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THE MECHANICS OF EXPANSIVE PRESSURE GENERATION WITH EXPANSIVE DEMOLITION AGENTS

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SYNOPSIS

There have been no rigorous theories to explain the mechanics of expansive pressure generation using expansive demolition agents. Elucidation of the mechanics of this process would be helpful in improving the performance not only of expansive demolition agents but also of the expansive material used in anchoring FRP tendons and chemical jacks. We examined the relationship between expansive pressure, the degree of hydration, and pore structure for two types of expansive demolition agents at different curing temperatures and water-agent ratios. On the basis of the results of this examination, we reached certain conclusions about the expansive pressure generated by expansive demolition agents.

Keywords:expansive demolition agent, expansive pressure, degree of hydration, pore structure

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1. Introduction

The main ingredient in expansive demolition agents is quick lime, which hydrates and expands to demolish brittle materials. The hydration and expansion of quick lime has long been well understood. There have also been a number of theories explaining the mechanics of expansive pressure generation. However, none of these theories are conclusive. Chatterjy[1], Watanabe[2], and Kawano[3] concluded that, rather than a volume change as lime hydrates, crystal growth in the hydrated lime is mainly responsible for expansive pressure. Yamasaki[4,5] reported that no such crystal growth could be observed, but that the expansive pressure depended on the formation of hydrated lime.

One of the present authors[6] studied the effects of water-demolition agent ratio (W/B), ambient temperature, and restraint on the material to be demolished on the degree and time history of expansive pressure development. He found that ambient temperature has the greatest effect, and that, for a constant hydration ratio (i.e., $Ca(OH)_2$ generation ratio) in the expansive demolition agent, the expansive pressure is invariant even if the curing temperature varies. In this particular case, he used only one type of demolition agent (a summer agent with W/B = 25%). Consequently, his study was not complete enough to provide conclusive results about the effects of W/B.

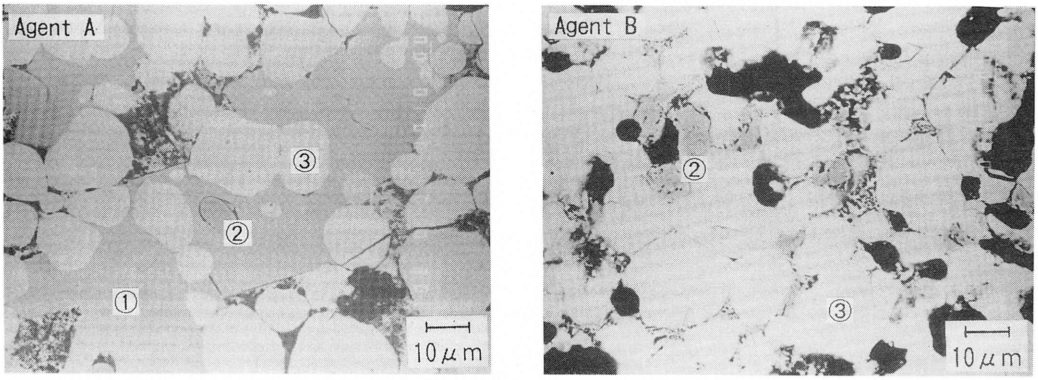
Thus, we felt it necessary to conduct a more comprehensive study to characterize the expansive pressure generated by demolition agents. In this study, we examined different types of agent to determine the effects of degree of hydration and pore structure on expansive pressure at various ambient (or curing) temperatures and various W/B ratios. Using the experimental results obtained, we discuss the mechanics of pressure generation in expansive demolition agents.

We believe that elucidation of the mechanic involved should prove not only in the accurate design of demolition procedures using expansive demolition agents and the improvement of such agents, but also in the design of anchors for FRP tendons[7] and chemical jacks.[8]

2. Materials

We examined two types of demolition agents: Agent A for use in spring and autumn (supplied by Onoda Cement) and Agent B for use in winter (also supplied by Onoda Cement). Table 1 gives the chemical compositions, constituent compounds and minerals, and the fineness of the powder for these agents. Figure 1 shows back-scattered electron images of both the agent clinkers.

The performance of demolition agents greatly depends on the ambient temperature. At lower temperatures, the generation of expansive pressure is delayed. Different agents are available to allow designers to choose an agent yielding a certain expansive pressure in almost the same amount of time after mixing at different temperatures. In Table 1, Agent B has about 20% more free CaO and less alite than Agent A, meaning that the former seemingly generates an expansive pressure at low temperatures in approximately the same time that the latter does at a higher temperature.[9,10]



① : alite ② : belite ③ : CaO

Fig. 1 Back-scattered electron image of clinker for Agent A and Agent B

Table 1 Chemical composition and main mineral content of expansive demolition Agents A and B

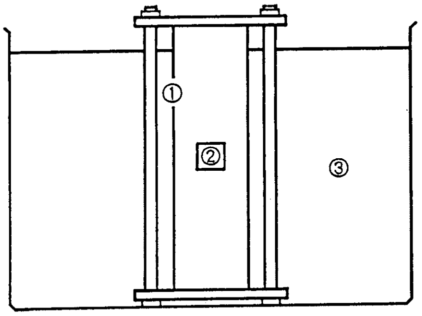
	Igloss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total
A	1.2	8.5	2.3	1.0	82.5	0.7	3.5	99.7
B	1.5	4.3	1.3	0.5	90.1	0.8	1.0	99.5

	Main minerals (wt%)				Superplasticizer (wt%)	Fineness (cm^2/g)
	free CaO	alite	belite	anhydrite		
A	55.0	28.5	3.0	6.0	1.0	3000
B	76.8	0	12.3	1.7	1.0	2200

3. Experimental Method

3.1 Measurement of Expansive Pressure

We used a mortar mixer (by Maruto Co.) to mix the demolition agent and water at low speed for one minute. A steel pipe 32.8 mm in diameter, 155 mm in length, and 4.95 mm in thickness, and with a strain gauge attached to its outer surface, had been waterproofed prior to mixing. The agent slurry was then poured into the steel pipe. With steel plates tightly fixed to both ends as restraining covers, it was then immersed in water, as shown in Figure 2. We used a strain meter (Model TDS-302; Tokyo Sokki Research Co.) to measure the strain on the strain gauge. The following equation was used to convert the measured strain to expansive pressure:



① Steel pipe ② Strain gauge ③ Water

Fig. 2 Measuring method for expansive pressure

$$p=\frac{E_s(k^2-1)}{2(1-\nu_s^2)}(\varepsilon_\theta+\nu_s\varepsilon_z) \cdots\cdots (1)$$

p : Expansive pressure (MPa)
ν_s : Poisson's ratio of steel pipe (0.3)
E_s Elastic modulus of steel pipe
k Outer diameter/ inner diameter ratio of steel pipe
ε_θ : Strain of circumferential direction
ε_z : Strain of axial direction

The Technical Evaluation Committee's test method, based on the Ministry of Construction's Standards for Technical Evaluation, normally requires strain measurements to be taken at the center of a one-meter-long steel pipe. It is very difficult, however, to take samples from such a long pipe. To facilitate sampling, we used a shorten pipe in this study and covered the top and bottom ends with steel plates, a procedure used in this group to control quality. These covers serve to prevent the slight loss of expansive pressure that would normally result from the openings in such a short pipe. We confirmed that a standard-length pipe and our short pipe generated similar expansive pressure conditions at the center, demonstrating that the restraining covers had no undesirable effects.

Table 2 shows the experimental conditions. Two different curing temperatures were used (5°C and 20°C) and one basic W/B ratio (30%). A thermostatic chamber kept the temperature within the target range, 20 ±1 °C, 5 ±1°C. Two additional values of W/B (25% and 27%) were employed to examine the effect of W/B in the case of Agent A.

Table 2 Materials and test conditions

No	Agent	Curing temp. (℃)	Water/agent ratio (%)
1	A	20	30
2	A	5	30
3	A	20	27
4	A	20	25
5	B	20	30
6	B	5	30

3.2 Measurement of $Ca(OH)_2$ generation

Specimens used for $Ca(OH)_2$ measurements were similar to the pressure measurement specimens. After pouring for 4, 8, 24, or 48 hours, each sample was removed from the pipe, washed with acetone to stop hydration, and D dried.
A differential thermogravimeter (DTG; Rigaku Co.) was used to

measure the weight loss attributable to dehydration of $Ca(OH)_2$ at around 460°C and to decarboxylation of $CaCO_3$.(The very small quantity of $CaCO_3$ was produced by treating sample.) The $CaCO_3$ measurement was converted and added to the dehydration weight loss of $Ca(OH)_2$. This total dehydration loss of $Ca(OH)_2$ was converted into a weight percentage of $Ca(OH)_2$ in the hydrated agent remaining after D drying. This value included the amount of $Ca(OH)_2$ produced by the hydration of calcined lime and other mineral components in the specimen.

3.3 Pore Structure of Hardened Specimen

3.3.1 Porosity and Distribution of Pores

Pore measurement samples were prepared similarly to those used to prepare the samples used in observations of $Ca(OH)_2$ generation. We used a mercury porosimeter (Shimazu) to measure the porosity and pore distribution. The upper limit of the measurable pores was 60.3 μm, while the lower limit was 0.003 μm.

3.3.2 Observation of the Rupture Surface

Specimens used in observations of the rupture surface were prepared in a way similar to those made for observations $Ca(OH)_2$ generation. We used a scanning electron microscope (Nihon Electron) to observe the surface of a section broken off a hydrated specimen. We also observed non-hydrated powder agents for the sake of comparison.

4. Results

4.1 Measurement of Expansive Pressure

Figure 3 shows changes in expansive pressure over time for Agents A and B at 5°C and 20°C. Figure 4 shows the effect of W/B on this expansive pressure. These measurements reveal that Agent B generates expansive pressure earlier, and reaches a larger ultimate pressure than Agent A. With both agents, the pressure began to rise

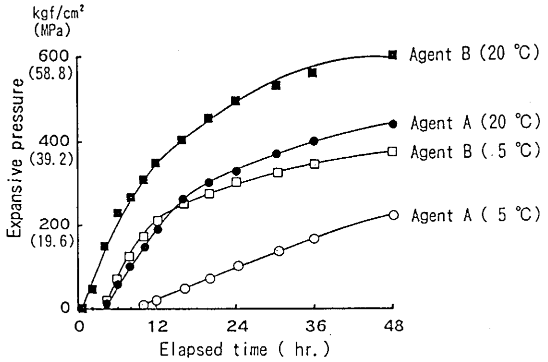


Fig. 3 Expansive pressure of agents

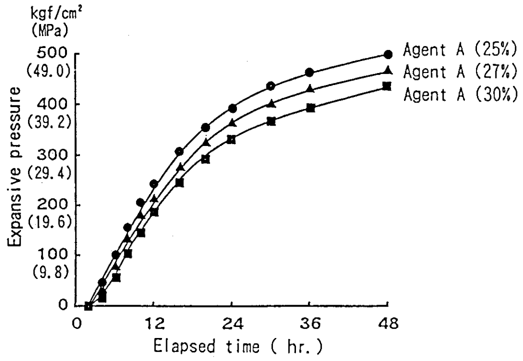
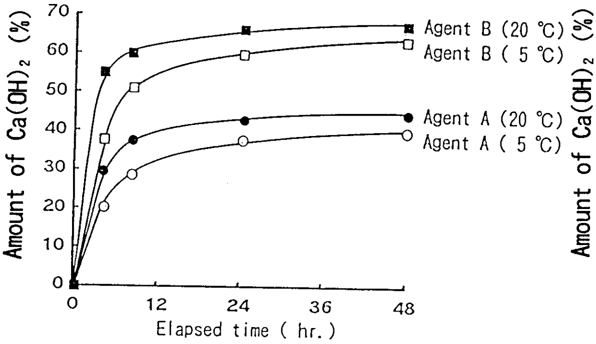


Fig. 4 Expansive pressure of Agent A with varing the water/agent ratio

earlier when the curing temperature was increased. A smaller W/B ratio resulted in higher expansive pressure.

4.2 Generation of $Ca(OH)_2$

Figure 5 shows the changes in $Ca(OH)_2$ generation over time at 5°C and 20 °C. Figure 6 shows the effect of W/B on this generation process. These measurements reveal that Agent B produces $Ca(OH)_2$ more quickly than Agent A. In both cases, the rate of generation was higher at a higher curing temperature. A smaller W/B ratio resulted in a lower generation rate.



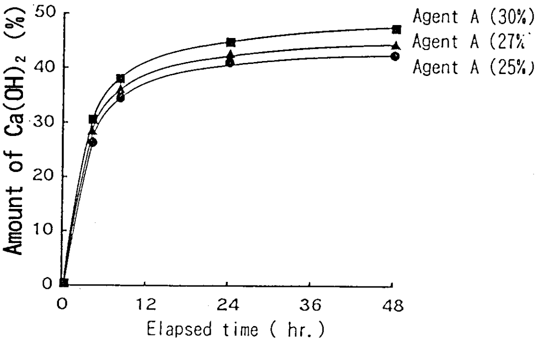


Fig. 5 Amount of $Ca(OH)_2$ in the hydrated agents

Fig. 6 Amount of $Ca(OH)_2$ in the hydrated Agent A with varing water/agent ratio

4.3 Pore Structure of Hardened Agents

4.3.1 Porosity and Distribution of Pores

Figure 7 and 8 show changes in the porosity of Agents A and B over time. These measurements reveal that porosity decreases over time. Agent B had a smaller porosity than Agent A. In both cases, the porosity was lower at higher curing temperatures. A smaller W/B ratio gave lower porosity.

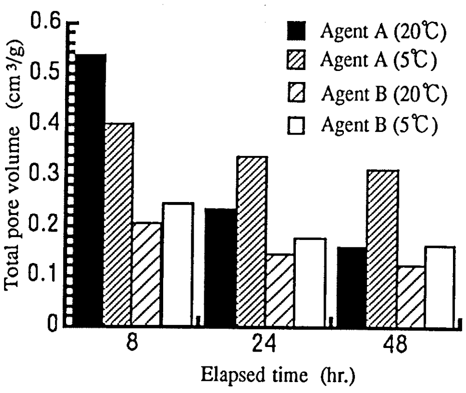


Fig.7 Total pore volume of the hydrated agents

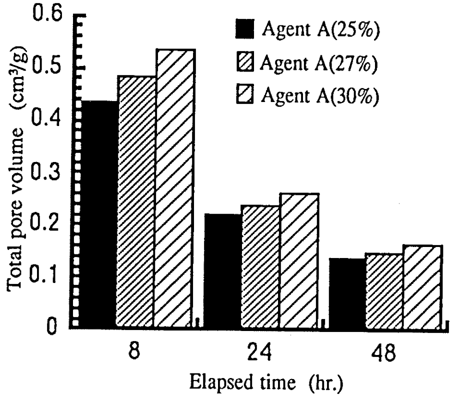
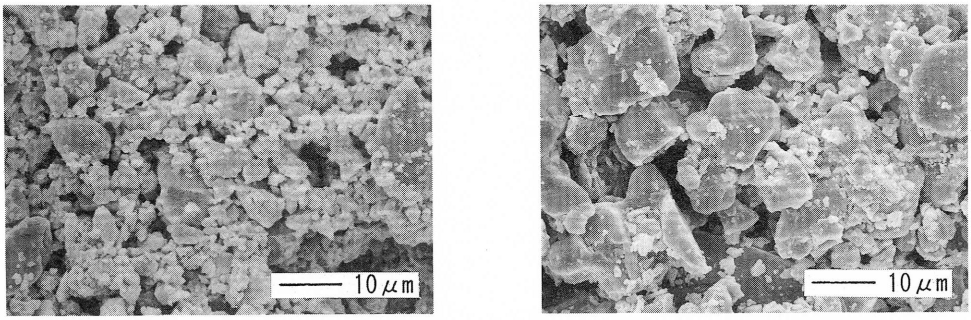


Fig.8 Total pore volume of the hydrated agents with varing water/agent ratio

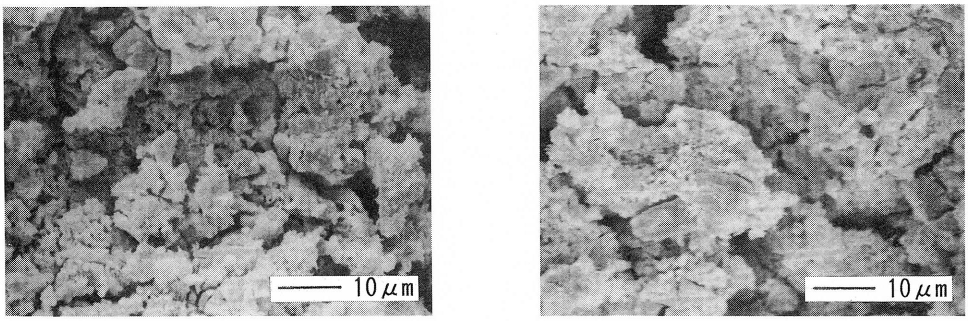
4.3.2 Structure of the Rupture Surface

Figure 9 gives SEM images of a non-hydrated demolition agent powder and a hydrated agent rupture surface over an 8-hour and 24-hour period. These images reveal that the structure of the hydrated agents becomes denser over time.



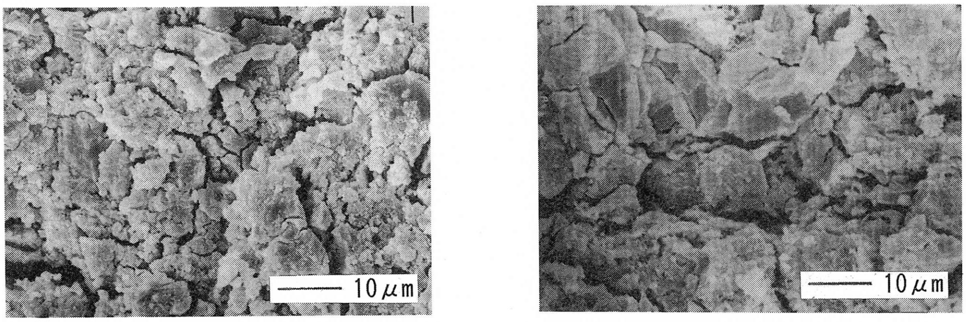
Unhydrated Agent A

Unhydrated Agent B



Agent A (8hr.)

Agent B (8hr.)



Agent A (24hr.)

Agent B (24hr.)

Curing temp. 20 ℃

Fig. 9 SEM images of the hydrated agents

5. Discussion

5.1 Effect of Demolition Agent on Expansive Pressure

In this study, Agent A began generating expansive pressure later than Agent B. In a previous report[10], we found that alite very effectively retards the hydration of quick lime, while belite is relatively ineffective. As Table 1 shows, Agent A contains more alite than Agent B. This seems to be a main cause of the delay in generation of expansive pressure in Agent A. The small amount of free CaO contained in Agent A seems to have caused the pressure to decrease.

5.2 Effect of $Ca(OH)_2$ Formation on Expansive Pressure

Figure 10 shows the effect of $Ca(OH)_2$ generation on expansive pressure. For one type of demolition agent, the expansive pressure is independent of the curing temperature, although it does depend on the amount of $Ca(OH)_2$ generated. This corroborates the results of Yamasaki, et al.[4,5], who concluded that the expansive pressure generated by a demolition agent depends on the degree of hydration of the quick lime in the agent. The effect of curing temperature seen in this study was probably due to the higher rate of hydration, and hence the higher rate of $Ca(OH)_2$ generation, at higher temperatures. This result agrees with the results in a previous report[6]. Accordingly, it is now clear that temperature has a direct effect on $Ca(OH)_2$ generation, which in turn controls the degree of expansive pressure.

These findings apply to one of the agents. The pressure-$Ca(OH)_2$ generation curve of Agent A was different from that of Agent B. Although a smaller amount of $Ca(OH)_2$ was generated, Agent A produced nearly the same pressure as Agent B.

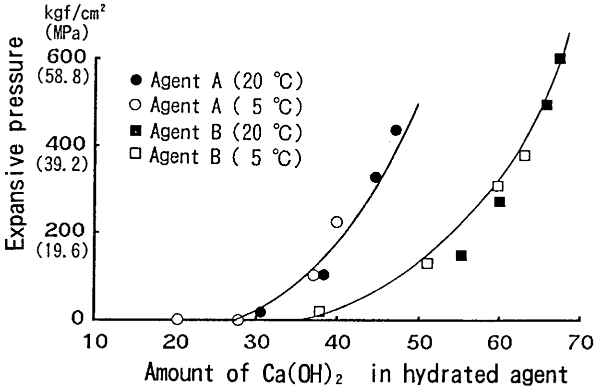


Fig. 10 Relationship between the expansive pressure and the amount of $Ca(OH)_2$

Ish-Shalom and Bentur[11-13] proposed a sphere model, as shown in Figure 11, to explain the mechanics of expansion in CSA-type expansive additives. In this model, $Ca(OH)_2$ is formed during hydration and grows on the quick lime particles, eventually coming into contact with the $Ca(OH)_2$ layers on neighboring lime particles. This point they called the critical degree of hydration, α_{cr}. Before this point, there is no expansive pressure. After this point, the particles act against one another and exert an expansive force or pressure. In our experiments, we also reached this critical point. The value of α_{cr} in the case of Agent A was smaller than that in the case of Agent B. Therefore, it may be concluded that a smaller amount of $Ca(OH)_2$, such as that found in Agent A, should lead to earlier initiation of expansive pressure.

The above results tell us that the hydration of quick lime cannot alone explain the complex phenomenon of pressure generation.

Firstly, our results are inconsistent with the conclusions reached by Ish-Shalom, et al. In our study, α_{cr} did not change when the curing temperature was altered. Figure 12 shows the effect of W/B on the $Ca(OH)_2$ generation-pressure relationship. As W/B decreases, the relationship indicates a smaller amount of $Ca(OH)_2$: that is,

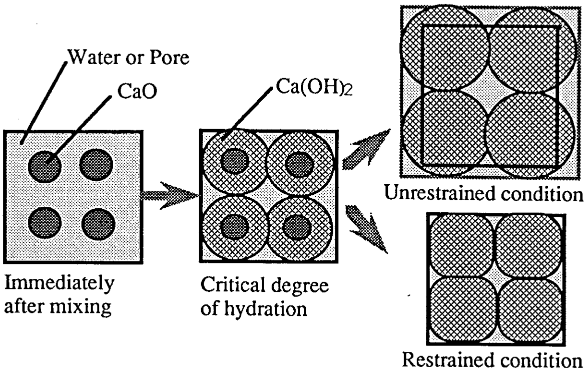


Fig.11 Shalom's sphere model for the expansion mechanism of expansive additives

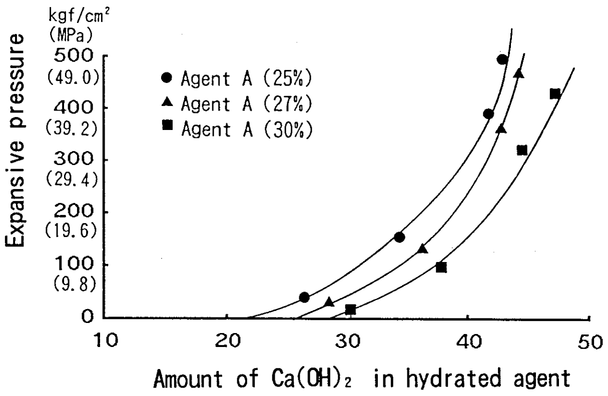


Fig. 12 Relationship between the expansive pressure and the amount of $Ca(OH)_2$ with varing the water/agent ratio

α_{cr} falls. Presumably, this occurs because a smaller W/B ratio results in a larger agent particle density, and hence in a smaller distance between neighboring particles. This means a lower degree of hydration will bring them into contact.

Table 3 gives values of α_{cr}. Applying the least squares method to the data in Figures 10 and 12, we obtain equations (2) through (5) below, which we found best explain the measured relationships between $Ca(OH)_2$ generation and expansive pressure:

Table 3 Critical degree of hydration (α_{cr})

Agent	Water/agent ratio (%)	α_{cr} (%)
A	30	27
A	27	25
A	25	21
B	30	33

Agent A, W/B 30% $$p=810\left(\frac{h-\alpha_{cr}}{100}\right)^{1.87} \quad \cdots\cdots (2)$$

Agent A, W/B 27% $$p=541\left(\frac{h-\alpha_{cr}}{100}\right)^{1.59} \quad \cdots\cdots (3)$$

Agent A, W/B 25% $$p=590\left(\frac{h-\alpha_{cr}}{100}\right)^{1.72} \quad \cdots\cdots (4)$$

Agent B, W/B 30% $$p=315\left(\frac{h-\alpha_{cr}}{100}\right)^{1.42} \quad \cdots\cdots (5)$$

p : Expansive pressure (MPa)
h : Amount of $Ca(OH)_2$ (%)
α_{cr} : Critical hydration ratio (%)
Eq. (2)~(5) hold true for $h \geq \alpha_{cr}$

These results demonstrate that the expansive pressure generated by demolition agents depended not only on the quantity of $Ca(OH)_2$ generated, but also on the concentration of the agent's particles.

5.3 Effect of Pore Structure on Expansive Pressure

Figures 7 and 8 indicate that, as aging proceeds and expansive pressure rises, porosity decreases. The SEM images shown in Fig. 9 reveal that as aging proceeds, or expansive pressure rises, the hardened structure becomes denser.

Figure 13 shows the effect of expansive pressure on total porosity. Figure 14 shows the effect of expansive pressure on the porosity for particular ranges of pore diameter.

These figures reveal that pores with a diameter of less than 0.1 µm yield no clear correlation between porosity and expansive pressure, although larger pores have a strong correlation. This correlation is independent of the curing temperature, the type of demolition agent, and W/B. Therefore, measuring the specific volume of pores over 0.1 µm in diameter may possibly be a help in computing expansive pressure.

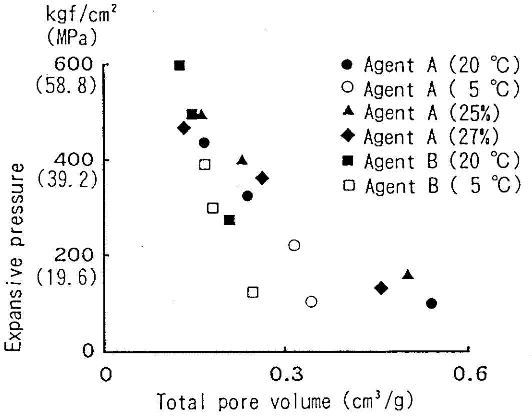


Fig. 13 Relationship between expansive pressure and total pore volume

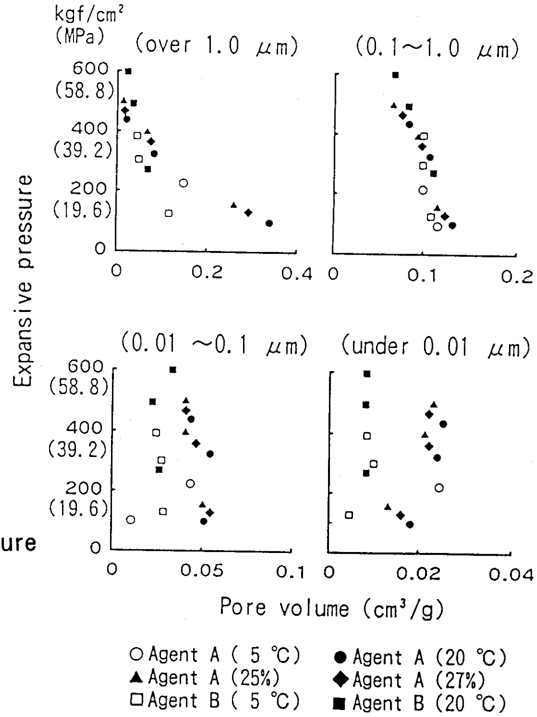


Fig. 14 Relationship between expansive pressure and various pore volume size ranges

5.4 Mechanics of Expansive Pressure Generation

Based on the above discussion, we may safely follow the sphere model of Shalom, et al., which is shown in Figure 11, to explain the mechanics of expansive pressure generation in an expansive demolition agent. First, we believe that hydration results in the formation of a $Ca(OH)_2$ layer on the surface of quick lime particles. As hydration proceeds, this layer grows, eventually coming into contact with the layers of neighboring particles. The degree of hydration at this critical point is called α_{cr}. Further hydration forces these particles to press against one another.

At this point, if there is no external restraint on the particles, the porosity will increase and the action of the particles against each other will not generate any expansive pressure. However, if there is an external restraint, the $Ca(OH)_2$ crystals will be deformed, developing pores and reducing the porosity. In this latter case, expansive pressure will appear as a reaction force against the restraint. Consequently, the greater the degree of external restraint, the higher the expansive pressure will be. This conclusion corroborates the report published by Kobayashi, et al.[14] Above a certain point, the restraint stops having an affect on the expansive pressure.[6]

A look at the pore structure, which is shown in Figure 15, tells us that there is a large number of pores in the initial stage of hydration. At this stage, the formation of $Ca(OH)_2$ may not be subject to restraint and, as a result, the expansive pressure will be insignificant. As hydration proceeds, not only does hydrated lime, $Ca(OH)_2$, grow in the structure but also the hydrates of cement components such as alite may be seen. This reduces porosity and makes the structure denser. At this stage, the $Ca(OH)_2$ crystals formed in the cement may be influenced by an external restraining force, in the form of a reaction force, from the surrounding hardened structure. This may be one of the main causes of the steep pressure rise accompanying a small amount of $Ca(OH)_2$, as shown in Figures 10 and 12.

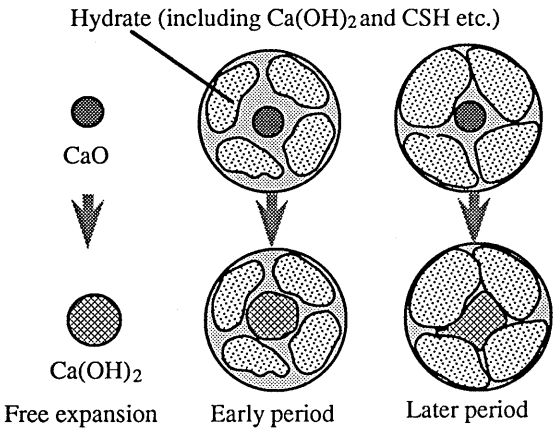


Fig.15 General idea for the expansion mechanism of an expansive demolition agent

We now assume that a hardened demolition agent is an elastic material with pores. As shown in Figure 16 (a), the elastic material fills a steel pipe. When a material with an expansion ß expands, the condition of compatibility (described in Figure 16 (b)) may generate the following contact pressure or expansive pressure at the boundary face:

$$p=\frac{E_s\cdot\beta}{(1-\nu_b)(1+\beta)\cdot\ n+\frac{k^2+1}{k^2-1}+\nu_s}\ \cdots\cdots(6)\qquad n=E_s/E_b\qquad k=r_1/r_0$$

Although the elastic modulus of the hardened agent increases over time, we assume it is constant at free age. If the steel pipe is assumed to be rigid, as is usual in qualitative discussions, Es may be assumed to be infinite. In this case, Eq. (6) may be simplified as follows:

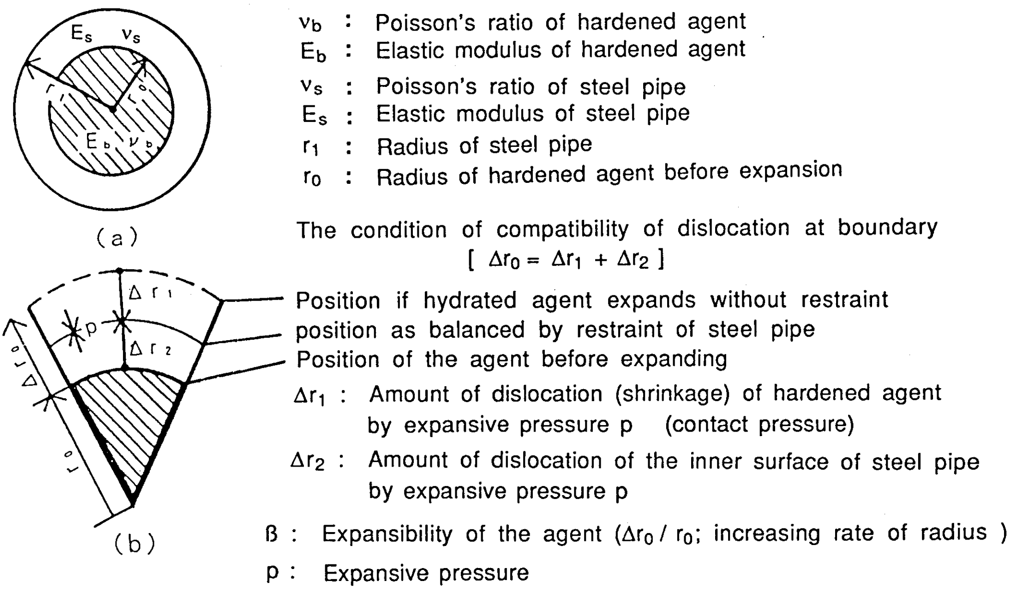
$$p=\frac{E_b\cdot\beta}{(1-\nu_b)(1+\beta)}\ \cdots\cdots(7)$$

Since ß is much smaller than 1, the pressure can be considered proportional to the product of elastic modulus and expansibility, E_b·ß.

It is a generally known that less porosity in a hardened material makes the elastic modulus larger.[15] In the initial stages of hydration, the porosity is usually great, while the elastic modulus is very small. In this case, Eq. (7) indicates that a large amount of $Ca(OH)_2$ will not significantly contribute to expansive pressure, since this would require an appreciable elastic modulus value. In the later stages of hydration, as the porosity falls, the modulus rises sharply (by as much as 5 x 10^3 MP, according to the experimental results obtained by Harada[6]). Therefore, even generation of a limited amount of $Ca(OH)_2$ will result in great expansive pressure. In this study, the value of α_{cr} for Agent A was small presumably because it contained such a large amount of cement minerals such as alite compared with Agent B. Such hydrated minerals fill the pores.

In previous reports[4,5], porosity has been reported to increase as the pressure rises. Another study[11] reported that the number of approximately 0.25 µm pores increase in the ettringite layer of CSA expansive materials. On the other hand, we found a decrease in the total volume of pores as the expansive pressure increased. This discrepancy may be attributable to differences in test methods and component materials. A further examination of this matter is required.

Given the above discussion, we know that to generate a high expansive pressure in an expansive demolition agent it may be necessary to ensure a small value of α_{cr}, and as well as an increase



ν_b : Poisson's ratio of hardened agent
E_b : Elastic modulus of hardened agent
ν_s : Poisson's ratio of steel pipe
E_s : Elastic modulus of steel pipe
r_1 : Radius of steel pipe
r_0 : Radius of hardened agent before expansion

The condition of compatibility of dislocation at boundary
[$\Delta r_0 = \Delta r_1 + \Delta r_2$]

Position if hydrated agent expands without restraint
position as balanced by restraint of steel pipe
Position of the agent before expanding

Δr_1 : Amount of dislocation (shrinkage) of hardened agent by expansive pressure p (contact pressure)
Δr_2 : Amount of dislocation of the inner surface of steel pipe by expansive pressure p

ß : Expansibility of the agent ($\Delta r_0 / r_0$; increasing rate of radius)
p : Expansive pressure

Fig. 16 Composite model of hydrated agent and restraining cylinder in $Ca(OH)_2$ generation or a greater degree of hydration. Other important factors are low porosity (or high density), and a large elastic modulus of the hardened agent.

6. Conclusions

In order to evaluate the expansive pressure generated by expansive demolition agents, we examined the relationships between expansive pressure, degree of hydration, and pore structure for different kinds of agent, various curing temperatures and water-agent ratios. We then discussed the mechanism of expansive pressure generation. The results obtained through this study are as follows.

(1)For the one type of expansive demolition agents and constant water-agent ratio (W/B), the pressure depends only on $Ca(OH)_2$ generation. The curing temperature indirectly affects the pressure because a rise in temperature causes an increase in $Ca(OH)_2$ generation. This means that the amount of $Ca(OH)_2$ may be a good indicator of the degree of expansive pressure achieved.

(2)When different kinds of agent are used, expansion does not depend on only $Ca(OH)_2$. Agent A produced the same level of pressure with less $Ca(OH)_2$ generation than Agent B. Therefore, we can conclude that even with the same degree of $Ca(OH)_2$ generation, different types of agent may exhibit different behavior.

(3) A smaller W/B value leads to the same expansive pressure at lower levels of $Ca(OH)_2$ generation, presumably because a smaller W/B value results in less distance between quick lime particles. Hence, the value of the critical degree of hydration (α_{cr}), as proposed by Shalom, et al., is lower.

(4) As expansive pressure rises, the porosity of a hardened agent decreases. In particular, the volume of pores with a diameter of 0.1 μm or more decreases. The porosity-pressure correlation is independent of the curing temperature, the demolition agent, or W/B. This means that measuring the porosity may make it possible to compute the expected expansive pressure.

(5) The sphere model proposed by Shalom et al. can explain the general mechanics of expansive pressure generation as found in this study. According to this model, a small value of α_{cr} and a higher degree of hydration are important factors influencing the generation of high expansive pressure. In a theoretical model, we assumed the demolition agent to be an elastic material with pores, and found that expansive pressure is proportional to the product of the elastic modulus and expansibility. In other words, large values of both elastic modulus and expansibility may lead to improved expansive pressure.

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