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# Crushing and Liberation of Materials by Electrical Disintegration

Toyohisa Fujita[1]*, Isao Yoshimi[2], Atsushi Shibayama[1], Toshio Miyazaki[1], Keisuke Abe[1], Masashi Sato[1], Wan Tai Yen[3] and Jan Svoboda[4]

[1] *Faculty of Engineering and Resource Science, Akita University, Akita 010-8502, Japan*
[2] *Nittetsu Mining Co. Ltd., Hinodemachi, Nishitama-gun, Tokyo1990-01, Japan*
[3] *Mining Department Queen's University, Kingston, Ontario, Canada*
[4] *Advanced Technologies (Pty.) Ltd., Johannesburg, South Africa*

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ABSTRACT

Liberation by crushing is very important for separation of different materials in mineral beneficiation and for the recycling of the components. The mechanical crushing and grinding usually liberate minerals from rocks. However, it is difficult to crush the materials along the boundaries of different components. In this study, the voltage, electric current and energy used in several applications have been measured for the dielectric breakdown in liquid phase. The crushing of mortar, granite and concrete in water or oil by the impulse high voltage supply (a lightning discharge impulse) has been investigated. It is important for the large energy supply on the sample to decrease the duration of the wave front to reach the maximum voltage. The energy consumption by the electrical disintegration is greatly reduced as compared with the conventional compression test. The liberation along the boundaries of materials is possible by electrical crushing (disintegration). 

Keywords: Liberation; Electrical Crushing; Electrical Disintegration; Lightning Discharge Impulse; Electric Current

## 1. INTRODUCTION

Particle liberation is very important for mineral processing and the recycling practices. This paper presents a method of electrical crushing (disintegration) to liberate minerals. Conventional crushing and grinding equipment breaks the materials into a random pattern from rocks, concrete and waste electric tools, and results in a high consumption of energy. Instead of conventional comminution methods, the technology of electrical disintegration (ED) using a lightning discharge impulse were investigated in this study.

The principle of ED is the application of the plasma current flowing along the grain boundaries of different components. An expansion of the heated boundary causes a breakage of minerals and composite materials. This fragmentation occurs mainly by exceeding the tensile strength of the specimen. Andres (1983, 1995, 1996, 2001) reviewed the technique of the electrical disintegration of rocks, which is commercially used to liberate diamonds and emeralds from the host rock. The relationship between electrical breakdown voltage and time required for application of high voltage was reported in FRANKA-Process of Germany (1997).

On the other hand, it was reported that the electrohydraulic disintegration (EHD) method, where the electrode is not directly attached on the specimen but a shock wave in water is used could also disintegrate materials along the boundaries. The differences between EHD and ED are shown in Figure 1. In the EHD method the breakage occurs mainly by exceeding the compressive strength of the specimen and much more energy will be required as compared to the breakage occurring when exceeding the tensile strength in the ED method.

* Corresponding author. E-mail: fujita@ipc.akita-u.ac.jp

Komatsu Ltd. have developed the electrohydraulic disintegration of rocks using small bubbles in water (1998a) or disintegration of concrete by applying a high voltage between an electrode in water and a grounded steel bar in concrete (1998b). Hitachi Zosen Corp. (1998) have reported the fracturing method employing a shock wave by an electrical discharge cartridge with a metal wire in a special chemical liquid.

Other liberation methods using electric and magnetic fields have been also investigated in previous studies (Fujita et al., 1999a, b). The high frequency heating of wet granodiorite caused the decrease of the tensile strength and the boundaries of mineral grains were observed on the breakage surface. Microwave heating was applied to crushing taconite in Minnesota. The heated magnetite in taconite was expanded and liberated from the unheated quartz. The principle of all these liberation methods is based on the difference in magnetic and electric physical properties of each individual component of minerals.

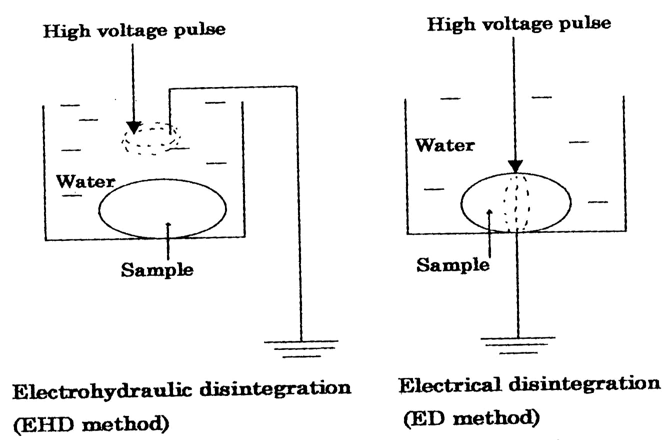


Figure 1. Comparison between EHD and ED methods

## 2. EXPERIMENTAL

### 2.1. Material

Disk-shaped specimens of mortar, granite and artificial concrete were used in this study. The samples consisted of particles of different sizes and the mean size of each particle ranged from 0.1mm to10mm. The physical characteristics of some composite minerals are listed in Table 1. The height (thickness) of disk samples ranged from 2mm to 10mm for mortal and granite. The concrete specimen height was 22mm. The diameter of the disk-shaped specimens was 40mm. The solid samples were immersed in distilled water or insulating oil. When the mortar and concrete samples are immersed in the distilled water, some substances (ions) are dissolved in the water and the hydrophilic water will penetrate through small cracks of these materials. The conductivity of water-dissolved ions is $10^{-3}\Omega$m. However, granite does not have the dissolved ions, and it produces small cracks. The hydrophobic oil is difficult to penetrate the cracks. When a high voltage is applied to the samples, the electric current flows through the materials of a higher conductivity. The areas through which the electric current flows expand by the Joule heat and samples are thus crushed.

The 0.1mm sand in mortar and the 10mm borosilicate glass bead (ball) in concrete are used to make up artificial gravel, which is well mixed with Portland cement and water. The mortar and concrete blocks were immersed in the water for two weeks to increase their strength. A uniaxial compression test machine was used to measure the compressive strength of the samples. A photograph of a sample containing 6mm glass beads broken by mechanical compression test is shown in Figure 2. The mortar remained around the glass beads and most of the beads were not liberated. Some glass beads were broken or cracked. The compressive strength was approximately $240 kg/cm^2$ and the energy required to break the sample was about 7kJ based on the stress-strain curve.

Table 1
Physical properties of grain particles and solvents

| | Volume resistivity Ωm at 110°C | Specific Heat kJ/kg°C at 25°C | Coefficient of linear expansion, $K^{-1}$ at 20°C |
|---|---|---|---|
| Quartz | $4.5\times 10^{11}$ | 0.7 | $10\times10^{-6}$ |
| Calcite | $1.0\times10^{9}$ | 0.8 | 5 to $26\times10^{-6}$ |
| Magnetite | $5\times 10^{-5}$ | 0.7 | |
| Orthoclase | $4.5\times10^{11}$ | | |
| Hornblende | $2.8\times10^{11}$ | 0.2 | |
| Soda glass | $1.0\times 10^{10}$ | 0.7 | 3 to $6\times10^{-6}$ |
| Granite | | 0.8 | 4 to$10\times10^{-6}$ |
| Mortar | | 0.8 | 7 to$14\times10^{-6}$ |
| Distilled water | $10^{9}$ | 4 | *$0.2\times10^{-3}$ |
| Vegetable oil | $10^{11}$ | 2 | *$1\times 10^{-3}$ |

*Coefficient of cubical expansion

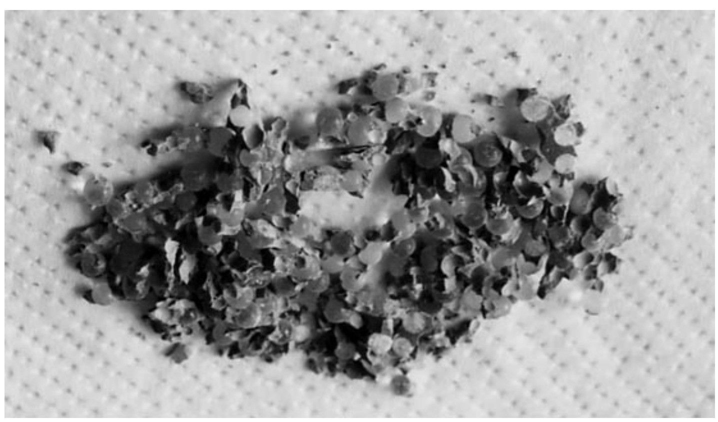

Figure 2. A sample of concrete crushed by compression test

## 2.2. Apparatus

The impulse high-voltage supply apparatus was constructed by Pulse Electronic Engineering Co, Ltd., Japan and the dependence of voltage on time is shown in Figure 3. Duration of the wave front can be adjusted to 0.2, 0.5 and 1.2μs. The maximum applied voltage and the charge energy are about 70kV and 800J, respectively. The schematic diagram of the experimental setup of the electrical crushing is shown in Figure 4. The sample blocks are immersed in the distilled water and are sandwiched between a rod-like iron electrode and a grounded copper plate. Fujita et al. have reported (1999) that the shape of the electrode is very important for the crushing process. In the present study a wedge type electrode of 5mm diameter is used for a higher energy supply. The electrode is set in contact with the center of the cylindrical core surface or a few millimeters above the center. As shown in this Figure a coil type ammeter was placed around the electric wire connecting between ground and bottom electrode and the oscilloscope measures the current. The voltage between the impulse-voltage-generator and the ground-electrode was measured by a probe, which was connected to the oscilloscope.

The charging energy $E_1$ of the high voltage generator is expressed by:

$$E_1 = 0.5CV^2 \quad (1)$$

where C is the electrostatic capacity of the generator (0.25μF in this study) and V is the applied voltage.

When the sample is broken by the impulse, the consumed energy $E_2$ is calculated from equation (2) by using the sum of the products of the voltage V per period $\Delta t$ and the sum of the current I per the period $\Delta t$ of the applied voltage, measured by the oscilloscope.

$$E_2 = \Sigma VI\Delta t \qquad (2)$$

Although the resistivity of the initial distilled water is rather high, it should decrease significantly due to the dissolved calcium ions released from the concrete powder. The mortar has a large porosity and its conductivity is much higher. When the lightning discharge is applied to the sample, a large electric current will flow along the boundaries between the gravel and the mortar but not inside the gravels because of their high resistivity. In granite the current will flow through the lower resistivity minerals or the cracks containing water.

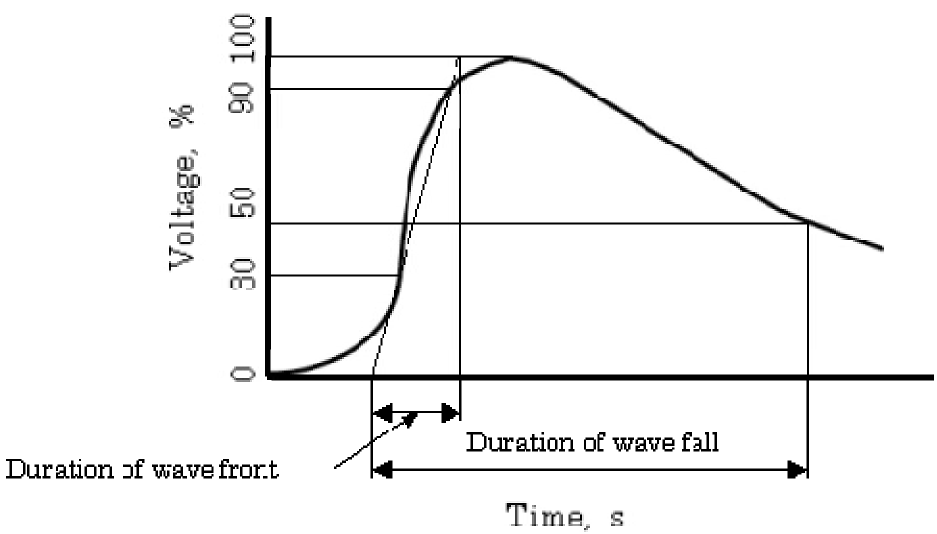


Figure 3. The property of the impulse high voltage generator

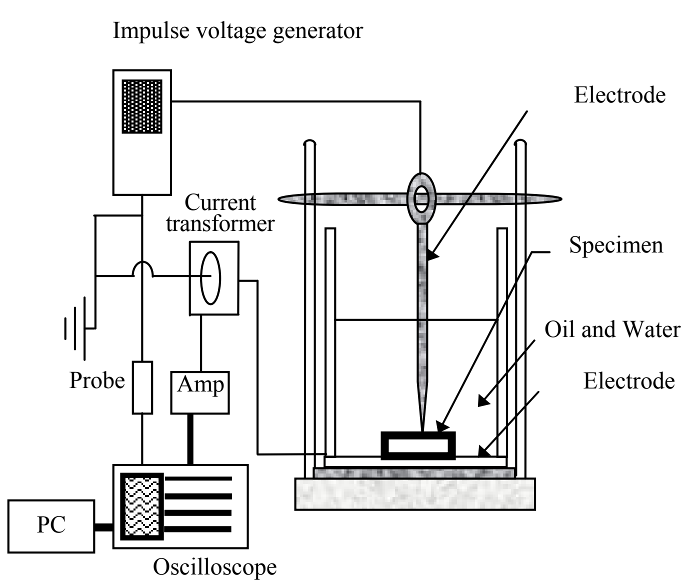


Figure 4. Experimental setup for electrical crushing by using lightning discharge impulse generator

## 3. RESULTS AND DISCUSSION

### 3.1. No samples placed between the electrodes

Figure 5 shows the voltage patterns of dielectric breakdown for various distances between the electrodes in water and its relationship with the duration of the wave front. In this case, there is no specimen between the electrodes. The same maximum voltage of 45kV is applied for all distances between the electrodes. Comparing the period of dielectric breakdown for two values of duration of the wave front, namely 1.2µs and 0.2µs, the time to reach the dielectric breakdown is longer for 0.2µs, for the same electrode distance. Therefore, during the longer period to reach the dielectric breakdown, a higher voltage must be applied between the electrodes for the shorter duration of wave front. The integration of the applied voltage multiplied by the electric current means the higher energy application between the electrodes in the shorter duration of the wave front. The slope of the decreasing voltage before the dielectric breakdown is almost the same for any distance between the electrodes and for the two values of duration of the wave front. As the distance between the electrodes increases, the longer period of the high voltage is necessary to reach the dielectric breakdown.

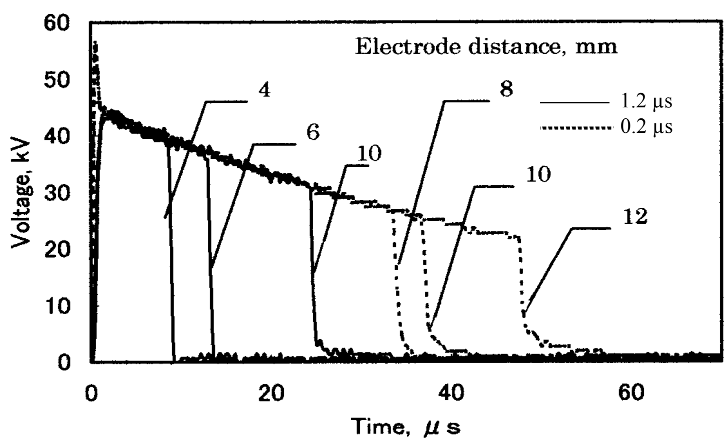


Figure 5. Voltage patterns of dielectric breakdown for several distances of electrode in water (no specimen)

The comparison of the voltage pattern between two solvents of different conductivities (water and oil) is shown in Figure 6, if the dielectric breakdown occurs at the minimum voltage. The same duration of the wave front of 1.2µs is employed. The resistivity of the insulating oil is $10^{12}\Omega m$, while that of water is several tens of $\Omega m$ in this study.

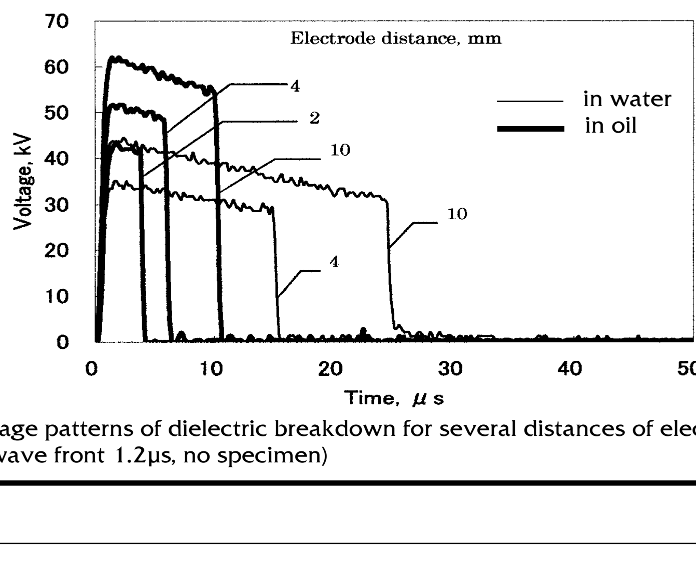


Figure 6. The voltage patterns of dielectric breakdown for several distances of electrodes in water and oil (Duration of the wave front 1.2µs, no specimen)

The dielectric breakdown strength of oil is much greater than that of water. However, the time to reach the dielectric breakdown is shorter than that of water for the same electrode distance. In the case of the same duration of the wave front, the consumed energy for the electric breakdown is considered to be almost the same in the water and the oil.

### 3.2. Samples placed between electrodes

The voltage patterns of electrical disintegration of mortar samples of various thicknesses in water are shown in Figure 7, when the dielectric breakdown occurs at the minimum voltage. Three different periods of duration of the wave fronts, namely 0.2μs, 0.5μs and 1.2μs, were used in the electrical crushing. The maximum voltage used in this study is less than 70kV. The actual maximum voltage for crushing increased by the utilization of a longer period of the duration of the wave front. When the duration of the wave front of 1.2μs is employed, the mortar sample thicker greater than 8mm cannot be fractured. When the duration of the wave front is decreased, the applied voltage period increases and a larger thickness of the mortar samples was crushed. For example, to crush a thickness of 10mm, the maximum voltage of 68kV and the dielectric breakdown period of about 10μs were used. The duration of wave fronts was 0.5μs, while the maximum voltage decreased to 62kV. The breakdown period increased to15μs for the duration of the wave front of 0.2μs.

The measured voltage and the electric current to crush a 6mm thick mortar sample are shown in Figure 8. The electric current flowing in the mortar sample is delayed after the high voltage is applied to the sample. The difference between the maximum voltage time and maximum current time is approximately 8μs. The consumed energy was about 0.35J and the maximum electric current was 2300A. As the small current flows after the high voltage is employed, the used energy appears mainly in a period when the high voltage was applied in the crushing. The photograph of the crushed mortar sample is shown in Figure 9. The mortar sample was crushed into several pieces from the center of sample. The mortar sample was broken mainly by exceeding its tensile strength due to the thermal expansion of the heated portion from the large current flow.

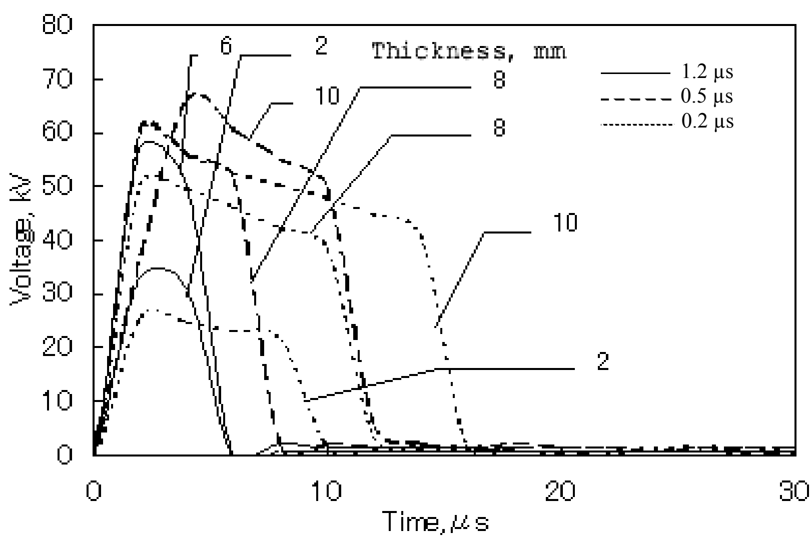


Figure 7. Voltage patterns of electrical disintegration for several thicknesses of mortar samples in water by using different duration of the wave front

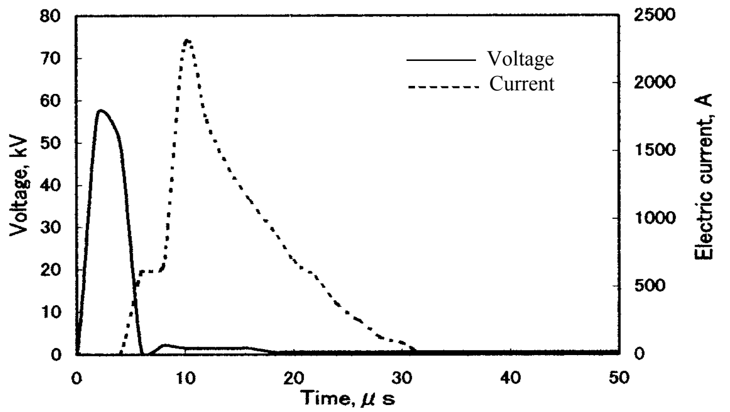


Figure 8. The voltage and current in electrical crushing of mortar in water (Duration of the wave front 1.2μs, thickness of the mortar sample 6mm)

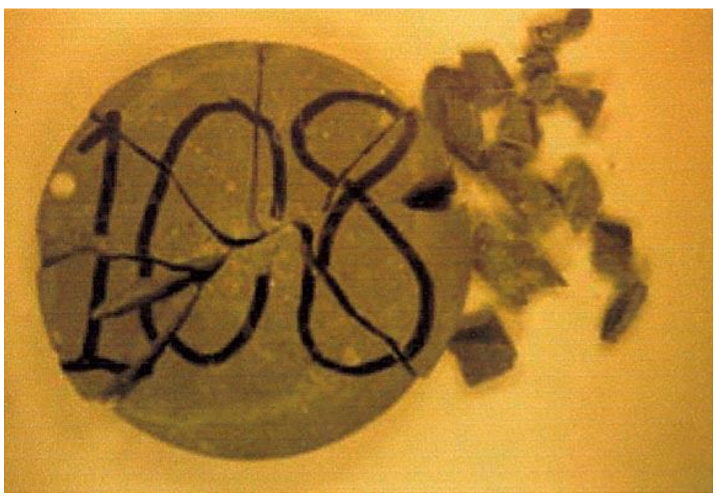


Figure 9. A photograph of a mortar specimen after electrical crushing

The voltage patterns of electrical disintegration for various thicknesses of granite specimens in water and oil are shown in Figure 10, when the dielectric breakdown occurs at the minimum voltage. The duration of the wave front is 1.2μs. Almost same dielectric breakdown strength (voltage) caused the electrical crushing of granite in both water and oil. However, the period to reach the dielectric breakdown in the oil is shorter than that in the water for the same thickness of the granite specimen. This phenomenon is quite different from the voltage patterns of Figure 6 when no specimen was placed between the two electrodes. As the electric resistivity of granite is smaller than that of the insulating oil used, a large electric current flows through the granite by applying the high voltage.

On the other hand, the water penetrates into the cracks of granite and the water resistivity is smaller than that of the minerals constituting the granite. As the electric current flows along the water filling the cracks, a larger energy was required to crush the granite in water. Therefore, the period to reach the dielectric breakdown in water after a high voltage was turned on is estimated to be longer than that in oil. The photograph of crushed granite is shown in Figure 11. The granite is crushed into several pieces from the centre and the crushed shapes are almost the same in both oil and water. The measured voltage and current to crush the granite of 8mm thickness are shown in Figure 12. The maximum electric current of 1800A flows after the dielectric breakdown. This result is similar to that observed with mortar, as shown in Figure 8. The consumed energy appears mainly in the period of the applied high voltage and the total energy is about 0.1J.

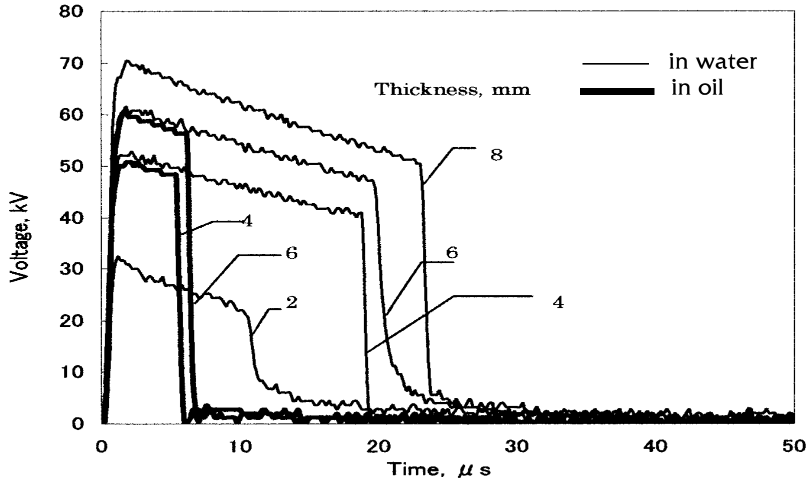


Figure 10. The voltage patterns of electrical disintegration for several thicknesses of granite in water and oil (Duration of wave front 1.2μs)


Figure 11. A photograph of a granite specimen after electrical crushing

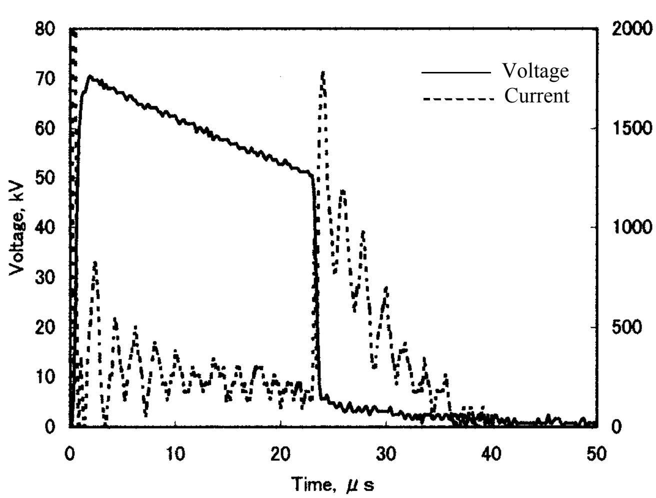


Figure 12. The voltage and current for electrical crushing of the 8 mm granite specimen in water (Duration of the wave front 1.2μs)

The wave patterns of the fragmentation pulse of the concrete specimen containing 10mm glass beads are shown in Figure 13. Though the duration of the wave front is 1.2μs, the maximum voltage of 68kV was achieved in 2μs and then the voltage decreased in several steps. The electric current gradually increased until the voltage dropped to about 10kV and the maximum current was observed at the end of voltage decrease. The maximum electric current was 400A.

The glass beads were distributed in two layers. It is assumed that the first step in the voltage decrease is due to the liberation of the first layer of the glass beads and the second step is due to the liberation of the second layer of the glass beads. The crushed and removed glass beads decreased the voltage as the current increased at a constant rate. By using the equation (2), the consumed energy to break the sample was calculated to be 0.2kJ, which was much smaller than the energy of about 7kJ consumed by the mechanical crushing. Generally the tensile strength of rocks is 10 to 30 times smaller than the compressive strength (Andres et al., 1995). The impulse disintegration of concrete caused the fragmentation by the tensile strength and the resulting consumed energy was much lower than that required for the mechanical compressive breakage. The concrete was broken mainly by exceeding the tensile strength due to the thermal expansion caused by the large current flow of plasma. The photograph of the crushed concrete is shown in Figure 14. Most of the glass beads are liberated and are not broken. Compared to the mechanical crushing, as shown in Figure 2, better liberation of gravel particles by electrical disintegration was achieved.

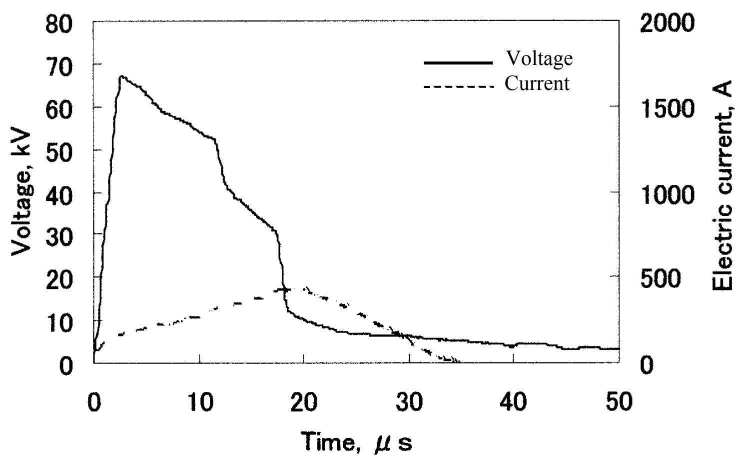


Figure 13. The voltage and current for the electrical crushing of concrete in water (Duration of wave front 1.2μs, thickness of concrete 22mm)

Figure 14. A photograph of concrete after electrical crushing

The application of liberation by electrical crushing method is very useful for separation pre-treatment in the recycling of many types of materials with different combined resistivities, such as electric tools.

## 4. CONCLUSIONS

The electrical crushing of disk-shaped specimens containing particles ranging from 0.1 to 10mm in size was investigated by the electrical disintegration method using the lightning discharge impulse. The high voltage was supplied to the specimens or in the absence of specimens in water or oil by using a lightning discharge impulse generator. The results obtained can be summarised as follows:

When there was no specimen between the electrodes, a shorter duration of the wave front can keep the high voltage for a longer period of time. A higher voltage is required for the dielectric breakdown because of a higher electric resistivity of oil as compared to that of water.

As the samples are being set between the electrodes, all materials are crushed into several pieces radially from the centre. The materials have been broken mainly by exceeding their tensile strength due to the thermal expansion of the heated portion from the large current flow. In the mortar sample, the use of the wave front of a shorter duration could crush a thicker mortar applying a lower voltage. In the granite sample, almost the same dielectric breakdown strength (voltage) could cause the electrical crushing in both water and oil. In the artificial concrete disk specimen, some glass beads could be liberated retaining their different spherical shapes. The energy consumption was greatly reduced as compared with the conventional compression test. This electrical crushing method is useful to liberate components having different resistivity in recycling applications.

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