Journal of Materials and Applications 2022;11(1):1-9
https://doi.org/10.32732/jma.2022.11.1.1

Demolition of Reinforced Concrete by Steam Pressure Cracking System

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Received: 12 December 2021; Accepted: 4 February 2022; Available online: 15 March 2022

Abstract: The authors developed an environment-friendly demolition mechanical system for a large reinforced concrete structure for an actual site. The steam pressure cracking agent (SPC, non-explosive) is a method that can safely and quickly separate concrete because it produces lesser vibration and sound than the blasting method, which uses explosives. The authors showed that the direction of cracking can be controlled by an induction hole. The principle of control is that the elastic wave of the compression stress generated from the SPC reaction changes to a tensile elastic wave at the induction hole, which initiates a crack. Furthermore, in the SPC method, a large amount of concrete powder generated by the explosion method was not produced, and there was no risk of secondary contamination by fine concrete powder. The area over which the crack propagated depends on the energy generated from the SPC. The relationship between the two is linear. For reinforced concrete, the energy of the SPC is used for both the destructive energy of the concrete and the energy of the cutting of the reinforcing steel bar, which quickly breaks with low energy. By applying an SPC to dismantle large reinforced concrete structures, controlled cracking can be achieved safely and quickly without any environmental pollution. A fracturing method using a SPC is an effective method for the decommissioning of nuclear power plants and the dismantling of concrete structures. In this report, we report a remote drilling system that can be used to remotely install loading holes and guiding holes for the SPC and perform effective controlled fracturing.
Keywords: Steam pressure cracking agent (SPC); Reinforced concrete; Induction hole.

1. Introduction

Demolition of large reinforced concrete structures at actual hazard sites is dangerous for workers and may cause environmental pollution. The dismantling of nuclear power plant buildings is a typical example [1, 2]. The purpose of this study was to develop a total remote demolition system that is safe and does not cause environmental problems. Therefore, the authors focus on developing a remote mechanical system consisting of a positioner, drilling and insert, and a steam pressure cracking agent (SPC) [3, 4]. Explosive agents generate many fine particles [4] and cause secondary contamination, so they cannot be used for the dismantling of nuclear reactors. SPC is nonexplosive and thermite reaction agent. Most conventional nonexplosive blasting techniques are static chemical reaction agent that causes compressive pressure [5], but it takes long time, several hours, to break the concrete. Therefore, remote systems using SPC have advantages over another reinforced concrete cracking methods, such as rapid, safe, and controlled [4] crack propagation. In this study, the steam pressure cracking system operation and cracking characteristics of large concrete structures using an SPC were elucidated using experimental analysis. The authors proposed a planning method for the drilling position and amount of SPC for the target structures.

In the past, decommissioning technology in Japan was based on the decommissioning of the power test reactor JPDR in Tokai Village, Ibaraki Prefecture (1981-1996) [6], and the demolition work of bio-shielded concrete was carried out by, (1) dismantling by mechanical cutting, (2) dismantling by water jet cutting, and (3) dismantling by controlling bombing. In these demolition methods, large amounts of fine particles can cause secondary contamination of the environment. In addition, in the decommissioning of commercial power generation reactors, the radiation level inside the bio-shielded concrete is high. As such, it is assumed that no one can enter, and hence, a remote dismantling method is required [6]. We study a remote cracking system using steam crushing agents with the goal of enabling remote operation and perform demolition in a short period of time and at low cost. In this study, we explain a remote crushing system using a steam pressure cracking agent [7, 8].

Moreover, the system can be used to crack an unnecessary reinforced concrete structure due to disasters such as tsunamis, as shown in Figure 1. Waste concrete structures have become a social problem and require safe and urgent dismantling.

Figure 1. Cracking construction of an unnecessary concrete caisson by SPC.

Therefore, in this study, to solve the problems of the conventional method, we developed a controlled cracking system that uses an SPC [9, 10]. SPC are safe chemicals used to inflate car airbags [11]. In this study, we showed that this agent can be used to quickly crush large amounts of concrete by controlling the cracking direction [4].

2. Experimental methods

2.1 Concrete test materials

The material properties of concrete are listed in Table 1. The concrete used in the experiment was composed of cement, sand, gravel, and water with a volume ratio of 1:2:4:0.5, poured into the mold, and cured for more than 3 weeks. Reinforcing steel with a diameter of 12 mm was arranged from the bottom to 50, 250, and 450 mm [8].

Table 1. Nominal material properties of concrete used

Material properties	Value	[unit]
Compressive Strength, σ_c	20～50	[N/mm^2]
Tensile strength, σ_t [7]	$\lvert\sigma_t\rvert < \lvert\sigma_c/10\rvert$	[N/mm^2]
Density, ρ	2.3～2.5	[g/cm^3]
Elastic Modulus, E	10～50	[GPa]
Schmidt values	10～60	[R] *
Velocity of elastic wave	4500～5400	[m/s] *

* Values measured by the authors

2.2 Characteristics of the SPC agent

The chemical composition of the SPC agent used in the experiment is shown in Table 2, and its physical properties are listed in Table 3 [11].

Table 2. Chemical composition of the SPC

Composition materials	Mass %
Alum ($nKAl(SO_4)_2 12 \cdot H_2O$)	50
Copper (II) oxide (CuO)	38
Al fine powder	11
Binder	1.0

Table 3. Physical properties of the SPC

Ignition point	793 K (520 ℃) or higher	
Reaction speed	Less than 300 [m/s]	
Rise time to maximum pressure	30～50	[10^{-3}s]
Sealed combustion pressure	300	MPa
Volume of gas produced	330	l/kg
Theoretical energy product with standard mixture	1170	kJ/kg

The appropriate amount of SPC agent was analyzed using the method shown in this study. The SPC was heated to 793 K(520 °C) using an igniter. The agent causes the chemical reaction shown in equation (1), which creates water and heat. The water evaporates in a short time, and then the concrete is crushed by the high-pressure steam and elastic waves generated by it. It is a type of thermite reaction (Goldschmidt reaction).

$$2\mathrm{Al} + 6\mathrm{CuO} + \mathrm{nKAl(SO_4)_2 \cdot 12H_2O} \rightarrow \mathrm{Al_2O_3} + 3\mathrm{Cu_2O} + \mathrm{nKAl(SO_4)_2} + 12\mathrm{nH_2O} \uparrow + 1170\ \mathrm{kJ/kg} \quad (1)$$

The pre-experiment result is shown in Figure 2, which is well controlled by the SPC and induction hole. The mechanism of control cracking by induction holes was analyzed in a previous paper by the authors. The theoretical background of controlled cracking is presented in the appendix by the authors [4].

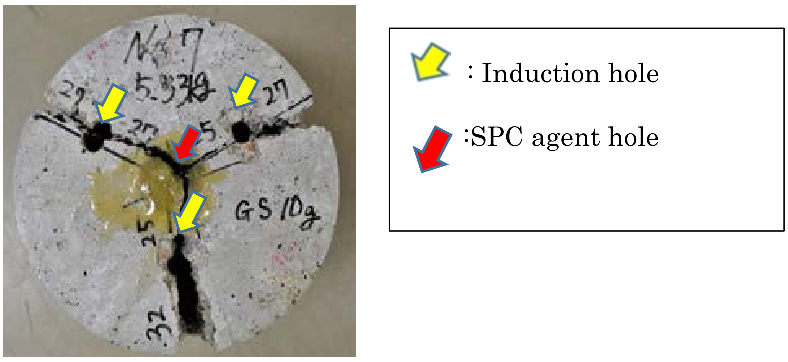

Figure 2. Controlled cracking of a small concrete piece by the SPC agent [4].

3. Results and discussion

3.1 Developing remote-control cracking system

The mechanical structure of the remote-control steam pressure cracking system is shown in Figure 3 [10]. The system is capable of cracking a large reinforced concrete that includes a steel bar using the SPC [8]. This system performs drilling of concrete in extreme environments with high radiation levels. Therefore, to avoid failure, the system was configured to perform remote operation only by supplying air without using an electrical sensor or any microtip because the electrical microcircuit is weak for radiation [12, 13]. In this system, an appropriate hole can be formed into the reinforced concrete, and an SPC agent capsule can be inserted immediately and automatically [10].

3.2 Operating results of mechanical systems

The greatest advantage of this system is that it is driven by air pressure without a semiconductor. This is because it does not break down under extreme environments, such as severe radiation, water, and high temperature. It is difficult to use a robot system under high-density radiation because semiconductors can easily cause damage owing to the effects of total ionizing dose (TID), displacement damage (DD), and single event effects (SEE) by severe radiation [12].

Steam cracking is usually performed as follows: (1) demolition total planning, (2) cracking design, (3) positioning by precision crane, (4) drilling by remote control cracking system, (5) SPC cartridge insert, (6) closing the hole with glue, (7) SPC wiring, (8) covering to block the stepping stones, (9) confirmation of wire connection, (10) ignition by electrical current, and (11) confirmation of total cracking status [8].

Because the remote steam pressure cracking can be performed automatically rather than manually, long-term drilling work is also possible, and it is assumed that it can be used inside water; therefore, air pressure-driven rock drills, air cylinders, and oil-free linear guides are adopted.

The remote control cracking system was precisely set using the crane, as shown in Figure 4(a), and holes were made to the reinforced concrete, as shown in Figure 4(b). The system operated under the conditions shown in Table 4. The concrete test block included a steel bar for reinforcement. This system uses a root-hammer to drill holes into the concrete. The drilling bit was operated under the following conditions : 76.4 N of press load and 0.6 mm/s of drilling speed. This machine bit can cut the steel bar in concrete as reinforcement, as shown in Figure 5.

Immediately after drilling the hole, the hand of the system can hold and insert the SPC agent into the hole, as shown in Figure 6. With this mechanism, it is possible to insert an SPC without having to detect the hole position using a sensor [9]. By designing an analog machine that does not use a semiconductor, it is possible to prevent failure under high radiation.

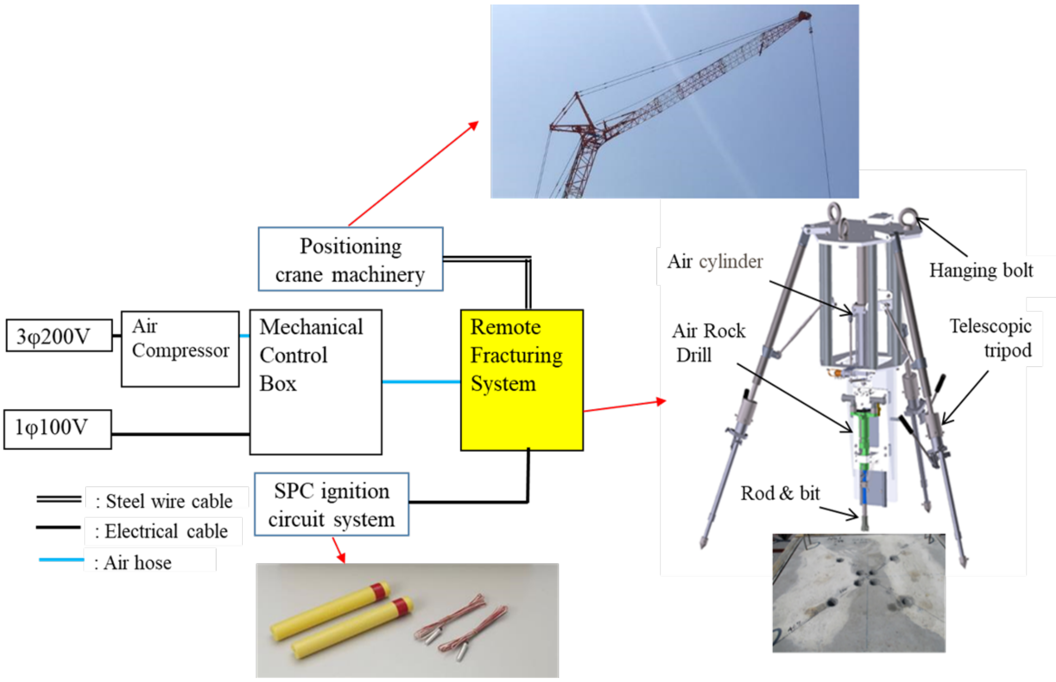

Figure 3. Total design of Remote-Control Cracking System by SPC

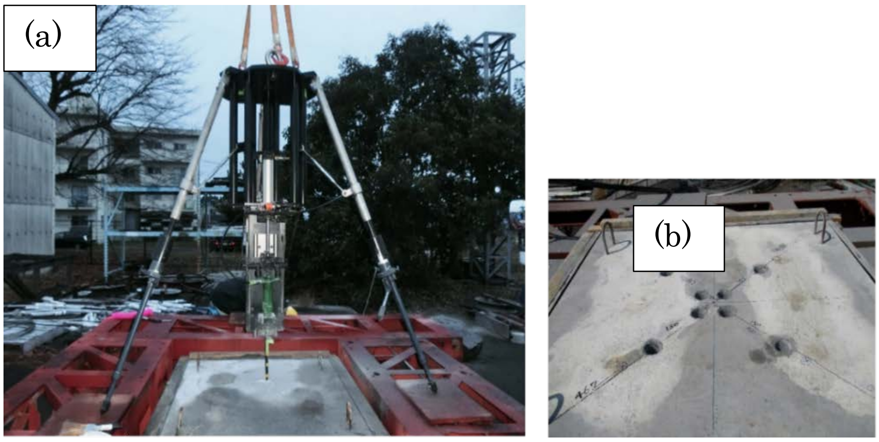

Figure 4. (a) Setting of Remote Cutting System and (b) boring test of reinforced concrete

Table 4. Specification of remote control cracking system

Dimension	W1524×D1319×H1520 [mm]
Weight	250 [kgf]
Drilling stroke	250 [mm]
Bit type	φ18~42 [mm]
Pressing force	0~200 [N]
Drilling Performance	900~1000 [mm^3/s]
Drilling angle	75~90 [°]
Tripod stroke	400 [mm]

A drill bit with a diameter of φ 34 mm was installed in this system, and holes were drilled up to the target drilling depth of 270 mm, as shown in Figure 7. The bit pushes the adhesive that exists at the capsule head and fixes the SPC into the hole. The lead wire of the SPC was connected to the ignition system. After confirming the electrical conduction, the SPC igniter was applied to start ignition, and the high-pressure steam was generated by a chemical reaction, and the pressure initiated and propagated the crack into the concrete.

Figure 5. Steel bar which was cut by the concrete bit

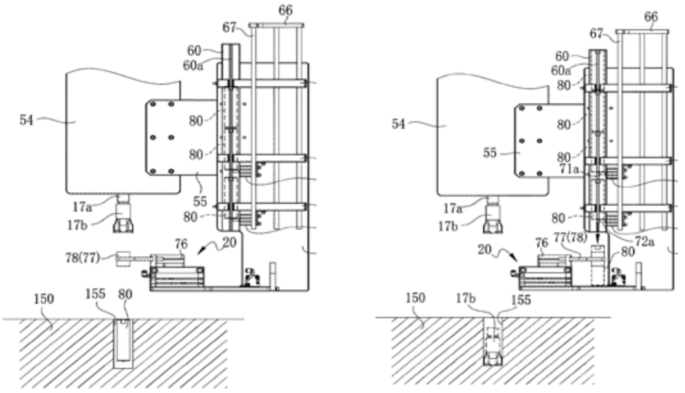

Figure 6. Mechanism for drilling and inserting SPC in concrete hole

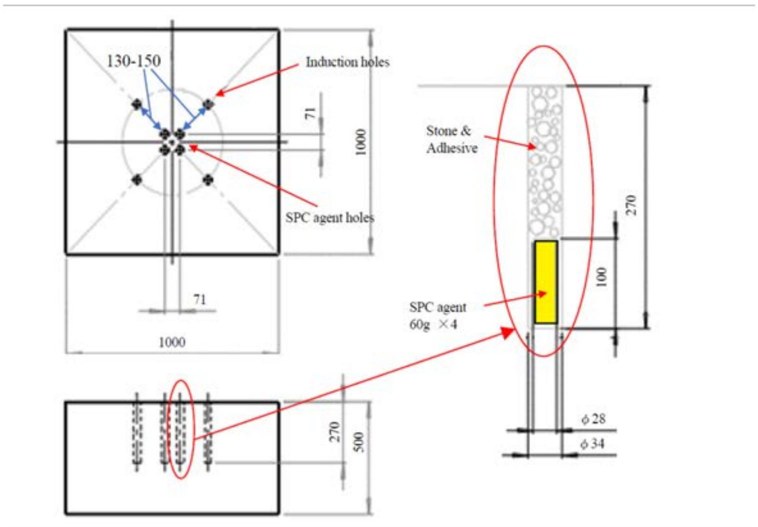

Figure 7. SPC cartridge inserting to hole and close by glue

3.3 Cutting result of reinforced concrete by remote control cracking system

The cutting results of reinforced concrete by remote control cracking system is shown in Figure 8. The reinforced concrete was mainly separated into three parts. Broken rebars were also present on the fracture surface. The cracks were predominantly controlled by induction holes. The mechanism of control cracking was analyzed in a previous study [7]. In this study, the relationship between SPC energy and crack surface area was examined. If a clear relationship is obtained, the amount of SPC and the distance between the holes with respect to the cracking target concrete can be determined.

Figure 10 shows the relationship between the energy W of the SPC and the crack surface area of concrete structures of different sizes. Based on fracture mechanics, it can be concluded that the internal strain energy is released by forming a fracture surface. The pressure energy caused by the SPC agent is converted to strain energy, W, which is called the elastic wave, and W is released by crack propagation of length c. Fracture energy can perceived as the surface energy γ_s of the fracture surface. This can be expressed by the following formula:

$$W=2c\gamma_s \tag{2}$$

where W is the total strain energy corresponding to the energy of the SPC agent, c is the crack length corresponding to the area of the fracture surface, and γ_s is the surface energy as a material constant of the concrete used.

The energy of the SPC required to form a 1 m2 crack in the concrete was 276.7kJ/m^2, which corresponds to γ_s of equation (2).

$$W=276.7s \quad [kJ] \tag{3}$$

Where s is the area of the fracture surface,

Figure 8. Cracked concrete and steel bars cut by SPC on concrete surface

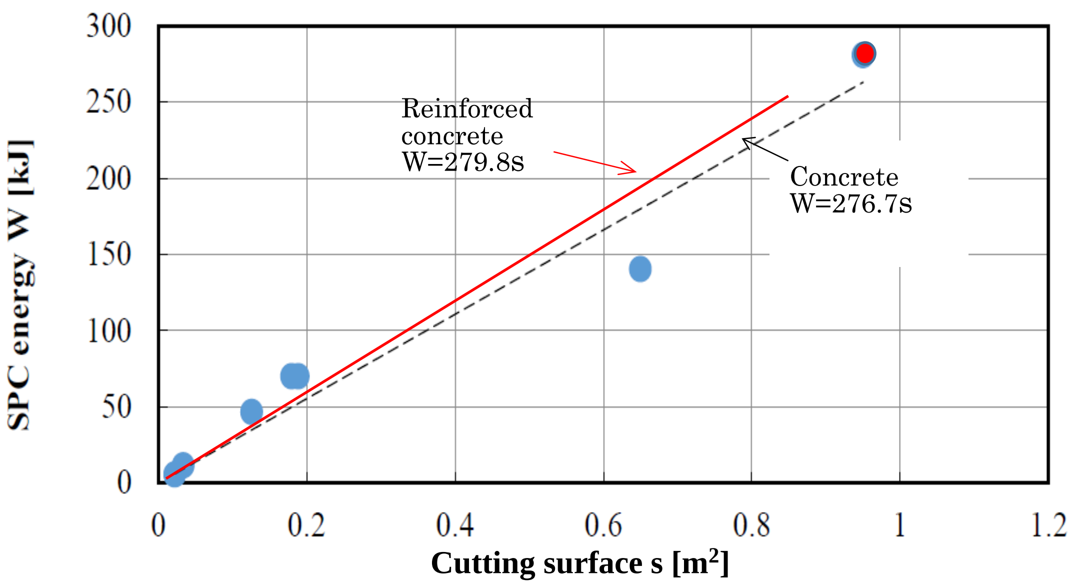

Figure 9. Relationship between amount of SPC energy and cutting surface area

The impact value when the general steel bar is broken is approximately 100 J / cm^2. When 10 bars of 12 mm diameter are arranged in concrete 1 m^2, the sum of the energy when impacting and destroying this is 3.14 kJ. This value is sufficiently small when compared to the coefficient of 279.8 kJ/m^2, as shown in Figure 9.

Figure 10 shows the broken reinforced bars on the fracture concrete surface. It is presumed that the hole and reinforcing bar correspond, or the deformation to destruction is small. Moreover, this is a brittle low strain energy.

From a practical perspective, as shown in Figure 11, the cutting length x and the amount of SPC y are proportional, as shown in equation (3). The crack length corresponds to the concrete with a thickness of 1 m. Using these data, the amount of SPC and the mechanism of drilling holes can be designed in advance when crushing reinforced concrete with the SPC system.

$$y = 517.4x \ [g] \tag{4}$$

For example, if a 0.5-m long crack is formed at a thickness of 1 m, the SPC weighs 250 g. Based on previous experience, it is proposed that induction holes for crack direction control be opened at a position of approximately half the crack length. To cut 10-m long concrete, this technique can be superimposed 20 times. Thus, once the size of the concrete to be cut is determined, the amount of SPC and the position of ignition can also be determined.

Furthermore, from the results obtained thus far, the cracking direction can be controlled by opening the induction hole halfway through the SPC intervals. In other words, in this example case, the induction hole that is present 0.25 m from the SPC hole.

In the future, it will be necessary to examine the coefficient of Equation (4) using different types of samples.

Figure 10 Broken steel bar surface with low energy by high-speed tensile condition

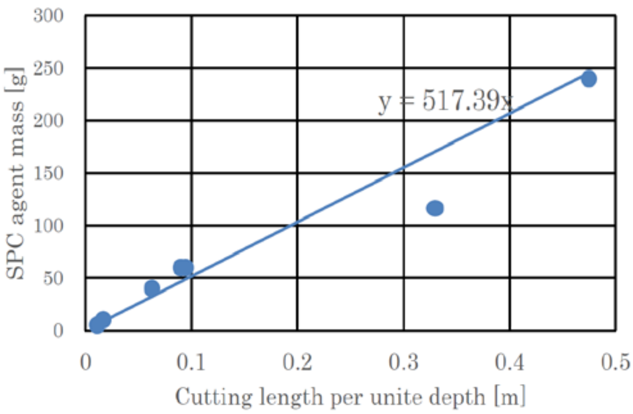

Figure 11. Relationship between SPC mass y and crack length x per unit depth.

4. Conclusions

In this study, the authors developed an SPC system for a large reinforced concrete structure in an actual site. We examined a method for controlling the cracking.

1) Using an SPC agent that generated high-pressure steam with almost no vibration, it was possible to crush reinforced concrete more safely than explosives and without generating dust, causing secondary pollution.

2) Using an induction hole located at the center between the SPC holes, the crack direction could be effectively controlled. The controlling mechanism can be explained by the reflection of elastic waves from the induction hole surfaces.

3) The impact toughness value of concrete can be estimated from the relationship between the fracture surface area and energy. The authors also demonstrated a linear relationship between the cutting length and the amount of SPC, which can be used to design the cracking planning by the SPC system that was developed.

4) Steel bars in reinforced concrete could be easily cut by SPC.

5) The amount of SPC and the position of ignition and induction holes could be designed according to the size of the concrete, using the experimental equation.

Acknowledgment

We would like to thank Nippon Koki Co., Ltd. and SANWA TEKKI CORPORATION for providing experimental facilities and for their technical support. We would also like to thank Editage (https://www.editage.jp/) for English language editing.

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Appendix

Theoretical background - Elastic wave propagation and controlled cracking [2]

To explain the controlled cracking phenomena using the elastic wave theory, the author schematically shows Figure A-1, which indicates the arrangement of the SPC and the induction hole, as well as the propagation and reflection of elastic waves in large concrete.

The SPC cracking phenomena are based on three-dimensional elastic wave propagation; however, to understand the phenomena, the authors used the following equation, which is a one-dimensional elastic wave equation [21]:

$$\frac{\partial^2 u(x,t)}{\partial t^2} - v^2 \frac{\partial^2 u(x,t)}{\partial x^2} = 0 \quad \text{(A-1)}$$

where u is the displacement produced by the SPC, v is the velocity of the elastic wave, x is the distance from the induction hole surface, t is the time, and $v = \sqrt{E/\rho}$ $(E: Young's\ modulus,\ \rho: density$ of concrete) in an elastic solid. Concrete is considered a composite elastic solid with homogeneous E and ρ as average values of sand, aggregate, and cement.

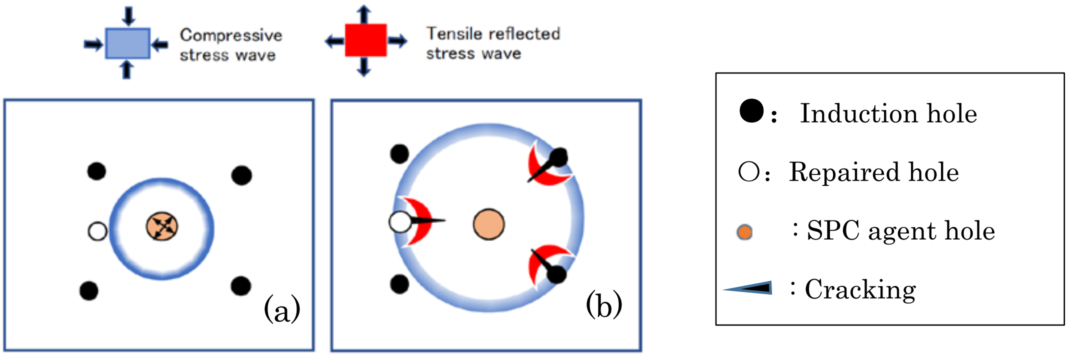

Figure A-1. Schematic illustration of tested concrete, indicating SPC agent, induction hole, and repaired hole. The elastic wave initiates from SPC in Figure A-1(a) and reflect at induction hole Figure A-1(b). Areas of compressive stress are shown in blue, and red areas represent tensile stress.

Longitudinal elastic waves were generated by the reaction of the SPC agent. As a general solution of equation (3–1), the following d'Alembert equation is given as:

$$u(x,t) = f(x - vt) + g(x + vt) \tag{A-2}$$

where $f(s), and\ g(s)$ are arbitrary functions that correspond to the "driving wave" and the "reflected wave," respectively. (A-2) can be confirmed to be the correct solution by substituting Equation (3-1).[21]

The functions of $f(s)$ and $g(s)$ indicate the displacement of elastic waves that move in opposite directions at speeds of $+vt$ and $-vt$, respectively. The driving wave $f(s)$ is related to the reflected wave $g(s)$ at the free surface of the induction hole as follows [21]:

$$f(-s) = g(s) \tag{A-3}$$

The shapes of the $f(s)$ and $g(s)$ functions corresponding to the actual elastic wave generated by SPC compressive pressure can use Gaussian functions or wave packets. The peak value corresponds to the maximum pressure of the SPC agent, which is approximately 300 MPa, and the time spread is approximately 50 ms. In the future, we would like to determine the elastic wave function form of the SPC agent after accurately measuring the data.

The stress σ of the elastic body produced by displacement u is expressed by the following equation:

$$\sigma(x,t) = E \cdot u'(x,t) \tag{A-4}$$

where $u'(x,t)$ is the value of the partial deviations for x.

$$\sigma(x,t) = E \cdot f'(x - vt) + E \cdot g'(x + vt) \tag{A-5}$$

Considering $x = 0$, $\sigma = 0$ at the free surface of the induction hole, as shown in Figure A-1.

$$u'(x,t) \ = f'(-vt) + g'(vt) = 0 \tag{A-6}$$

$$f'(-vt) = -g'(vt) \tag{A-7}$$

Equations (A–4) and (A-7) indicate that the stress of the driving wave $E \cdot f'(-vt)$ is compressive; however, the stress of the reflected wave $E \cdot g'(vt)$ is tensile. The principle of these phenomena is known as the Hopkinson effect, which is applied for dynamic testing. We applied this phenomenon to analyze the controlled cracking in concrete.