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DEMOLITION OF CONCRETE WITH EXPANSIVE DEMOLITION AGENT

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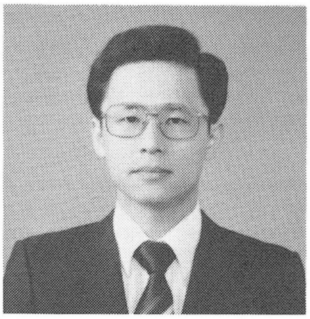
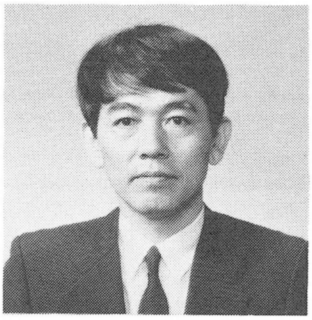


Tetsuo HARADA Takashi IDEMITSU Akira WATANABE

SYNOPSIS

Recently in Japan, some chemical expansive materials have a tendency to be used for demolition for rock-like materials, old concrete structures etc.. Those are called "expansive demolition agent". With the agent, demolition work can be done in safety without sound, vibration and any other pollution, since high expansive pressure is obtained gradually by only mixing the agents with water and pouring the slurry into boreholes. In order to estimate the time for demolition works, it is necessary to clarify the amount of the expansive pressure acting on the inner surface of the boreholes and mechanism of fracture of materials to be demolished. The authors carried out experimental and theoretical studies to clarify the above problems, and give how to design the demolition works with the agent.

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1. INTRODUCTION

Recently in Japan, some concrete structures, which still maintain their own strength enough, have a tendency to be demolished intentionally to utilize the spaces of the city widely and effectively. In these demolition works, explosives such as dynamite, or heavy machines have been used, but sounds, vibrations and some other pollution are also caused. Thus, it is required to consider the safety and the prevention of pollution. In order to solve the problems in these situations, some chemical expansive materials called "expansive demolition agents" have been developed and used in the demolition works of concrete structures and rocks.

With these agents, demolition works can be done in safety without sounds, vibrations, fly rocks, gases, and considerable reduction of dusts and some other pollution, since high expansive pressure is obtained gradually by only mixing the agents with water and pouring the slurry into boreholes, and after several hours, cracks occur statically between each of two boreholes. From the above points, the method using these agents is the most suitable one for demolition works. However, practical demolition works with these agents depend mainly on experiences because there are still many unknown points regarding fundamental matters such as estimating method of expansive pressure and the mechanism of demolition by expansive pressure which plays a principal role in demolition.

In order to estimate a rational design method using these agents, the relation between the spacing of the boreholes to inject the slurry and the demolition time are required. In this research, the following items should be clarified experimentally and theoretically: 1) characteristics of expansive pressure of the agent and of newly developed pressure transducers, 2) the measurement of expansive pressures at fracture of concrete specimens and demolition time, 3) mechanism of demolition of materials like concrete subjected to the expansive pressure. As a result, the authors indicate the important and fundamental data for the design of the demolition, and present the estimating method of demolition time. Moreover, the demolition of reinforced concrete members using this method is also discussed.

In this paper, although, the definition of fracture is different from that of demolition, the authors regard demolition as the state when the crack occurs from the inside surface of the borehole to the outside one.

2. MEASUREMENT OF EXPANSIVE PRESSURE OF THE AGENTS

The most important thing is to investigate the characteristics of the expansive pressure of the agents. In particular, it is necessary to actually measure the amount of the expansive pressure acting on the inner surface of the boreholes or the ditches made by concrete cutters, Thus, first of all, new pressure transducers were developed to measure the expansive pressure exactly. In practical demolition works with these agents, boreholes drilled with hand hammer or crawler drill were mainly used to inject the slurry of these agents. In the following sections 2.1 ∿2.3, indirect and direct methods of measuring expansive pressure acting on the inner surface of the boreholes, that is, the development of pressure transducers were examined, and the characteristics of the expansive pressure in the boreholes were investigated. Also, in the section 2.4, the measuring method and behavior of expansive pressure in narrow ditches were discussed.

The specific gravity and fineness of the agent were 3.12 and 2380 cm^2/g, respectively. All experiments were carried out in a room of constant temperature and moisture.

2-1 Indirect measuring method of expansive pressure with steel pipe

a) Outline of experiment

As shown in Fig.1(a), a steel pipe on the outer surface of which orthogonal strain gauges were attached was treated as a pressure transducer. After the slurry was poured into the pipe, the circumferential and axial strains at the outer surface were measured successively and the corresponding internal expansive pressures were calculated by using the elastic theory of thick-walled cylinder. This method is named "outer pipe method". These obtained expansive pressures may be slightly different from those actually acting on the inner surfaces of the boreholes, since this is an indirect measuring method. However, this is a practical and simple method to measure the fundamental characteristics of the expansive pressure. With this transducer the following items were investigated: 1) the relation between the amount of expansive pressure and water-agent ratio, 2) the influence of temperature to the expansive pressure, 3) the change of expansive pressure due to the degree of physical restraint caused by surroundings.

The expansive pressure P is calculated from the following equation (1) by using the circumferential strain ε_θ and axial strain ε_z measured at a constant interval.

$$P = \frac{E(K^2 - 1)}{2(1 - \nu^2)}(\varepsilon_\theta + \nu\varepsilon_z) \tag{1}$$

where, E:Young's modulus of steel pipe
ν:Poisson's ratio of steel pipe
k:Ratio of outer diameter to inner one (k=outer diameter/ inner diameter)

b) Experimental results

Although the maker's recommended value of water-agent ratio (W/B) was 30%, preliminary experiments were carried out to find the most suitable W/B considering workability and degree of expansion. The steel pipe, which was used, had 2.72 cm in outer diameter, 2.34 cm in inner one, and 100 cm in length.

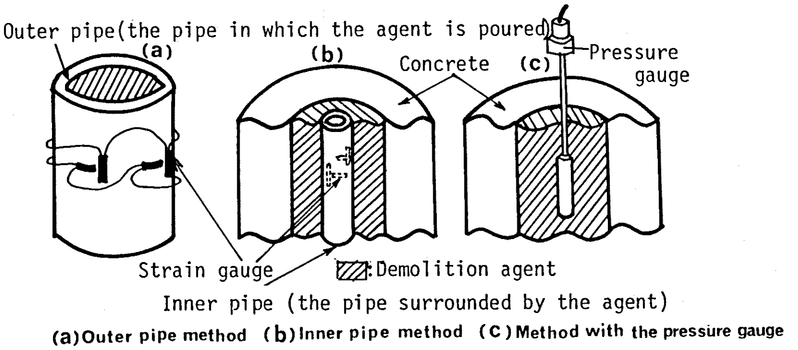


Fig.1 Methods of measurement of expansive pressure.

Fig.2 shows the expansive pressure measured at the middle of the steel pipe 24 hours after the mixing of the agent. It was found that the expansive pressure P increases when W/B decreases. When W/B<20%, it was difficult to pour the slurry into the pipe. When W/B>35%, the expansive pressure at the upper part of the pipe was smaller than that of any other part, because the slurry was segregated into water and the agent by bleeding. Since the uniform pressure distribution along the axial direction of the pipe was obtained when W/B=25%, the following experiments were carried out using W/B=25%.

Fig.3 shows the results of the influence of temperature to the expansive pressure. In this figure, the expansive pressure depends on the temperature remarkably, and the pressure measured at 30°C is 1.5 times of that measured at 20°C 24 hours after the mixing of the agent. The interval between agent mixing and the time the pressure starts to act gets smaller as the temperature increases and the pressure keeps on increasing continuously.

Fig.4 shows the time-dependent changes of expansive pressures in air and in water at 20°C. It was found that the expansive pressure in air is larger than that in water. For the same ambient temperature, thermal conductivity of water is larger than that of air. The heat of hydration of CaO transfers easily to the surrounding of water as compared with air. In air, a higher expansive pressure is caused by further growth of crystallines of $Ca(OH)_2$ due to hydration of CaO, because the temperature in the pipe increases, and consequently the chemical reactions are accelerated. From the same reason, Kawano[1] explained that the expansive pressure increases as the diameter of the pipe gets larger.

The expansion of the demolition agent is caused by the chemical reaction, but, if there is no physical restraint of the boundary, the expansive pressure does not occur and only the volume expands. The expansive pressure is regarded as the contact pressure which is caused by restraining the free expansion of volume. The relation between internal pressure P and the displacement U of the inner surface of the cylinder is described in Eq. (2) using the elastic theory.

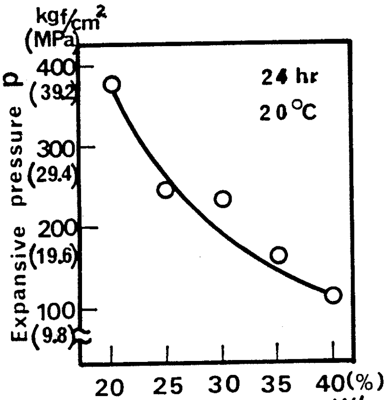


Fig.2 Relationship between expansive pressure and W/B.

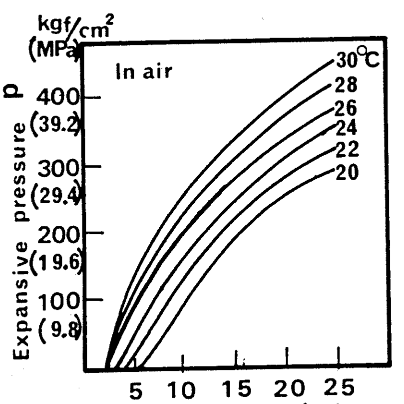


Fig.3 Expansive pressure-time curves at various ambient temperatures.

$$P = \frac{E(k^2 - 1)}{r_1 [k^2 + 1 - \nu(2 - k^2)]} U = R\ U \tag{2}$$

where, R is the degree of restraint to the internal pressure and is named "Restraint Modulus". Fig.5 shows the relation between the expansive pressure and R. For the same time, the expansive pressure becomes larger as R increases but not linearly. In this experiment it seems that the influence of the physical restraint to the expansive pressure is smaller than that of temperature, diameter and W/B.

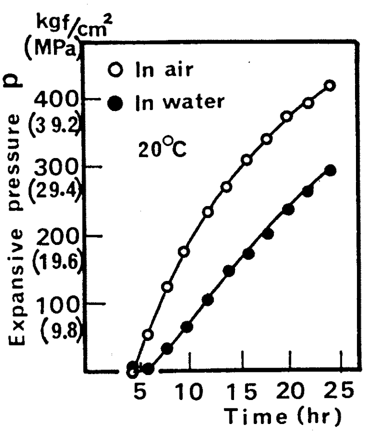


Fig.4 Expansive pressure-time curves in air and in water at 20 ℃. (Axial expansion was restrained.)

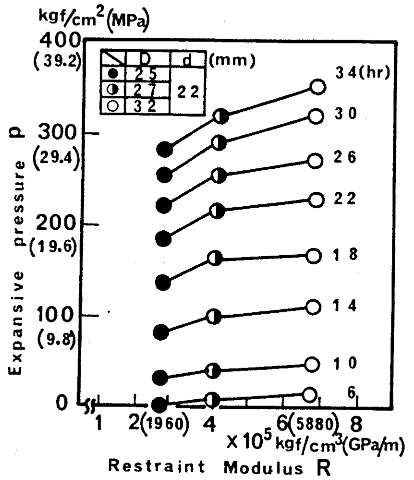


Fig.5 Expansive pressure versus Restraint Modulus.

2-2 Direct measuring method of expansive pressure with steel pipe

In the outer pipe method, the expansive pressure can only be measured indirectly even when temperature and physical restraint of the pipe as well as surrounding of boreholes are in the same condition. It is better that the expansive pressures measured directly and accurately in the boreholes. And the method of measuring the expansive pressure demands special devices, since a high pressure of about 20 ∿30 MPa occurs after the slurry of demolition agent hardens such as concrete. The authors developed a new method using a kind of embedding type of pressure transducer which is named "inner pipe method". It is made of a steel pipe and orthogonal strain gauges are attached to its inner surface as shown in Fig.1(b). This transducer can be located in the center of a borehole filled with the slurry and the external expansive pressure acting on the transducer can be directly measured in the boreholes. The expansive pressure P is calculated from Eq.(3) using the strains ε_θ and ε_z measured by this transducer.

$$P = \frac{-E(k^2 - 1)}{2(1 - \nu^2)k^2} (\varepsilon_\theta + \nu\varepsilon_z) \tag{3}$$

In order to verify how accurately the pressure transducer can measure the expansive pressure, a double pipe test in which the outer pipe acts as a borehole and the inner pipe as a transducer was carried out. As shown in Fig.6, Pi measured by the inner pipe was in good agreement with Po measured by the outer pipe. Fig.7 shows the relation between expansive pressure ratio Po/Pi and cross-sectional area ratio Ab/Ai of the slurry of the agent considering various diameters of the outer pipe. It was found that Po/Pi is hardly influenced by Ab/Ai. From the above results, it was proved that the expansive pressure acting on the surface of the borehole can be measured directly and accurately when using the inner pipe method.

Since restraints due to friction exist at the outer surface of the inner pipe and the inner surface of the outer pipe, it is considered that expansive pressure is also produced in the axial direction. Fig.8 shows the comparison of the expansive axial force due to the agent and the sum of axial tensile forces acting on the inner pipe and the outer one. As the two lines in this figure are in good agreement, it can be said that the amount of expansive pressure in the axial direction is the same as that in the radial direction.
From the above results, it is concluded that the transmission of the expansive pressure in the hardened agent is similar to that of a fluid. Therefore, when the expansive pressure is measured by using the outer pipe method, the value of P can be calculated from Eq.(4) instead of Eq.(1) using only ε_θ.

$$P = \frac{E(k^2 - 1)}{2 - \nu} \varepsilon_\theta \qquad (4)$$

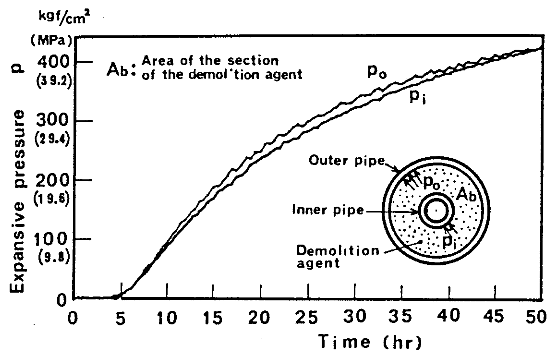


Fig.6 Comparison of expansive pressure acting on the outer pipe with the one on the inner pipe.

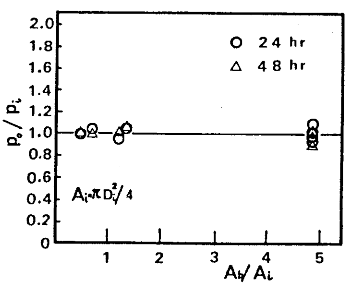


Fig.7 Relationship between Po/Pi and Ab/Ai.

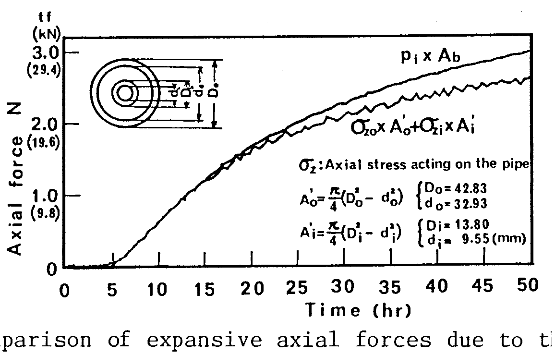


Fig.8 Comparison of expansive axial forces due to the agent with the sum of axial tensile forces acting on the inner and outer pipes.

2-3 Direct measuring method of expansive pressure with pressure gauge

As shown in Fig.1(c), a sensitive part that encloses an inert gas is joined with a pressure gauge. And the external expansive pressure acting on the sensitive part can be obtained by measuring the gas pressure. This measuring method, as well as the inner pipe method, is a embedding type one. The sensitivity of this pressure transducer was calibrated by oil-hydraulic pressure. The double pipe test was carried out in the same way as the inner pipe method. As a result, it was found that the expansive pressure can be measured directly and accurately, too. But, making this pressure transducer requires much time and money as compared with other methods.

2-4 Measurement of expansive pressure in ditches made by concrete cutters

If ditches made by concrete cutters can be used for demolition instead of boreholes, the cutting points and directions can be controlled without difficulty and demolition works can be done efficiently. It is necessary to confirm the amount of expansive pressure that occurs in the narrow ditches. The test apparatus to measure the expansive pressure in narrow ditches is shown in Fig.9, but the pressure can be measured only indirectly. Two concrete cylindrical specimens with various ditches were set on the compression testing machine and the slurry was poured into the ditch. Time-dependent changes of the load, which was caused by keeping the distance between the plates fixed were measured. The expansive pressure was calculated by dividing the load by the injecting area of the demolition agent. As shown in Fig.10, it was found that expansive pressures increase constantly, and even in ditches 6 mm wide, the expansive pressure of 14.7 MPa is obtained. Since the amount of slurry per unit area increases when the width of the ditch t increases, a higher expansive pressure is obtained.

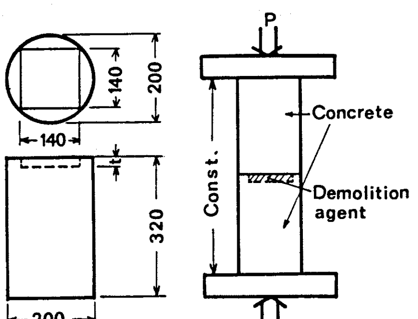


Fig.9 Indirect measuring method of expansive pressure in a ditch.

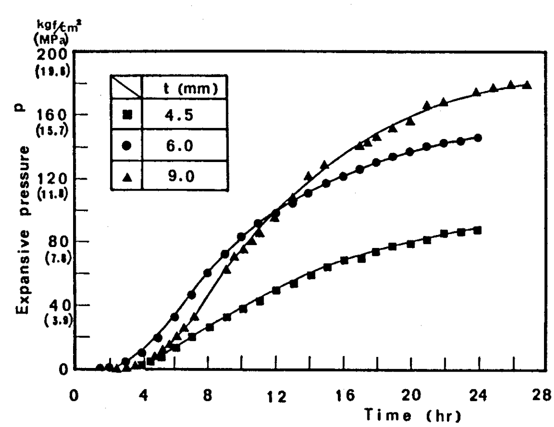


Fig.10 Expansive pressure-time curves in ditches.

3. DEMOLITION OF HOLLOW CONCRETE CYLINDERS

It is necessary to clarify the demolition criteria, the mechanism of demolition and what amount of expansive pressure is required for the demolition when using hollow concrete cylinders as specimens. The expansive pressure at fracture was measured by the pressure transducers explained in section 2. And also some instantaneous tests simulating the demolition were conducted, in which oil-hydraulic pressure was applied instead of the agent, since it was considered that the pressure at fracture was not influenced by the pressure medium. The pressure at fracture was regarded as the maximum, when the oil-hydraulic pressure was used.

3-1 Measurement of the pressure at fracture

a) Outline of experiment

Physical properties of concrete or mortar specimens are shown in Table 1. A borehole was made by pulling out a vinyl chloride pipe which was set previously after the concrete hardened. The pressure of the specimen at fracture was measured not only by the inner pipe method but also by the outer pipe method. In the outer pipe method, measured values would be reformed by using the expansive pressure-time curve. Test specimens have 15 cm in height, 2.2∿4.8 cm in inner diameter and 7.5 ∿60 cm in outer diameter.

A testing apparatus using oil pressure is shown in Fig.11. The oil-hydraulic pressure was increased at the rate of 0.78∿0.98 MPa a minute. The pressure was kept constant by bolting the circular plates with O-rings. Since the axial strain of specimen caused by bolting was only $5 \sim 10 \times 10^{-6}$, its influence to the pressure at fracture was neglected. It is necessary to coat the upper and lower ends and inner surface of the specimen in order to prevent the permeation of pressurized oil. According to the preliminary test, it was found that the most suitable materials to coat the specimen were soft-type vinyl tube and epoxy adhesive. Therefore, in all tests with hydraulic pressure, specimens were coated with above materials. Hollow cylindrical specimens made of concrete or mortar have various sizes: 7.5 ∿30 cm in outer diameter, 0.9 ∿3.2 cm in inner one and 15 cm in height.

Table 1 Physical properties of specimens.

Kinds of cocrete	Compressive strength kgf/cm^2 (MPa)	Tensile strength kgf/cm^2 (MPa)	Young's modulus $\times 10^5 kgf/cm^2$ (GPa)
Plain concrete	305～456 (29.9～44.7)	23.8～32.8 (2.33～3.21)	2.77 ～ 3.63 (27.1 ～ 35.6)
Mortar	382～490 (37.4～48.0)	22.7～29.8 (2.22～2.92)	2.68 ～ 3.70 (26.3 ～ 36.3)
High strength concrete	616 (60.4)	43 (4.21)	4.00 (39.2)

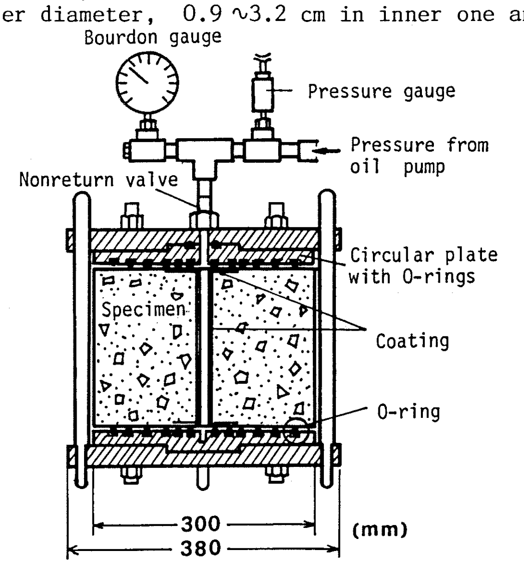


Fig.11 Specimen and device for oil-hydraulic pressure test.

b) Experimental results and discussion

In Figs.12 and 13, ⓐ indicates the cracks which occurred first. In the tests with hydraulic pressure, the crack ⓐ occurred suddenly and the crack width at the outer surface of the specimens was about 5 mm. In the tests with demolition agent, as shown in Fig.15, two kinds of fracture mode were observed at the moment of fracture according to the ratio k of the hollow cylinder. One was an instantaneous straight cracking from the inside surface to the outside one when k<5 and the other was a successive cracking following the initial crack which did not reach the outer surface when k>5. The crack ⓐ was caused by a circumferential stress σ_θ since the crack mode of the outside surface occurred parallel to the longitudinal direction as shown in Fig.14.

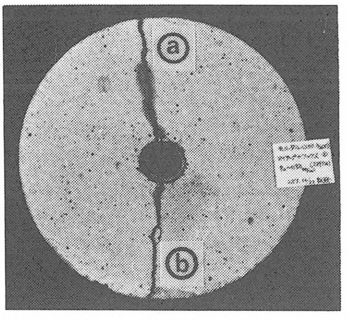


Fig.12 Fracture mode of the cylinder demolished by oil-hydraulic pressure. (D=15, d=2.2 cm)

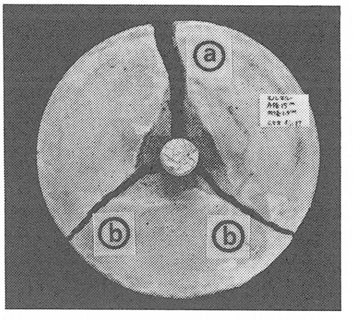


Fig.13 Fracture mode of the cylinder demolished by the agent. (D=15, d=1.5 cm)

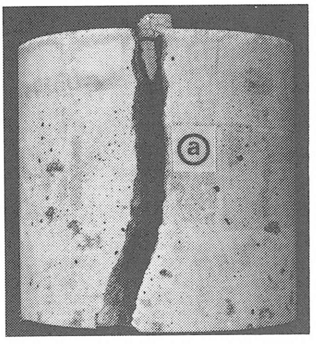


Fig.14 The crack mode of the outside surface.

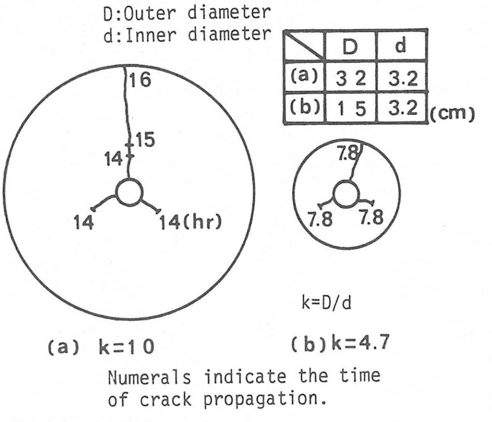


Fig.15 Difference of the crack mode due to k. (a) k>5, (b) k<5

Figs.16 and 17 show the relations between Pu/σ_t and the ratio k, where Pu is the internal pressure at fracture and σ_t is the splitting tensile strength. The values measured by the outer pipe method are corrected and then plotted in Fig.17.

Sato et al.[4] reported that the results of the fracture tests with brittle materials are plotted in the range between lines (I) and (II) and explained that the fracture is influenced by the ductility of the materials, that is, when the material is more ductile, the value of Pu/σ_t is plotted near the straight line (I), and when the material is more brittle, the value of Pu/σ_t is plotted near the curve (II). It was found that the authors' results are almost plotted in the range of (I) and (II).

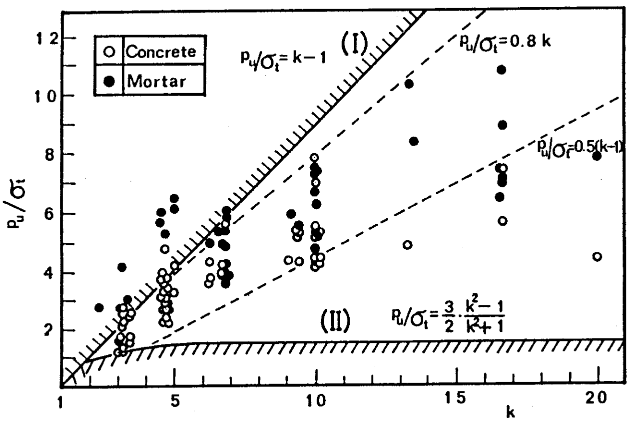


Fig.16 Relationship between Pu/σ_t and k when using oil-hydraulic pressure.

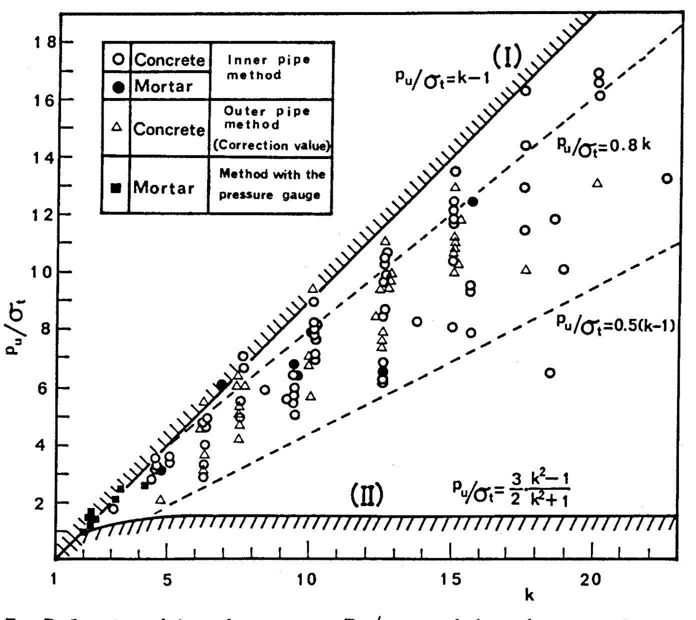


Fig.17 Relationship between Pu/σ_t and k when using the demolition agent.

When k<5, many values exist near the straight line (I) in Figs.16 and 17. It is considered that the fracture is caused when the mean value of the circumferential stress reaches the tensile strength of the specimen. That is,

$$\bar{\sigma}_\theta = \sigma_t \tag{5}$$

From the circumferential equilibrium at t-t section, as shown in Fig.18.

$$P_i\, r_1 = \bar{\sigma}_\theta (r_2 - r_1) \tag{6}$$

$$\bar{\sigma}_\theta = P_i / (k-1) \qquad (k = r_2 / r_1) \tag{7}$$

The internal pressure at fracture Pu is described as

$$Pu / \sigma_t = k - 1 \tag{8}$$

thus, Eq.(8) agrees with curve (I). Also, Eq(8) represents the fracture criterion of a hollow cylinder regarded as a thin-walled or a perfectly plastic cylinder.

When k<5, even if a circumferential stress at the inner surface of a borehole reaches the tensile strength of the specimen, its fracture does not occur because the outer part which has small circumferential stress and large volume prevents cracks to occur in the inner part. Thus, fracture occurs when the plastic zone of the surrounding of a borehole spreads up to the outside surface.

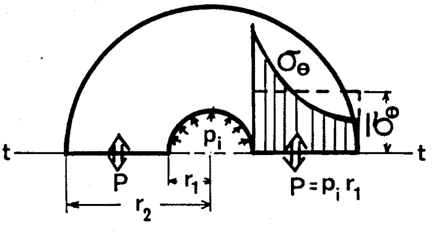


Fig.18 Circumferential equilibrium at t-t section in the case of one borehole.

When k>5, in both pressure media, values of $Pu/\sigma t$ deviate from the straight line (I) as k increases. In the case of k>5 and with demolition agent, initial crack occurs at the surrounding of a borehole before the average value of circumferential stress reaches the tensile strength of the specimen, although the initial crack does not cause the instantaneous fracture. It is necessary to increase the expansive pressure for the propagation of the initial crack up to occurrence of fracture. However, since the expansive pressure does not increase until the average value of the circumferential stress reaches the tensile strength, values of $Pu/\sigma t$ deviate from the line (I). On the other hand, in the case of oil-hydraulic pressure, fracture occurs instantaneously, since the hydraulic pressure acts on the crack tip when the coating of the specimen ruptures as soon as a initial crack occurs. Thus, the value of $Pu/\sigma t$ in the case of hydraulic pressure is smaller than those in the case of demolition agent.

When using the demolition agent, the tensile axial stress σz occurs but its influence to the fracture is negligibly small. And as the ratio of $\bar{\sigma} z$(average value of axial stress) to $\bar{\sigma}_\theta$(average value of circumferential stress) is 1/(k+1) then $\bar{\sigma}_z$ is much less than $\bar{\sigma}_\theta$.

Based on the above results, the practical demolition criterion is written as

$$\bar{\sigma}_\theta / \sigma_t = \alpha \tag{9}$$

When k<5, Eq.(8) is obtained by adopting $\alpha=1$ in Eq.(9). When k>5, the values estimated from the experimental results varied from 0.5 to 0.8 in Fig.17. If the value of $\alpha=0.8$ is adopted, the estimated demolition time is longer than the practical demolition time, so the design of demolition using the agent is safe. Then the following equation is proposed.

$$P_u/\sigma_t = 0.8\,k \tag{10}$$

Equations (8) and (10) that describe the demolition criterion give the same value of $Pu/\sigma t$ for k=5, so the two lines defined by these equations are connected smoothly.

3-2 Behavior of circumferential strain at the inner surface of boreholes

It is important to verify the relation between the expansive pressure and the circumferential strain since the strain at fracture can be adopted for the design of demolition instead of expansive pressure. Then, the behavior of the circumferential strain at the inner surface of hollow concrete or mortar cylinders on which strain gauges are attached at the position of $3\sim4$ cm from the end is investigated by using oil-hydraulic pressure.

Fig.19 shows the behavior of the circumferential strain at the inner surface of mortar specimens up to fracture. There is a slow bend at $200\sim300\times10^{-6}$ and this is so-called the limit value of extensibility. However, the change of strain is so small that the behavior of the strain is almost indicated by a straight line until fracture. The values of tensile strain at fracture are about $500\sim750\times10^{-6}$. These values are two or three times larger than those obtained from the splitting test. The P- ε_θ relations calcurated from Eq.(11) are also shown in Fig.19.

$$\varepsilon_\theta = \frac{P[(k^2+1)+\nu_c(k^2-1)]}{Ec(k^2-1)} \tag{11}$$

In computation, Young's modulus Ec and Poisson's ratio ν_c obtained from the compression tests are used. The measured value of strain is larger than the calculated one. It is considered that the properties of deformation under the compressive stress differ from those under the tensile stress.

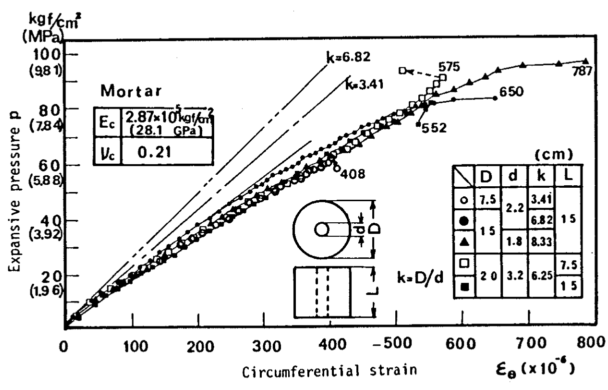


Fig.19 Behavior of the circumferential strain at the inner surface of mortar cylinder up to rupture.

3-3 Mechanism of demolition

Two kinds of fracture modes when using hydraulic pressure or demolition agent are shown in Figs.12 and 13. Let us now compare the mechanism of demolition and the fracture mode of hollow cylinders. The initial cracks (a) are similar, but the other cracks differ from each other. While the mode of cracking of specimens under the oil-hydraulic pressure is that the specimen is separated into two blocks, in the case of the expansive pressure of the agent, the cross section is separated into three fan-shaped parts at vertical angles of about 120°. Thus, crack (b) is caused by the bending moment due to the internal pressure. The internal pressure does not become zero as soon as crack (a) occurs. The point on the inner surface that has the maximum bending moment as well as the principal stress under the hydraulic pressure is opposite to crack (a). In the case of demolition agent, two points of maximum bending moment originate because of the friction between the surface of a borehole and the hardened agent. Therefore, the point of origin of crack (b) changes according to the conditions of the inner surface of boreholes. These typical fracture mode, when using demolition agent, can be applied to make the arrangement of boreholes, that is, the hexagonal arrangement. The demolition of concrete slab with the hexagonal arrangement of boreholes will be described in the following section.

4. DESIGN OF DEMOLITION AND ESTIMATION OF DEMOLITION TIME

4-1 Basic concepts

Considering two boreholes in an infinite plate, the internal pressures act on the inner surfaces as shown in Fig.20. The average of the circumferential stress is given by the circumferential equilibrium at t-t section and is expressed in Eq.(12), where Pi is the internal pressure and ℓ is the distance between a borehole and another one.

$$\bar{\sigma}_\theta = \frac{P_i r_1}{\ell/2 - r_1} = \frac{P_i}{k-1} \qquad (12)$$

where, $k=(\ell/2)/r_1$.

By using the demolition criterion $\sigma_\theta/\sigma_t=1$, Pu is written as

$$Pu/\sigma_t = k - 1$$

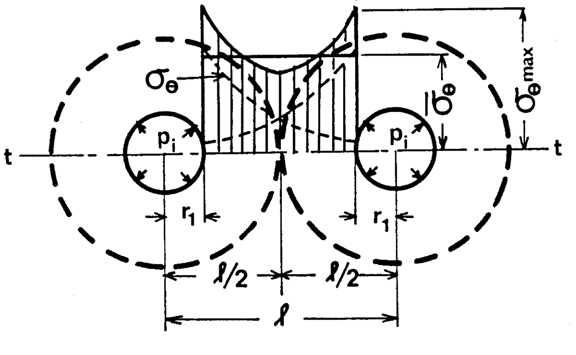


Fig.20 Circumferential stress and its average value at t-t section in the case of two boreholes.

This equation is the same as Eq.(8). In the case of two boreholes, it can be treated that there are two hollow cylinders whose inner and outer diameters are $2r_1$ and ℓ, respectively. The tensile strength σt of the material of the object to be demolished and k are substituted into Eq.(8) or Eq.(10), and the expansive pressure Pu required for demolition is computed. By using this expansive pressure, it becomes possible to estimate demolition time from Fig.21. As shown in Fig.21, the solid and broken curves are expressed as the regression curves of time-dependent change of expansive pressure measured by the inner pipe method and the outer pipe method, respectively. The regression curves computed using a least squares method are given by the following equations.

$$P= 418 - 560 \exp(-0.0460\ T) \quad \text{(by the inner pipe method)} \qquad (13)$$

$$P= 553 - 672 \exp(-0.0328\ T) \quad \text{(by the outer pipe method)} \qquad (14)$$

Fig.22 shows the relation between demolition time Tu and k calculated by using tensile strength as the parameter, where the solid and broken curves are calculated by using Eq.(8),(10),(13), and Eqs.(8),(14), respectively. Table 2 shows the comparison of calculated and measured values of expansive pressure. It was found that the calculated values are in good agreement with the measured ones.

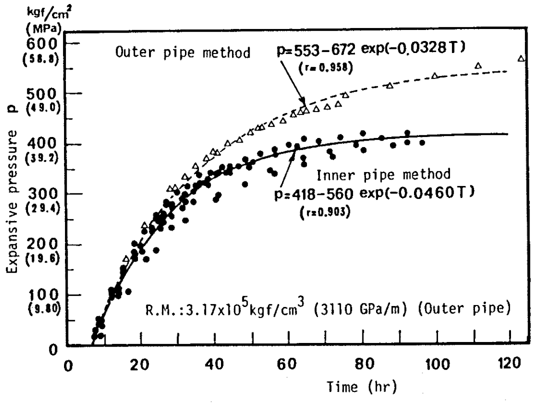


Fig.21 Regression curves of expansive pressures.

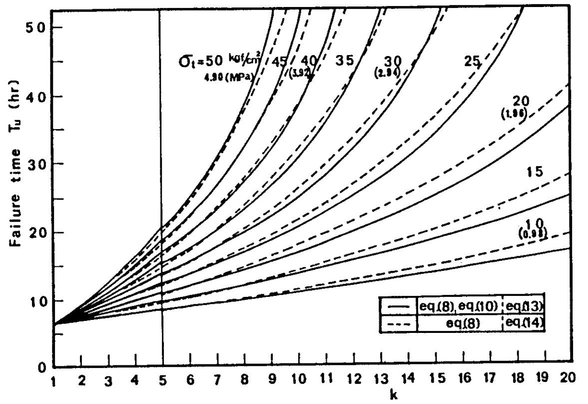


Fig.22 Relationship between failure time and k for various tensile strengths of concrete.

In the practical demolition work, if the curves shown in Figs.21 and 22 are obtained by using the inner pipe method, the design of demolition can be done more accurately. However, the difference between the demolition time estimated by the solid and broken curves in Figs.22 is only 10% for the range of σ_t<3.4 Mpa and k<15. When the external conditions during the experimental tests and execution of demolition works are the same, estimation of the demolition time by the outer pipe method is also effective.

4-2 Demolition time and demolition mode

The demolition time would be changed owing to the arrangement, the length and any other conditions of boreholes. Thus, the fundamental experiments were carried out in order to do the demolition works more effectively and economically.

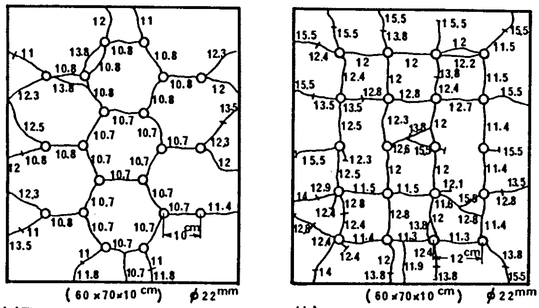
The demolition tests are carried out using high strength concrete slabs with the hexagonal and square arrangements and same number of boreholes. The results are shown in Fig.23. In the hexagonal arrangement, cracks occurred between a borehole and another one from 10.5 to 12.5 hours after mixing and divided the specimen plate into hexagonal blocks just as expected. But in the square arrangement, cracks occurred a little later and there were a few cracks that did not reach the next borehole. It was found that the hexagonal arrangement of the boreholes is advantageous when the same number and diameter of boreholes are used.

Making free surfaces of the object to be demolished is advantageous to demolish effectively. Fig.24 shows the relation between failure time and the distance from a borehole to the free end. Test specimens have various spacings "ℓ" between boreholes and distances "a" from the borehole to the free end. When the distance from the borehole to the free end is short, the crack on the free end occurs earlier but the extention of the cracks between boreholes that induce fracture is slow. From this figure, it is found that when the distance from the borehole to the free end is half the spacing of boreholes, the demolition time is the shortest and the demolition can be done effectively.

Table 2 Comparison of the calculated values with measured ones.

		k*	Expansive pressure at failure kgf/cm² (MPa)		Failure time (hr)	
			Calculated	Measured	Calculated	Measured
A	i)	1	—	—	—	—
	ii)	5.91	126 (12.3)	—	14.1	12.8
B	i)	1.88	23 (2.25)	57 (5.59)	9.0	8.5
	ii)	5.63	120 (11.8)	—	13.7	13.5
C	i)	3.13	57 (5.59)	57 (5.59)	8.0	8.5
	ii)	5.22	111 (10.9)	—	13.1	12.0
D	i)	4.69	98 (9.60)	71 (6.96)	10.4	9.5
	ii)	4.69	98 (9.60)	88 8.62	10.4	10.5
E	i)	6.25	133 (13.0)	90 (8.82)	14.7	11.0
	ii)	4.16	84 (8.23)	—	9.6	11.5
F	i)	7.5	160 (15.7)	90 (8.82)	16.8	11.0
	ii)	3.75	73 (7.15)	90 (8.82)	8.9	11.0

k* i) (Distance from a borehole to a free end / Radius of a borehole)
ii) (Distance between boreholes/ Diameter of a borehole)



(a) The hexagonal arrangement of boreholes
(b) The square arrangement of boreholes

σ_t= 43kgf/cm² (4.21 MPa)

Fig.23 The crack modes of concrete slabs. (Numerals indicate the cracking time.)

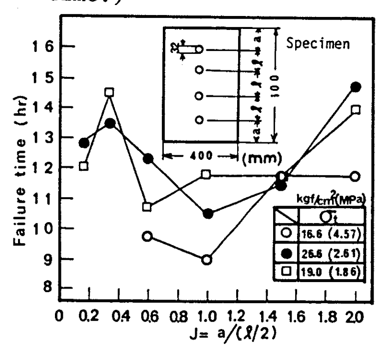


Fig.24 Relationship between failure time and J.

In the previous experiments, the effect of demolition in two dimensions was investigated with concrete slab specimens. The following experiments were carried out to investigate the demolition of mass concrete. The test specimens were concrete blocks with the following dimensions 60x70x40 cm^3 and the hexagonal arrangement was adopted. In order to examine how deep the boreholes should be drilled to demolish effectively, various depths of boreholes were made in the specimens. When the depth of a borehole is deeper, the crack occurs earlier and the crack width increases remarkably. Fig.25 shows experimental results. The cracking time was 9 hours when h/H was 1 or 3/4, 13 hours when h/H was 1/2 and 18 hours when h/H was 1/4. The demolished shape of concrete block indicated hexagonal column when h/H was 1 or 3/4. When h/H was 1/2, the lower half part of the specimen did not divide as expected and large blocks remained indivisible. When h/H was 1/4, the lower part of the specimen also did not demolish perfectly. The demolition time is the shortest when the borehole is drilled from top to bottom of the specimen. But as economical aspects should be considered, it is not advised to drill such deep boreholes. Based on the above results, the demolition can be done easily when the depth of borehole to be drilled is about three quarters of total height of the block. When the depth of borehole is larger than half of total height, although demolition can be done, the demolition time is longer.

Demolition experiments were also carried out to investigate the relation between the shape of boreholes and the cracking time. The test specimen was a rectangular concrete plate with two boreholes at 10 and 20 cm from the free end and it was reinforced by reinforcing bars at the other three sides. Fig.26 shows the behavior of strain at the free end for various shapes of boreholes. In the case of acute angled hole, as the degree of stress concentration was higher, crack appeared more promptly than that of a circular one. In particular, the cracking time of the borehole with a vertical angle of 30° is less than half of that of a circular one. When the borehole is not circular, the direction of crack propagation is easier to control. The effect of the borehole with acute angle on shortening the demolition time was clearly observed.

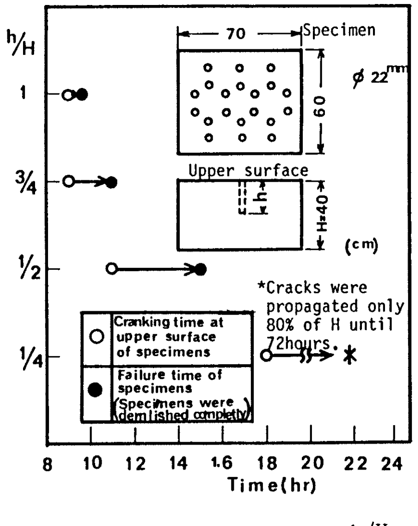


Fig.25 Relationship between h/H and failure time.

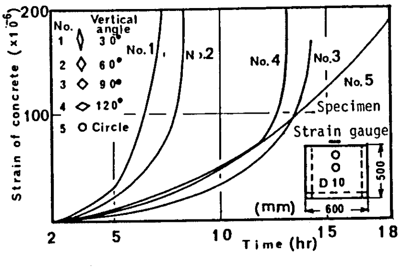


Fig.26 The cracking time versus the shape of borehole.

Moreover, the effect of demolition with ditches made by concrete cutters was investigated. As shown in Fig.27 concrete blocks with ditches having width of 9.5 mm and depth of h were used as specimens. Table 3 shows the relation between the demolition time and the depth h of the ditch. When the depth of ditch was deeper than a quater of the total height, the difference of demolition time was very small.

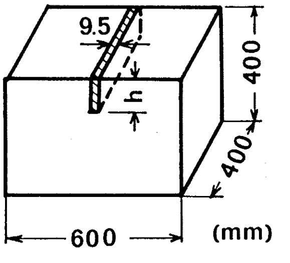


Fig.27 Concrete specimen containing a ditch.

Table 3 Relationship between h and failure time.

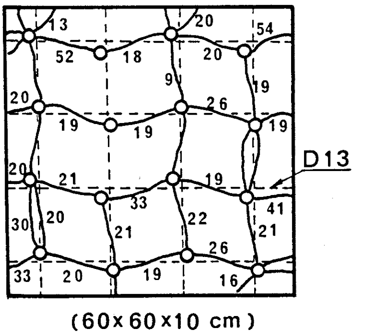
h (mm)	50	100	150	200
Failure time (hr)	16	9	7	6

σ_t=30 kgf/cm^2 (2.94 Mpa)

5. DEMOLITION OF REINFORCED CONCRETE MEMBERS

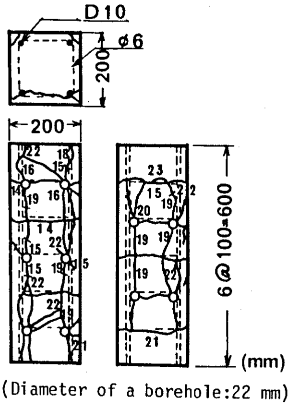
With the demolition agent, it is easy to demolish brittle materials, but difficult to demolish composite materials with high ductility such as reinforced concrete. In this case, it is necessary to do the demolition works by steps. As the first step of demolition, the concrete cover should be removed from the body to break the bond between reinforcing bars and concrete. As the second step, reinforcing bars should be cut by the method of gas or cutter machines. Finally, the inside concrete block should be demolished.

Preliminary experiments, in which RC slab and RC column were demolished with the agent, were carried out as shown in Figs.28 and 29. In RC slab specimens cracks occurred along the reinforcing bars, but the reinforcing bars restrained the width of cracks to extend until the bond between concrete and reinforcing bars was broken. The crack mode of RC column is shown in Fig.29. Boreholes were made along the reinforcing bars, where cracks occurred later. After that, the concrete cover could be removed easily from the body by inserting a driver and the reinforcing bars were exposed. When the bars were cut, the inside concrete block was separated into pieces because the expansive pressure was still acting on the concrete.



(60x60x10 cm)
(Diameter of a borehole:22 mm)

Fig.28 Fracture mode of RC slab specimen.(Numerals indicate the cracking time.)



(Diameter of a borehole:22 mm)

Fig.29 Fracture mode of RC column specimen.(Numerals indicate the cracking time.)

Based on the above results, it is advisable to do the phased demolition whose first step is the removal of concrete cover, the second one is the cutting of reinforcing bars and the final one is the demolition of the inside concrete block. In this process, only concrete demolition occur in the first and final steps, therefore, the design of demolition described in section 4 can also be applied in this case.

6. CONCLUSIONS

The results from these studies are summarized below.

(1) From the viewpoint of workability of the slurry and expansive pressure, water-agent ratio of 25 ∿30% is considered to be proper.

(2) New pressure transducers were developed and named "outer pipe method", "inner pipe method" and "pressure gauge method". In particular, with the inner pipe method, the expansive pressure at fracture can be accurately and directly measured in the borehole.

(3) The behavior of expansive pressure is under the influence of temperature but scarcely depends on the physical restraint of surroundings of materials. Also, the transmission of expansive pressure in the hardened agent is similar to that in a fluid.

(4) The initial crack of concrete hollow cylinders subjected to the expansive pressure was caused by a circumferential stress. Two kinds of cracking modes were observed at the moment of fracture. One was an instantaneous straight cracking from the inside surface to the outside one, and the other one consisted of successive crackings following the initial crack which did not reach the other surface. In the typical mode of cracking of the specimens under the expansive pressure of the agent, the cross section is separated into three fan-shaped parts at vertical angles of about 120° .

(5) The demolition criterion is defined by this equation $\overline{\sigma}_\theta/\sigma t = \alpha$. When $k<5$, $\alpha=1$ is taken and the equation is written as $Pu/\sigma t = k-1$. When $k>5$, $\alpha=0.8$ is taken, and the equation is written as $Pu/\sigma t=0.8k$.

(6) Demolition time can be estimated accurately by using the time-dependent changes of expansive pressure measured by the inner pipe method and the demolition criterion with the tensile strength as parameter. When the estimation of demolition time is done by the outer pipe method, if the surrounding conditions are considered, the range of mistake is not more than 10%, so it is also effective.

(7) The fundamental shape of a borehole is circular, but with an acute angled hole or a ditch made by a concrete cutter the direction of crack propagation is easier to control.

(8) The demolition of RC members with the demolition agent is not so easy as the demolition of plain concrete. It is necessary to do the demolition by the following steps: the removal of concrete cover, cutting of reinforcing bars and the demolition of the inside concrete block.

We must recognize that concrete structures are not eternal monuments and someday will be demolished in a cycle of construction-demolition due to public requirements. In future, the demolition works using demolition agents will increase from the viewpoint of economy and prevention of pollution. Therefore, when new concrete structures are constructed, it is necessary to provide pipes or holes to inject the slurry of the demolition agent considering the strength of the structure and the workability of concreting in order to do the demolition work easily later.

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