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Pulsed Power Application to Production of Recycled Aggregate

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ABSTRACT

New application using pulsed power discharge has been developed as the recycling method of the coarse aggregates from the waste concrete scraps. The optimal processing parameters on pulsed electric discharge underwater for the separation and recovery of high-quality recycled coarse aggregate from a concrete mass by pulsed power technique are investigated in terms of the capacitance of the pulse generator device, the discharge voltage, and the amount of energy discharged. In experiments, when the energy per pulse is set to 1.6 kJ and 160 pulses are applied to the concrete mass, recycled coarse aggregate is recovered that satisfies the oven-dry density and water absorption quality standards of recycled coarse aggregate for concrete class H while minimizing the applied energy. Furthermore, recovery of higher quality recycled coarse aggregate may be possible by appropriately changing the energy per pulsed discharge during the concrete decomposition process.

Keywords. pulsed power, recycled coarse aggregate, waste reducing, reusing and recycling

INTRODUCTION

Recycling of Aggregate by Pulsed Power Discharge Technique. Waste materials from construction include concrete masses, construction sludge, construction lumber, and mixed construction waste. Concrete masses constitute a high proportion of this waste, with over 30 million tons disposed of in 2005. Although the recycling rate for concrete masses is high, reaching 98% in both 2002 and 2005, virtually all this recycled material is used in roadbase materials (MLIT, 2006). However, the demand for roadbase materials cannot be expected to grow into the future, whereas the amount of concrete masses disposed of is expected to remain high (MLIT, 2003). A large surplus of concrete masses is therefore forecast. Furthermore, there are also concerns over future exhaustion of natural aggregate, which is a natural resource used in concrete, and thus there is a need to promote the use of concrete masses as a source of aggregate for use in concrete. Against this background, JIS A 5021 “Recycled aggregate for concrete-class H” (JSA, 2005) was established in March 2005 as a standard for recycled aggregate to be used in concrete (Table 1).

The possibility of separating and recovering high-quality recycled coarse aggregate through the decomposition of concrete masses by a pulsed power discharge technique has therefore been investigated. Previous research has shown that high-quality recycled coarse aggregate can be separated and recovered by such techniques (Takaki, 2007). The present research investigates the output from a pulsed power generator for recovering recycled coarse aggregate that meets the quality requirements of recycled coarse aggregate for concrete class H while minimizing the applied energy. The energy per pulsed power discharge is varied by changing the capacitance of the capacitors and the generated voltage of the pulsed power generator, and the optimal processing parameters are investigated in terms of the oven-dry density, water absorption coefficient, and fineness modulus of the recovered recycled coarse aggregate. We refer to the recycled coarse aggregate obtained by using this method as pulsed power recycled coarse aggregate.

Table 1. Quality Standards for Recycled Coarse Aggregate for Concrete Class H

	Oven-dry density (g/cm3)	Water absorption coefficient (%)
Standard	≥ 2.5	≤ 3.0

The Pulsed Power Discharge Technique. Pulsed power discharge is a technique that spatially and temporally compresses and superimposes stored energy, thereby concentrating, controlling, and transmitting a large amount of power within a small space, although for only a short period of time (Akiyama, 2003).

Recycled aggregate can be recovered by applying pulsed power to concrete specimens immersed in water. The fragmentation phenomenon can be considered as follows (Akiyama, 2003). Because electrical breakdown in a gas generally occurs more easily than in a solid insulator and the permittivity and conductivity of gases are also generally lower, when a rising voltage is applied, electrical breakdown occurs in the gas first. When the areas of mortar and aggregate in concrete are compared, the mortar areas are found to contain much more air. Electrical breakdown therefore occurs in the mortar before the aggregate, and thereby separation and recovery is possible by electrical breakdown along the boundary surface between the two cohered media. In this research, we attempt to apply the electrical breakdown of gases and solids by pulsed power discharge as a technique for achieving controlled fragmentation of concrete.

EXPERIMENTAL METHODS

Experimental Decomposition of Concrete Specimens by the Pulsed Discharge Method. The pulsed power generator used for decomposing the concrete specimens in this research is called a Marx pulsed power generator (Akiyama, 2003). The circuit diagram is shown in Figure 1. This device employs a mechanism where a designated number of capacitors are charged while connected in parallel and discharged by connecting them in series through spark gaps.

To apply the pulsed power discharge to a concrete specimen in water, the concrete specimen is placed in a hemispherical stainless steel mesh with 5 mm square openings which is immersed in water. A polyethylene-coated copper wire of 5 mm in diameter is used as the high-voltage electrode, with the bottom end of the electrode fixed in contact with the concrete specimen before decomposition. During discharge, the stainless steel hemispherical mesh is connected to ground and serves as the low-voltage electrode (Figure 2). The reason for using 5 mm mesh is that the recycled coarse aggregate in this research is separated and recovered by decomposition of the concrete specimen, and excludes fragments that are able to pass through a 5-mm sieve.

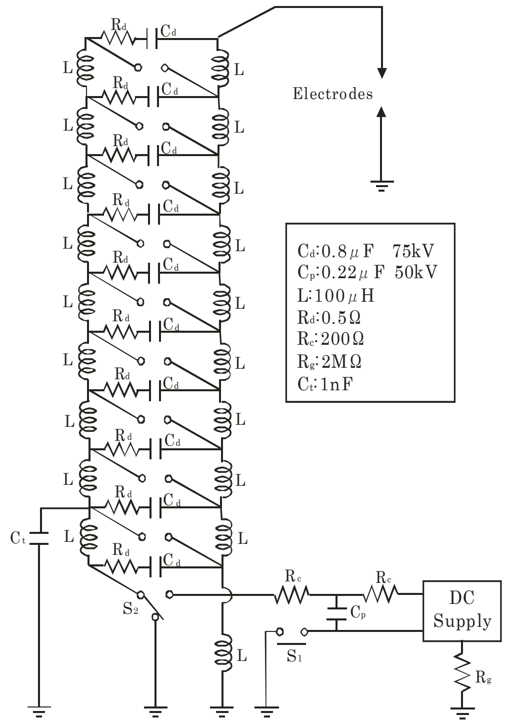

Figure 1. Marx Generator Circuit Diagram

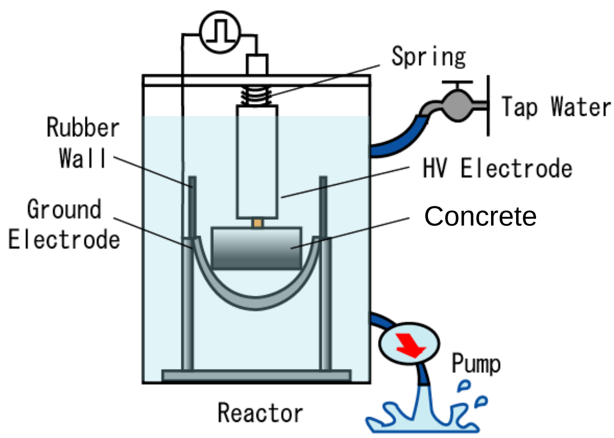

Figure 2. Aggregate Recovery Apparatus

Concrete Specimens. The concrete specimens used for the extraction of pulsed power recycled coarse aggregate in this research were 150 × 150 × 75 mm rectangular specimens (Figure 3). The coarse aggregate used in the specimens was gabbro from Yamaga in Kumamoto Prefecture; Japan, the physical properties of the aggregate are shown in Table 2. The specified mix proportions of the concrete specimens are listed in Table 3. The concrete specimens were cured in water for 28 days after pouring, and were dried for one week at 105 ± 5 °C in a drying oven in order to remove moisture from inside the concrete specimens and to obtain a constant mass before use.

Figure 3. Concrete Specimen Used in Experiment

Table 2. Quality of Raw Coarse Aggregate

Oven-dry density (g/cm^3)	Water absorption coefficient (%)	Fineness modulus
3.04	0.49	6.66

Table 3. Specified Mix Proportions of Concrete Specimens

Max. of aggregate (mm)	Slump (cm)	W/C (%)	air (%)	s/a (%)	Specific mass (kg/m^3)				AE agent (g/m^3)
					W	C	S	G	
20	8	55	6	44	175	318	742	1134	95

Selection of Pulsed Power Processing Parameters. After first charging ten 0.8-μF capacitors to 40 kV, 100 pulses of power were applied to the concrete specimens at a high voltage of 400 kV[4)]. During this process, density tests, water absorption tests, and sieve separation tests were performed every 20 pulses to evaluate the quality of the pulsed power recycled coarse aggregate. The result was that the oven-dry density and water absorption coefficient of the pulsed power recycled coarse aggregate fulfilled the criteria for recycled coarse aggregate for concrete class H after 60 pulses. The energy per pulse during these experiments was 6.4 kJ, giving 640 kJ after 100 pulses. The total amount of energy applied using this method can be calculated from

$$E = \frac{1}{2}CV^2 \times M \times N, \qquad (1)$$

where E is the total amount of energy in joules, C is the capacitance of the capacitors in farads, V is the potential in volts to which each capacitor was charged, M is the number of capacitors, and N is the number of pulses that were applied.

In this research, the optimal pulsed power processing parameters are taken to be those under which the oven-dry density and water absorption coefficient of the pulsed power recycled coarse aggregate satisfy the criteria for recycled coarse aggregate for concrete class H when using the minimum energy. Accordingly, the quality of the pulsed power recycled coarse aggregate was evaluated while varying the energy per pulse.

The pulsed power discharge decomposition experiments were therefore performed using capacitors having two different capacitances of 0.8 μF and 0.2 μF, with either ten or five capacitors charged to 40 kV to generate high voltages of either 400 kV or 200 kV. The amount of energy per pulse for these four sets of parameters were E/N = 6.4 kJ for ten 0.8 μF capacitors, E/N = 3.2 kJ for five 0.8 μF capacitors, E/N = 1.6 kJ for ten 0.2 μF capacitors, and E/N = 0.8 kJ for five 0.2 μF capacitors (Table 4). The density, water absorption coefficient, and sieve separation were tested at energies of 128, 256, 384, 512, and 640 kJ corresponding to numbers of pulses of 20, 40, 60, 80, and 100 from previous research.

Table 4. Processing Parameters

E \ E/N	6.4 kJ	3.2 kJ	1.6 kJ	0.8 kJ
128 kJ	20 pulses	40 pulses	80 pulses	160 pulses
256 kJ	40 pulses	80 pulses	160 pulses	320 pulses
384 kJ	60 pulses	120 pulses	240 pulses	480 pulses
512 kJ	80 pulses	160 pulses	320 pulses	640 pulses
640 kJ	100 pulses	200 pulses	400 pulses	800 pulses
Capacitance of capacitors	0.8 μF	0.8 μF	0.2 μF	0.2 μF
Number of capacitors	10	5	10	5
Applied voltage	400 kV	200 kV	400 kV	200 kV

E/N represents the energy per pulse.
E represents the total amount of energy.

DENSITY AND WATER ABSORPTION COEFFICIENT OF PULSED POWER RECYCLED COARSE AGGREGATE

Density and Water Absorption Coefficient Tests. The densities and water absorption coefficients were tested at energies of 128, 256, 384, 512, and 640 kJ during the application of 640 kJ of energy for the parameters 0.8 μF/400 kV, 0.8 μF/200 kV, 0.2 μF/400 kV, and 0.2 μF/200 kV. The results are shown in Tables 5 and 6 and in Figures 4 and 5, arranged by amount of energy.

Evaluation by Density and Water Absorption Coefficient. We next present evaluation results regarding the criteria for recycled coarse aggregate to be used in concrete class H. The pulsed power recycled coarse aggregate obtained by applying an energy of E/N

= 6.4 kJ per pulse at a capacitance of 0.8 μF and applied voltage of 400 kV satisfied the oven-dry density criterion when using an applied energy of 256 kJ; the water absorption coefficient criterion, 384 kJ. At an energy per pulse of *E*/*N* = 3.2 kJ using a capacitance of 0.8 μF and applied voltage of 200 kV, the criterion for oven-dry density was satisfied at 256 kJ; water absorption coefficient, 384 kJ. At 0.2 μF, 400 kV, and *E*/*N* = 1.6 kJ, the criteria for oven-dry density and water absorption coefficient were satisfied at 128 kJ and 256 kJ respectively, and at 0.2 μF, 200 kV, and *E*/*N* = 0.8 kJ, the criteria for oven-dry density and water absorption coefficient were both satisfied at 384 kJ.

Table 5. Oven-Dry Density Depending on Processing Parameters

E \ *E*/*N*	6.4 kJ	3.2 kJ	1.6 kJ	0.8 kJ
128 kJ	2.46	2.47	2.51	2.35
256 kJ	2.64	2.64	2.74	2.47
384 kJ	2.80	2.85	2.95	2.78
512 kJ	2.94	2.99	3.01	2.95
640 kJ	2.98	3.03	3.03	3.01

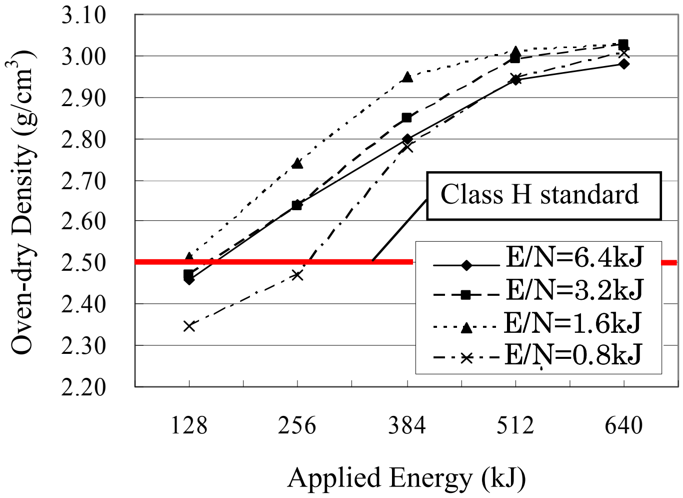

Figure 4. Oven-Dry Density versus Applied Energy

Table 6. Water Absorption Coefficient Depending on Processing Parameters

E \ *E*/*N*	6.4 kJ	3.2 kJ	1.6 kJ	0.8 kJ
128 kJ	5.34	5.31	5.21	8.34
256 kJ	3.75	3.91	2.94	5.37
384 kJ	2.43	2.02	1.09	2.46
512 kJ	1.58	1.06	0.84	1.03
640 kJ	1.55	0.71	0.57	0.61

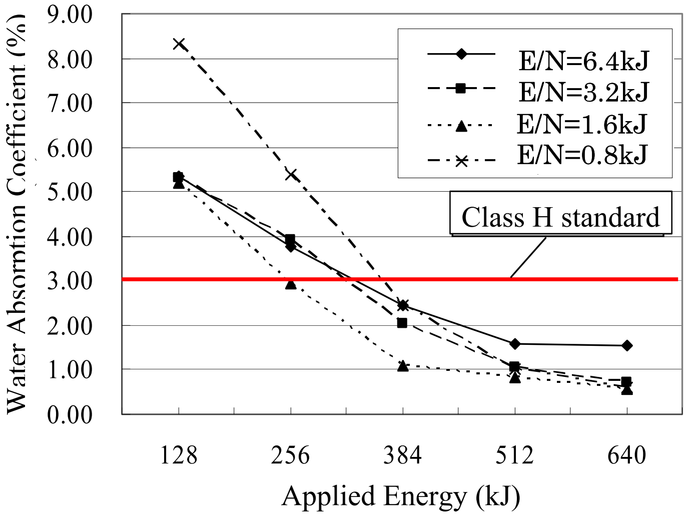

Figure 5. Water Absorption Coefficient versus Applied Energy

From the test results, the oven-dry density increased and the water absorption coefficient decreased as the number of pulses increased under all of the processing parameters. This is thought to be because adhered mortar was separated from the original coarse aggregate as the number of pulses increased, improving the quality of the pulsed power recycled coarse aggregate. Furthermore, the water absorption coefficient did not satisfy the criterion for recycled coarse aggregate for concrete class H before the oven-dry density did so in these experiments under any of the energy per pulse parameters. Both the oven-dry density and water absorption coefficient fully satisfied the quality standards for recycled coarse aggregate for concrete class H at an applied energy of 384 kJ. At values of applied energy per pulse of E/N = 3.2 kJ and E/N = 1.6 kJ, the oven-dry density of the pulsed power recycled coarse aggregate after an applied energy of 640 kJ was 3.03 g/cm^3, which is extremely close to the 3.04 g/cm^3 of the original coarse aggregate. Furthermore, under the 0.2 μF/200 kV parameters where the energy per pulse was the lowest, E/N = 0.8 kJ, the oven-dry density was the lowest and the water absorption coefficient was the highest in comparison with the other parameters at lower applied energy. Therefore, the concrete mass may become more finely decomposed as the energy per pulse is decreased. For the energy per pulse of E/N = 1.6 kJ, the oven-dry density was the highest for a given applied energy, and the water absorption coefficient was the lowest. Furthermore, the oven-dry density satisfied the standards for recycled coarse aggregate for concrete class H at an applied energy of 128 kJ, and the water absorption coefficient satisfied the standards at 256 kJ. This means that the oven-dry density and water absorption coefficient satisfied the standards for recycled coarse aggregate for concrete class H at an applied energy of 256 kJ after 160 pulses for the energy per pulse of 1.6 kJ.

FINENESS MODULUS OF PULSED POWER RECYCLED COARSE AGGREGATE

Sieve Separation Test. Sieve separation tests were performed for energies of 128, 256, 384, 512, and 640 kJ during the application of 640 kJ of energy for the parameters 0.8

μF/400 kV, 0.8 μF/200 kV, 0.2 μF/400 kV, and 0.2 μF/200 kV. The results are shown in Figures 6 and the fineness moduli obtained from the fineness curves are shown in Table 7 and Figure 7. The results are arranged by energy amount.

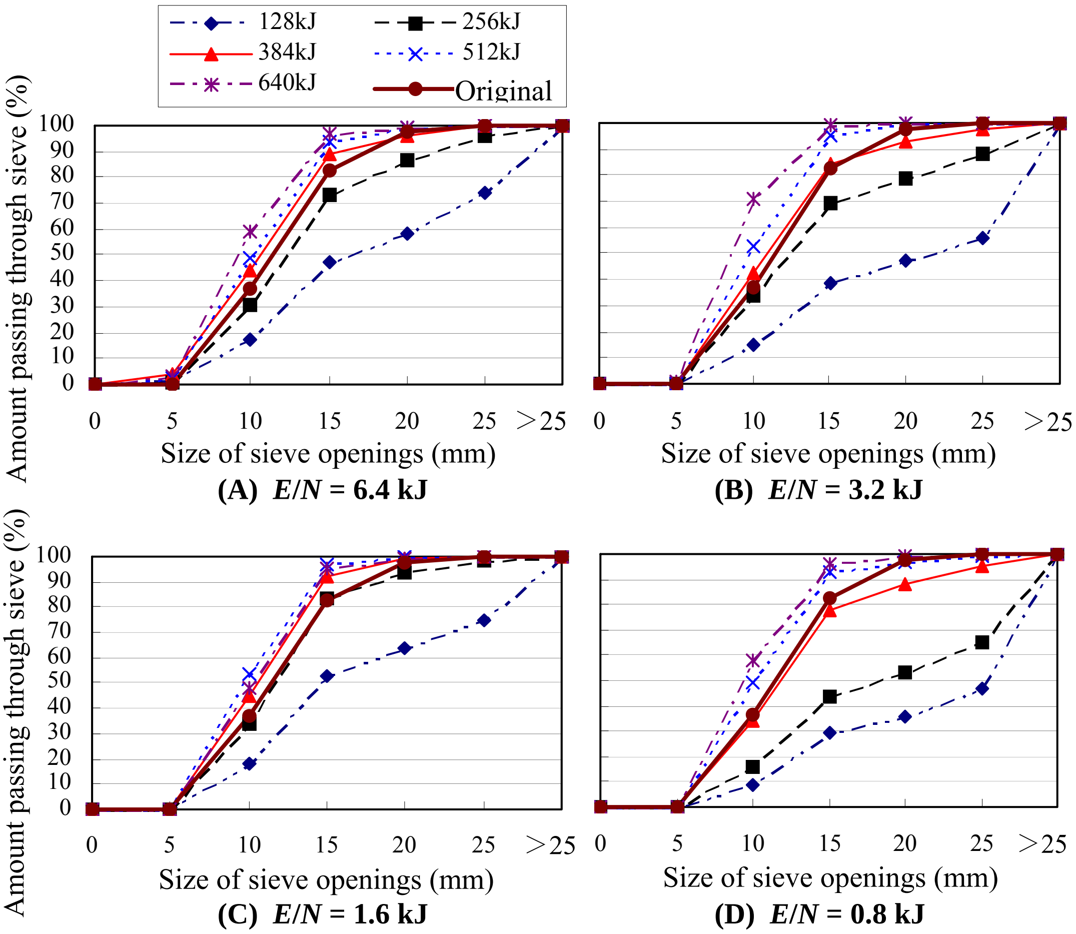

Figure 6. Fineness Modulus Curve of Recycled Coarse Aggregate

Table 7. Fineness Modulus Depending on Process Parameters

E \ *E/N*	6.4 kJ	3.2 kJ	1.6 kJ	0.8 kJ
128 kJ	7.23	7.38	7.18	7.55
256 kJ	6.82	6.87	6.73	7.31
384 kJ	6.56	6.64	6.56	6.78
512 kJ	6.50	6.47	6.52	6.54
640 kJ	6.38	6.28	6.47	6.43

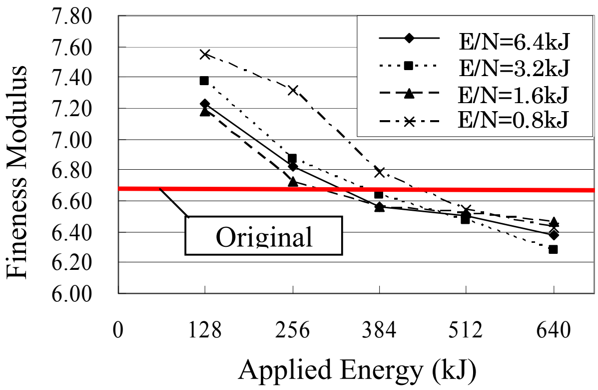

Figure 7. Fineness Modulus versus Applied Energy

Evaluation by Fineness Curve and Fineness Modulus. The fineness curve in Figure 6(A) shows that refinement advances beyond that of the original coarse aggregate at an applied energy of 384 kJ under energy per pulse of E/N = 6.4 kJ. The fineness curve in Figure 6(B) shows that refinement advances beyond that of the original coarse aggregate also at an applied energy of 384 kJ under energy per pulse of E/N = 3.2 kJ. Furthermore, in the case of E/N = 1.6 kJ, the fineness curve in Figure 6(C) approaches extremely close to that of the original coarse aggregate at an applied energy of 256 kJ, and the refinement surpasses that of the original coarse aggregate at 384 kJ. The fineness curve in Figure 6(D) shows that the refinement surpasses that of the original coarse aggregate at 512 kJ for the case of E/N = 0.8 kJ. From Table 7 and Figure 7, at an applied energy of 384 kJ, the fineness modulus for E/N = 6.4 kJ became smaller than the fineness modulus of 6.66 of the original coarse aggregate. Similarly, the fineness moduli for E/N = 3.2 kJ and E/N = 1.6 kJ became smaller than the fineness modulus of the original coarse aggregate at an applied energy of 384 kJ. For E/N = 0.8 kJ, refinement occurred with the fineness modulus becoming smaller than that of the original coarse aggregate at an applied energy of 512 kJ.

Evaluation of Quality from Fineness Modulus and Water Absorption Coefficient. As the number of pulses was increased, the concrete mass broke apart, the pieces of mortar adhered to the recycled coarse aggregate separated, and the fineness modulus decreased. In other words, although the quality of the pulsed power recycled coarse aggregate increased as the number of pulses was increased, further refinement compared with that of the original coarse aggregate also occurs at the same time. To find the optimal processing parameters, we focused on the changes in the water absorption coefficient and fineness modulus in these experiments because the oven-dry densities satisfied the standards for recycled coarse aggregate for concrete class H whenever the water absorption coefficient satisfied the standards. Since decomposition mainly of the mortar component occurred at energies from 128 kJ to 256 kJ and the fineness modulus became lower than that of the original coarse aggregate at energies of 384 kJ and above, fracture of the original coarse aggregate is thought to have occurred. Decomposition of the mortar component, which is more fragile than coarse aggregate, is expected to make up a larger proportion of fineness modulus compared with when fracture of the aggregate occurs. In the present experiments, the oven-dry density and water absorption coefficient both satisfied the quality standards for recycled coarse aggregate for concrete class H when we used applied energy of 256 kJ for E/N = 1.6 kJ, and thus are thought to be the optimal parameters because the energy is minimized. In this case, the trend of the variation in the fineness modulus changed near an applied energy of 256 kJ, and this could be applied to finding the optimal applied energy from the variation in the fineness modulus. Furthermore, the variation in the fineness modulus for E/N = 0.8 kJ was smaller compared with the other processing parameters. This is attributed to the energy per pulse being low. From the oven-dry density and water absorption coefficient, lower energy per pulse is thought to cause less damage to the original coarse aggregate and is expected to more finely decompose the concrete. Therefore, initially applying a large energy per pulse to effectively break apart the concrete and then gradually reducing the energy per pulse may be effective for recovering better quality recycled coarse aggregate.

SUMMARY

This research investigated the capacitance, generated voltage, number of pulses, and amount of energy to use in the pulse discharge generation device in order to obtain the optimal processing parameters for performing decomposition of concrete masses by the pulse discharge method for separating and recovering high-quality recycled coarse aggregate for concrete class H. The results were that the oven-dry density and water absorption coefficient satisfied the quality standards for recycled coarse aggregate for concrete class H when using an applied energy of 256 kJ for the capacitance of 0.2 μF and applied voltage of 400 kV, and when using an applied energy of 384 kJ for other parameters. Similarly, the fineness modulus became slightly more refined than that of the original coarse aggregate when using applied energy of 512 kJ and higher for the capacitance of 0.2 μF and applied voltage of 200 kV, and when using applied energy of 384 kJ and higher for other parameters. The optimal processing parameters for minimizing the applied energy such that both the oven-dry density and water absorption coefficient satisfy the quality standards for recycled coarse aggregate for concrete class H is thought to be at an applied energy of 256 kJ with a capacitance of 0.2 μF and applied voltage of 400 kV and E/N = 1.6 kJ. Furthermore, the method for investigating the optimal applied energy from the trend of the variation in the fineness modulus was found to be applicable in some cases and not applicable in others. Moreover, more efficient recovery of recycled coarse aggregate may be possible by changing the energy per pulse during the process. In the future, we plan to search for the optimal processing parameters and number of pulses by considering all of the relevant factors, including quality, time, and cost.

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