Controlled Cracking for Industrial Concrete Waste by Steam Pressure Cracking Agent

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We propose a quick and controlled cracking method for industrial ceramic waste by applying a steam pressure cracking (SPC) agent. The agent is a non-explosive and low-vibration-type chemical, which was developed by one of the authors of this study. We prepared a concrete specimen that had a diameter and cylinder height of 150 mm. Several grams of the agent cracked the specimen. We could control the cracking better in water than air when the air and water conditions were compared. When tested in water, the agent was placed in the hole of the concrete specimen and ignited, and the specimen could be split into two or three pieces of the same size. However, using another SPC agent that was explosive, the concrete specimen was broken into small fragments and size of the concrete pieces could not be controlled. The crushing mechanism was different for the two cases. The explosive crushed the concrete mainly through elastic shock waves. However, the steam pressure cracking agent breaks the specimen using the steam pressure and shock waves. We demonstrated that the cracking can also be controlled using guide holes. This steam pressure method can be applied to industrial waste as a safe and well-controlled method.

Keywords: Steam Pressure Cracking Agent, Industrial Ceramics Waste, Recycling Process

1 INTRODUCTION

For the sustainable development goals established by the United Nations [1], the treatment and recycling of industrial waste structures is an essential technology. Industrial waste is a mixture of many kinds of materials, including hard, soft, useful, and hazardous elements. Therefore, the first process of treatment is reducing them into small sizes and decomposing each material.

The objective of this study is to develop a new cracking method for industrial ceramic waste, such as concrete, rock, slag, and melted debris. Separating methods for ceramics are classified as static mechanical cutting and dynamic explosive crushing. The plasma arc, abrasive water jet, and band saw are typical examples of static cutting methods. These mechanical methods are well-controlled in the cutting direction; however, the cutting speed is slow and secondary waste products, such as melted slug and cutting scrape, are produced [2]. However, the dynamic separation method for cutting by means of explosion is difficult to control [3] and has safety challenges. A speedy and safe separation method is strongly desired, particularly for the decommissioning of nuclear facilities [3, 4].

We studied the steam pressure cracking (SPC) agent as a quick and safe treatment method for industrial ceramic waste. It involves static expanding chemicals inserting cracks for crushing the rock and concrete [5]. However, expanding chemicals take several hours to react.

The SPC agent is a non-explosive and low-vibration-type chemical, which was developed by one of the authors of this study. The steam pressure agent had been studied as an industrial recycling method by Fujita et al. [6-9]. They applied the agent for disassembling electrical equipment in water.

2 EXPERIMENTAL DETAILS

2.1 Concrete sample for testing

A cylindrical concrete specimen was used for the cracking test with a steam pressure agent, and it was easier to control the crack propagation in water than air. The agent was placed in the hole of the concrete specimen and ignited in water. The concrete sample tested, as shown in Figure 1, was made from a mixture of cement, sand, gravel, and water in the ratio of 1:2:4:0.5. The fresh concrete mixture was poured into molds and cured for 3 weeks. During this time, enough water was placed on the surface so that it did not crack. The mechanical strength of the concrete samples was tested using a Schmidt rock hammer of type KS manufactured by Proceq Swiss Aerospace (SA) of Switzerland. The Schmidt values \( c \) of the samples changed from 10 to 40, depending on the position of the concrete surface because the concrete was composite [10]. The nominal material properties of concrete used are shown in Table 1.

The mean Schmidt value was approximately 20 in this study. The compression strength \( \sigma \), can be evaluated using the following
equation [10]:
\[ \sigma_c = 0.9294 x^{1.1219} \text{ [N/mm}^2] \]       (2-1)
where \( x \) is Schmidt value.

2.2 Steam-pressure cracking agent used

The chemical composition of the SPC agent is listed in Table 2. The SPC agent was set into the bottom of center hole of the concrete sample and covered with quick-drying adhesive as shown in Figure 2. The agent ignites at over 793 K (520°C) using the following reaction formula:

\[
2\text{Al} + \frac{9}{2}\text{CuO} + n\text{KAl(SO}_4\text{)}_2 \cdot 12\text{H}_2\text{O} \rightarrow \frac{3}{2}\text{Al}_2\text{O}_3 + \frac{9}{4}\text{Cu}_2\text{O} + n\text{KAl(SO}_4\text{)}_2 + 12\text{nH}_2\text{O}^\uparrow + 1170 \text{kJ/kg.} [15] \quad (2-2)
\]

The physical properties resulting from the reaction are shown in Table 3. The chemical reaction products have a maximum pressure of 300 MPa and 330 l/kg of steam that is capable of crushing the concrete.

2.3 Experimental procedures for cracking tests

A hole with a diameter of 18 and depth of 100 mm was created in the sample. The SPC agent with a weight of 10 g was coupled with an igniter, as shown in Figure 2, was placed at the bottom of the sample hole, and then fixed with epoxy resin. The cracking test was performed in water. For comparison, tests in air and explosive tests were also conducted.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Comparison of cracking tests in air and water

The results of the cracking tests in both air and water are shown in Table 4 and Figure 3. The total number of concrete pieces that cracked in air was more than that in water. The authors considered that water restrains the concrete sample from the outside under impact loading conditions.

The method of creating the hole in the sample significantly affects the crushing result. Regarding the depth of the hole, when we tried a depth of 90 mm, the sample was not crushed, and the fixing materials were discharged similar to a bullet from a gun. It is necessary for the center of the pressure source to coincide with the geometrical center of the sample. The type of material for fixing

![Figure 1](image1.png)

**Figure 1** Geometry of concrete sample and cross-section used with a hole of 18 diameter and 100-mm depth

![Figure 2](image2.png)

**Figure 2** Setting of steam pressure cracking agent to concrete sample. The yellow bar of left photo is a packaged SPC agent.

![Table 1](table1.png)

**Table 1** Nominal material property of concrete used

| Material property | Value [unit] |
|-------------------|-------------|
| Compressive strength \( \sigma_c \) | 20~50 [N/mm²] |
| Tensile strength \( \sigma_t \) | \( \sigma_t < \sigma_c / 10 \) [N/mm²] |
| Density \( \rho \) | 2.3~2.5 [GPa] |
| Elastic modulus | 10~50 [GPa] |
| Schmidt values | 10~40 |
| Velocity of elastic wave | 4500~5400 [m/s] |

* Measured values by authors

![Table 3](table3.png)

**Table 3** Physical properties of agent used

| Property | Value |
|----------|-------|
| Ignition point | 793 K (520 °C) |
| Reaction speed | 300 m/s |
| Time to maximum pressure | 30~50 ms |
| Sealed combustion pressure | 300 MPa |
| Volume of gas produced | 330 l/kg |
| Theoretical energy product with standard mixture | 1170 kJ/kg |

![Figure 3](image3.png)

**Figure 3** Concrete pieces subjected by steam pressure cracking test in (a) air and (b) water

![Table 4](table4.png)

**Table 4** Cracking conditions in air and water

| Test environment | Air | Water |
|------------------|-----|-------|
| Mass of sample | 5.78 kg | 5.89 kg |
| Mass of SPC agent | 10 g | 10 g |
| Method for fixing | Epoxy resin | Epoxy resin |
the hole also affects the cracking test results. When fresh concrete was used without enough hardening, the fresh concrete was also discharged in a similar manner. Finally, the depth was set to 100 mm, and the fixing material used was epoxy resin, which was cured for 20 min.

When applying these methods on-site, mechanical methods should be considered rather than cured resins. This is because there remains no time to mix the resin with the descending agent or wait for curing in water. It is our objective to create a method for decommissioning industrial waste by combining the SPC agent and a mechanical system in the future.

3.2 Effects of SPC agent amount

Figure 4 shows the results of the cracking tests with 5 g of the SPC agent as shown in Table 5. The concrete specimen was separated into two pieces. The authors considered symmetrical cracking with respect to the axis as characteristic of the SPC method, as shown in Figure 4(b) and Figure 4(c).

When applying this method to the treatment of industrial waste, it is better to use fewer crushed pieces. Because one initial hole corresponds to one crushing surface, as shown in Figure 4, it is easy to control the cutting because the position and direction of cutting can be controlled.

We can consider that the destructive energy is consumed in the formation of these fracture surfaces as impact energy. In typical impact tests, it is specified as the absorbed energy of the fracture surface [12, 13]. The agent has an energy of 1170 kJ/kg, as shown in Table 3; therefore, the energy of 5 g of the agent is $1.170 \times 5 = 5.85$ kJ. The area of the fracture surface in Figure 4 is $0.0225 \text{ m}^2$. We can approximately calculate the impact value of the concrete as $250 \text{ kJ/m}^2$.

| Table 5 | Small amount of SPC agent test conditions |
|---------|-----------------------------------------|
| Mass of water-gel explosive | 3.0 g |
| Ignitor type No.6 PETN | 0.5 g |
| Mass of sample | 5.48 kg |
| Method of fixing | Epoxy resin |
| Test environment | Water |

3.3 Comparative test by water-gel explosive

The result of the crushing test by a water-gel explosive in water is shown in Figure 5. The explosive has high energy and the fracture mechanism is elastic shock waves that are different from that of the SPC agent. The size of the crushed concrete pieces is small, as shown in Figure 5. It is considered that the maximum compressive pressure of the explosive is higher than the concrete strength. Fine pieces are likely to cause secondary pollution. Therefore, this method of explosives is not suitable for industrial concrete waste. On the other hand, the pressure of SPC agent was insufficient to crush the concrete into small pieces.

3.4 Distribution of cracked concrete pieces

Figure 6 shows the mass of the concrete pieces tested. The theoretical limit line indicates the data when all pieces have the same size. The data value 1 of the horizontal axis of Figure 6 indicates no cracking, and the data value 2 signifies splitting of the sample into two pieces with the same mass. All experimental data were obtained lower than the theoretical limit line. The authors consider the effective cutting condition as number 2, as shown in Figure 4. The number of pieces increases with the mass of the SPC.
agent. The explosive method produced too many pieces because of its high energy. These phenomena can be understood from the fracture toughness [13, 14]. In the case of the impact fracture, the toughness is mentioned by impact energy, which is consumed by the surface energy. We can approximately estimate that the total crushing energy is linearly related to the area of the crack surface. The minimum crack surface is the cross-sectional area of diameter (d) times the height, h, as shown in Figure 4.

The specimen was sliced into two or three pieces of the same size. However, when using another explosive, the concrete specimen was broken into fragments and size of the concrete fragments could not be controlled. The breaking mechanism was different for the two cases. The explosive broke the concrete by the propagation of shock waves, whereas the steam pressure cracking agent broke the specimen using hydrostatic pressure. We demonstrated that crack propagation could also be controlled using guide holes. This steam pressure method can be applied to industrial ceramic waste as a safe and well-controlled method.

3.5 Control cracking by SPC agent with guide holes

The explosive agent indicated in Figure 5 has a rapid reaction, and the initial elastic shock wave crushes the concrete; therefore, we cannot control the crack initiation and its propagation. The SPC reaction is milder than the explosive and can control the cracking. We demonstrated the effect of guide holes by using the SPC under the conditions listed in Table 7. The specimen was placed at the center, and the SPC agent and three guide holes for controlling cracks were placed as Figure 7(a) and (b). In the case of the 5 g SPC agent, the specimen did not crack, as shown in Figure (a). However, the 10 g agent propagated and cracked the specimen along the guide holes, as shown Figure 7(b). The energy of the 5 g agent was possibly not sufficient to produce a crack surface that is 1.5 times that of the straight crack, as shown in Figure 4.

The cracking phenomena by SPC is based on three-dimensional elastic wave propagation; however, to understand the phenomena, authors use the following equation, which is a one-dimensional elastic wave equation [14].

\[
\frac{\partial^2 u(x,t)}{\partial t^2} - v^2 \frac{\partial^2 u(x,t)}{\partial x^2} = 0, \quad (3-1)
\]

where \( u \) is the displacement produced by SPC, \( v \) is the velocity of the elastic wave, \( x \) is the distance from the guide hole surface, \( t \) is the time and

\[
v = \sqrt{E/\rho} \quad (E: Young’s modulus, \rho: density of concrete) \text{ in elastic solid.}
\]

Longitudinal elastic waves are generated by the reaction of the steam pressure braking agent. As a general solution of equation (3-1), the following d’Alembert equation is shown as,

\[
u(x,t) = f(x - vt) + g(x + vt), \quad (3-2)
\]

where \( f(s) \) and \( g(s) \) are arbitrary functions that correspond to “the driving wave” and the “reflected wave” respectively. The functions of \( f(s) \) and \( g(s) \) indicate the wave that moves in opposite directions at speeds of \(+ vt\) and \(- vt\) correspondingly.

The stress \( \sigma \) of the elastic body produced by displacement \( u \) is expressed by the following equation:

\[
\sigma(x,t) = E \cdot u'(x,t), \quad (3-3)
\]

where \( u'(x,t) \) is the value of the partial derivatives for \( x \).

\[
\sigma(x,t) = E \cdot f'(x - vt) + E \cdot g'(x + vt). \quad (3-4)
\]

Considering \( x = 0, \sigma = 0 \) at free surface of the guide hole, as shown in Figure 8.

\[
u'(x,t) = f'(- vt) + g'(vt) = 0, \quad (3-5)
\]

\[
f'(- vt) = - g'(vt). \quad (3-6)
\]

Equation (3-3) indicates that the stress of the driving wave \( \sigma = E \cdot f'(- vt) \) is compressive; however, the pressure of the reflected wave \( \sigma = - E \cdot g'(vt) \) is tensile stress. These phenomena are known as the Hopkinson effect, which is applied for dynamic testing [11]. However, no example has been found for controlled cracking in ceramics.

The magnitude of the stress \( \sigma \) is dependent on \( u'(x,t) \) instead of \( u(x,t) \), which means that the stress is not related to the maximum pressure but to the gradient of displacement. In other words, the level of \( \sigma \) depends on the speed of the reaction of each chemical agent. The maximum compression pressure of the SPC agent at the center is approximately 3,000 kgf/cm² (≈ 300 MPa), and the time scale is about 100 ms. However, the explosive pressure is high (10 GPa), and the time scale is small (100μs). The slower reaction

| Table 7 | Control cracking test condition |
|---------|-------------------------------|
| Mass of SPC agent | 5 g | 10 g |
| Mass of sample | 5.77 kg | 5.33 kg |
| Method of fixing | Epoxy resin | Epoxy resin |
| Test environment | Water | Water |

Figure 7 Control of cracking path by SPC agent and lead holes: (a) no cracking after testing by 5 g SPC agent; (b) after cracking by 10 g SPC

Figure 8 Images of longitudinal elastic wave generated by SPC. Compressive stress of blue changes to the tensile stress of red when the wave is reflected at the free surface of guide hole
times enable the SPC agent to control the cracking of the concrete. The authors propose the cracking control condition by using the guide hole,

\[
\begin{align*}
\sigma_{\text{cr}} &= E \cdot f'(x - vt) < \sigma_t \quad \text{ and } \\
\sigma_{\text{cr}}' &= -E \cdot g'(x + vt) > \sigma_t \, ,
\end{align*}
\]

(3-7)

where \(\sigma_{\text{cr}}\) is the maximum compressive stress of the driving elastic wave, \(\sigma_t\) : maximum tensile stress of the reflected elastic wave near the guide hole, \(\sigma_{\text{cr}}\) : tensile strength of concrete used.

The authors estimated the values of \(\sigma_t\) and \(\sigma_{\text{cr}}\) as -18 MPa and 1.8 MPa, respectively, in this study. The \(f'(x - vt)\) and \(g'(x + vt)\) have dimensions of strain and the values are related to the reaction speed of the explosive agent. We can analyze the critical values of \(f'(x - vt)\) by substituting the data in Table 1.

\[
\begin{align*}
{f'(x - vt) < \sigma_t/E} &= -18/30000 = -0.06\% \\
{g'(x + vt) < \sigma_t/E} &= 1.8/30000 = 0.006\%
\end{align*}
\]  

(3-8)  

(3-9)

Therefore, to design controlled cracking, it is essential to first to select SPC that has an appropriate reaction speed according to the strength of the target material. The values of the displacement gradient of concrete cannot be obtained by analytical methods but by experiments. The authors are developing a controlled cracking mechanical system for ceramics by applying the results of this research.

4 CONCLUSION

The steam pressure cracking (SPC) agent is studied as a quick and safe treatment method for industrial concrete waste. The results are summarized as follows:

(1) When tested in water, large pieces can be cut without producing fine pieces. Water is suitable for the cutting of industrial concrete waste.

(2) Energy is consumed to produce the crack surface. The surface energy is approximately analyzed as 250 kJ/m² in the SPS condition.

(3) The explosive has high stress and produces a large number of fine grains compared to the SPC agent.

(4) The explosive has high compressive stress and a different fracture mechanism from the SPC agent.

(5) The cracking can be controlled using guide holes because the compulsive stress changes to tensile stress by reflection at the guide hole surface.

(6) The SPC agent can produce lower compressive stress and higher tensile stress than the strength of target concrete materials to achieve controlled cracking.

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