	278 (278)	7	50	43	321
twice	93	258 (536)	15	50	92	628
3 times	85	236 (772)	22	50	134	906
4 times	78	216 (988)	33	50	201	1189

Ball-mill treatment made the grains more round and the surface more regular. The granulator treatment resulted in grains that were more round but retained the original irregular shape.

(3) Filling fraction was determined to be the index that expresses the flowability of the recycled mortar the best. The filling fraction of the recycled fine aggregate increased in processing by the ball mill and granulator, resulting in increased flow values.

(4) As an overall trend, a negative correlation existed between the fraction of defects in the aggregate and the compressive/flexural strength of the recycled mortar. The fraction of defects in the aggregate was the most effective index for expressing both the compressive and flexural strengths of the recycled mortar.

(5) Although the calculated amount of emitted CO_2 increased with every additional treatment, the strength of the recycled mortar did not always improve with further treatment of the material intended for use as the recycled fine aggregate. When treatment was repeated more than twice, the dry density of the aggregate increased and water absorption decreased. However, the strength of the recycled mortar did not improve, and negative environmental impacts increased. Therefore, excessive polishing of the recycled fine aggregate should be avoided.

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