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Effect of Finely Ground Calcium Hydroxide on the Strength Development of Steam-Cured Concrete

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In order to enable concrete production plants to reduce their manufacturing processes and costs, we prepared concrete with finely ground $Ca(OH)_2$, which improves the setting of concrete. We steam-cured concrete, and experimentally evaluated the effects of the added $Ca(OH)_2$ and the curing conditions on the concrete's strength development. The results show that adding finely ground $Ca(OH)_2$ enhances the early strength of concrete. At a maximum temperature of 80°C the concrete exhibited the same level of strength as concrete that had been cured for 24 hours before removing the mold, even though a shorter curing time was used.

Keywords: Finely Ground $Ca(OH)_2$, Steam-Curing, Rapid Demolding, Alite

1. INTRODUCTION

In general, concrete production plants employ atmospheric-pressure steam-curing of concrete as a means of accelerating curing to improve the molds' turnover ratios and to enable their products to be shipped sooner. Atmospheric-pressure steam-curing requires careful selection of the curing conditions, to prevent the quality of the concrete from being adversely affected. For this reason, one mold can be used only in one cycle per day [1]. Recently, however, various studies have been conducted into hardening accelerators, with the aim of enhancing the early strength of concrete and removing the mold earlier, thus increasing the turnover ratio of molds, reducing the curing time, and enabling shipments to be made earlier. All these results seek to reduce the manufacturing processes and costs [1], [2].

We reported previously that finely ground $Ca(OH)_2$ could be used to accelerate solidification of hardening cement [3], [4]. We therefore expected that steam-curing concrete containing finely ground $Ca(OH)_2$ could improve the early strength of concrete and shorten its curing time. In this study, we conducted an experiment to examine the effect of added finely ground $Ca(OH)_2$ and curing conditions on the strength development of concrete, and discovered the possibility of using $Ca(OH)_2$ as an admixture to enable earlier removal of the mold.

2. OUTLINE OF EXPERIMENTS

2.1 Materials Used

We used ordinary Portland cement (OPC) in our experiment. Table 1 shows the cement's chemical composition. It had a density of 3.16 g/cm^3 and a surface area of 3310 cm^2/g (Blaine).

To prepare finely ground $Ca(OH)_2$, we mixed $Ca(OH)_2$ of 99.4% purity and ion-exchanged water to give a mass concentration of 20.0% of the solid content of $Ca(OH)_2$. It was then pulverized with a wet grinding mill to give an average particle diameter of 0.25 μm. Polycarboxylate-based superplasticizer that had a solid content of 7.0 mass % of $Ca(OH)_2$ was added to the ground slurry. The average particle diameter was determined using a laser-scattering diffractive granularity analyzer.

For comparison, we used commercially available $Ca(OH)_2$ having an average particle diameter of 12.4 μm. We also used calcium chloride ($CaCl_2$) and calcium nitrite ($Ca(NO_2)_2$), which are known to be effective in accelerating cement's setting; they were used as reagents.

The fine aggregate used was a mixture (density: 2.57 g/cm^3, FM: 2.71) of sea sand (density: 2.56 g/cm^3, FM: 2.96) and land sand (density; 2.61 g/cm^3, FM: 1.29). The ratio of the volume of sea sand to that of land sand was 75:25. The coarse aggregate used was crushed stone (maximum diameter: 20 mm, density: 2.70 g/cm^3, FM: 6.79, solid volume: 60.5%).

Polycarboxylate-based superplasticizer was used as the chemical admixture, and tap water was used to mix the cement, aggregates, etc.

2.2 EXPERIMENTAL METHOD

2.2.1 Mix Proportion

Table I Chemical Composition of OPC (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	SO_3
20.90	5.67	3.08	63.87	0.23	0.41	2.00

Table II Mix Proportion of Concrete

MARK	W/C (%)	kg/m^3						
		W	C	S	G	Finely Ground $Ca(OH)_2$	Other Accelerator	AD
OPC	45	160	356	870	995	0	-	Cx1.25%
CH2%				861		8	-	Cx1.05%
CH4%				851		16	-	Cx0.60%
CHm4%				852		-	16	Cx1.20%
CN1%				865		-	4	Cx1.25%
CCl-1%				865		-	4	Cx1.25%

Table III Conditions for Steam-curing

No.	Pre-curing Time (hr)	Rising Temperature Rate (°C/hr)	Maximum Temperature (°C)	Hold Time (hr)	Cooling Temperature Rate (°C/hr)	Demolding Time (hr)
a-1	1	45	65	4	4.5	24
a-2	1	45	65	2	4.5	6
b-1	1	60	80	2	4.5	24
b-2	1	60	80	2	4.5	6
b-4	0	60	80	2	-	3
b-3	1	60	80	2	-	4
b-5	2	60	80	2	-	5

Table II shows the mix proportion of concrete specimens. The specimen was made from W/C = 45%, a slump of 12±1.5 cm, an air content of 2.5±0.5%, and a mixing temperature of 20±1°C, and mixing mass ratios of the finely ground $Ca(OH)_2$ were set to 0, 2, and 4% of the cement (OPC, CH2%, and CH4% respectively). The conventional practice of adding the additives to the concrete was followed. The commercially available was also added, in the same manner as finely ground $Ca(OH)_2$ was added; the mass mixing ratio of the lime was 4% to the cement (CHm4%). $Ca(NO_2)_2$ and $CaCl_2$ were also added at mass mixing ratios of 1% to the cement (CN1% and CCl-1%). The quantities of the added $CaCl_2$ and $Ca(NO_2)_2$ were selected so that setting would begin at approximately the same time as CH4% (Fig.1).

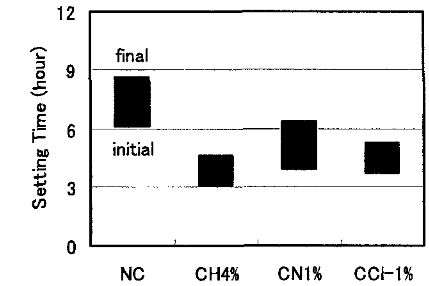

Fig.1 Setting Time of Concrete

2.2.2 Steam-curing Conditions

Table III shows the steam-curing conditions. The basic conditions were as follows: the pre-curing time was 1 hour, the temperature increased to the maximum temperature (65°C or 80°C) over a period of one hour, the molds were removed 24 hours after the pre-specified holding time had elapsed. In addition, to investigate the effects of reducing the curing time, we also used 6-hour curing, in which we maintained the mixtures at their respective temperatures for 2 hours and then allowed them to cool for 2 hours before removing the molds. Moreover, we also tried 4-hour curing, in which we kept the mixture at 80°C with no cooling period before removing the molds.

2.2.3 Compressive Strength of the Concrete

We prepared cylindrical test specimens (Ø10 x 20 cm) and, by following the JIS A1108 Test Method for the Compressive Strength of Concrete, measured their compressive strength immediately after the mold was removed as well as when they were 1, 7, 14, and 28 days old. We also measured the compressive strength of the test specimens containing the setting accelerators for comparison immediately after the mold was removed and when they were 1 and 7 days old.

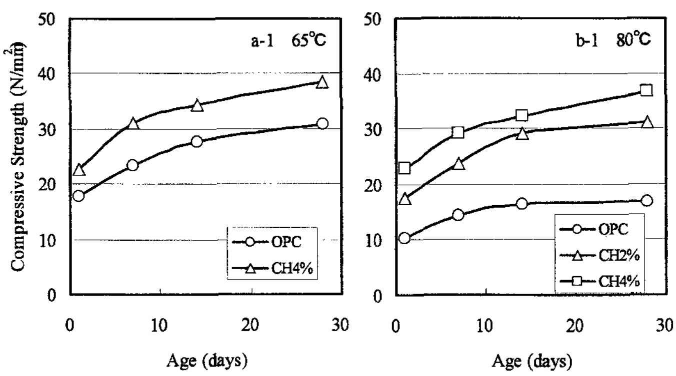

Fig.2 Compressive Strength of Concrete (a-1 and b-1)

3. RESULTS AND DISCUSSIONS

3.1 Effect of Adding Finely Ground $Ca(OH)_2$

Fig.2 shows the compressive strength test results under the steam-curing conditions a-1 and b-1. Under both conditions, adding finely ground $Ca(OH)_2$ enhanced their early strength. Under conditions b-1, the strength increased as we increased the amount of the fine powder. Furthermore, adding finely ground $Ca(OH)_2$ resulted in a strength far exceeding 10 N/mm^2, which is the level of strength commonly required when removing the mold.

Comparing the specimens under the two different conditions, a-1 and b-1, the effect of the added $Ca(OH)_2$ is evident in the early strength under b-1, which had a higher maximum temperature and a shorter holding time. When the molds were removed, we confirmed that CH4% was almost twice as strong as OPC. OPC also performed poorly in later strength development as its strength increased by only about 7 N/mm^2 after 28 days. In contrast, CH4% exhibited a similar strength to that of concrete of the same mixing prepared under a-1. Under both a-1 and b-1, adding finely ground $Ca(OH)_2$

increased its strength to almost 35 N/mm^2, which is the level of strength required after 14 days, when common concrete products are shipped.

The C_3S hydration rate is considered to remain unaffected by the temperature for 2 to 3 hours after water pouring due to insufficient nucleation; but the hydration rate increases dramatically with the temperature after sufficient nuclei have been formed [5]. Concerning OPC, we consider that the rise in temperature did not accelerate C_3S hydration because the pre-curing time was 1 hour under both a-1 and b-1. As has already been mentioned, a previous study found that adding finely ground $Ca(OH)_2$ accelerates C_3S hydration [4]. For this reason, adding finely ground $Ca(OH)_2$ contributed to the greater strength development compared to that of OPC.

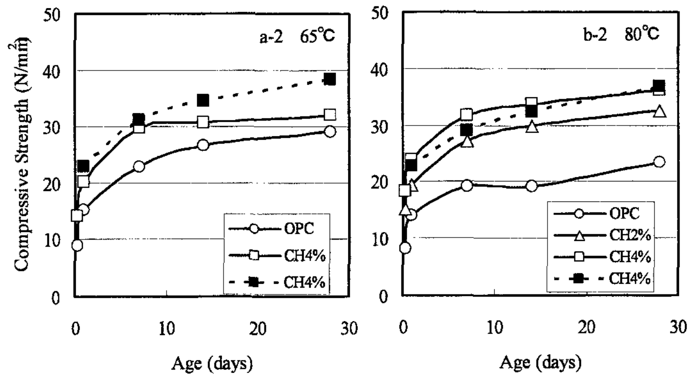

Fig.3 Compressive Strength of Concrete (6 hours, a-2 and b-2)

3.2 Effect of the Time before Mold Removal

Fig.3 shows the results of the compressive strength tests conducted under the two steam-curing conditions, a-2 and b-2. Under either of these conditions, the more of finely ground $Ca(OH)_2$ added, the higher the early strength was. Under b-2, CH4% had a strength that was almost twice as high as that of OPC. Similarly to the conditions a-1 and b-1, we confirmed that finely ground $Ca(OH)_2$ enhanced the early strength.

Under a-2, age 1 day and later, a shorter period of steam-curing tended to result in a lower strength than that observed under a-1 for all of the mix proportions tested. Under b-2, however, shorter steam-curing did not result in lower strength. Rather, age 28 days, mixings containing finely ground $Ca(OH)_2$ showed similar levels of strength to those observed under b-1. Moreover, for the case when the mixings were maintained at the maximum temperature under b-2 conditions and the molds were removed with no cooling down (Fig.4, condition b-3), CH4% exhibited a high strength development, although it was about 10% lower than those observed under conditions b-1 and b-2. OPC showed no strength development with a compressive strength of only about 10 N/mm^2 on age 28 days.

As described so far, when the maximum temperature was 65°C, the strength enhancement of every mixings tended to diminish with earlier removal of the molds. However, when the maximum temperature was 80°C, early removal of the molds produced no such effect. We conjecture that this is due to the different hydration rates caused by the different temperature rise rates and maximum temperatures. A difference in the hydration characteristics seemed to affect the long-term increase in strength. However, more detailed analysis is required to confirm this.

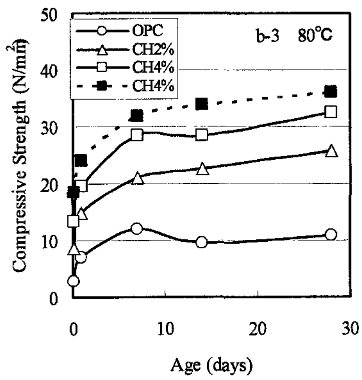

Fig.4 Compressive Strength at 4 hours curing

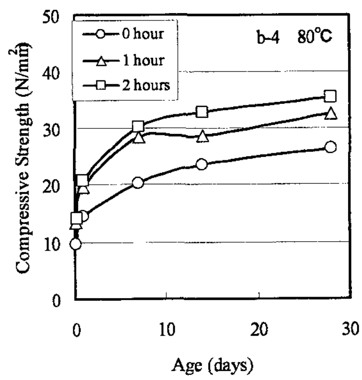

Fig.5 Relation of Between Pre-curing and Compressive strength

3.3 Influence of the Pre-curing Time

We varied the pre-curing time of OPC4% under the steam-curing conditions of b-3 and considered the results (Fig.5). With no pre-curing time (b-4), the strength was low immediately after the mold removal and there was little strength enhancement, although some strength development was observed. With a delay time of 2 hours (b-5), the strength was about 10% higher even on 28 days. Moreover, the strengths for b-3 and b-5 were almost equal immediately after removing the molds. These findings imply, that even with a 4% addition of finely ground $Ca(OH)_2$, which is known to accelerate hydration, a pre-curing time of around 1 hour is necessary for strength development.

3.4 Effect of the Particle Diameter of Finely Ground $Ca(OH)_2$

Fig.6 shows the results of the compressive strength tests for CH4% and CHm4% steam-cured under the conditions of b-3. The strength development level of CHm4% was not as high as that of CH4%, and we consider that this is because of difference in the particle diameters. It has been confirmed, that when finely ground $Ca(OH)_2$ that has an average particle diameter exceeding 5.0 μm is added to cement, the time required for setting to commence is not significantly reduced [3]. We conjecture that the commercially available hydrated lime did not accelerate setting much because it has an average particle diameter of 12.4 μm, and thus no strength development was observed even after steam-curing.

3.5 Comparison of Compressive Strength with Other Setting Accelerators

Fig.7 shows the compressive strength test results of CH4%, CN1%, and CCl-1% after they were steam-cured under the conditions of b-3.

CH4% had a strength development of around 16 N/mm^2 at the time of mold removal, and more than 20 N/mm^2 on age 1 day. The strength of CCl-1% at the time of the mold removal was by about 5 N/mm^2 lower than that of CH4%, and the strength of CN1% was less than a half of that of CH4%. $CaCl_2$ and $Ca(NO_2)_2$ are considered to accelerate C_3S hydration as finely ground $Ca(OH)_2$ does [6]. It is also confirmed that they enhance concrete's early strength both with standard curing and steam-curing [7]. In our study, however, a strength development as remarkable as that of CH4% was not observed, although the strength was higher than that of OPC. We therefore consider that $CaCl_2$ and $Ca(NO_2)_2$ do not work well under conditions such as a quick temperature rise or drop.

As discussed above, we believe that finely ground $Ca(OH)_2$ is a superior admixture for enabling early mold removal compared with other additives that accelerate setting.

4. CONCLUSION

In order to assist concrete production plants with early mold removal, we steam-cured concrete containing finely ground $Ca(OH)_2$ that accelerates setting. The experiments clarified the following:

1) Regardless of the steam-curing conditions, adding finely ground $Ca(OH)_2$ enhanced the early strength of concrete. This effect was most evident for a maximum temperature of 80°C. We ascribe this to C_3S hydration accelerated by finely ground $Ca(OH)_2$.

2) For a maximum temperature of 80°C, reducing the steam-curing time did not significantly affect the strength development of concrete containing added finely ground $Ca(OH)_2$. Even with 4 hours of curing, we observed a high strength development and confirmed that the strength was enhanced in older specimens. We believe that the addition of finely ground $Ca(OH)_2$ is helpful for achieving earlier removal of molds.

3) Among substances that accelerate setting under the harsh conditions of steam-curing, finely ground $Ca(OH)_2$ imparts a higher strength development to concrete than other substances do. We believe that this powder is an excellent admixture for facilitating the earlier removal of molds.

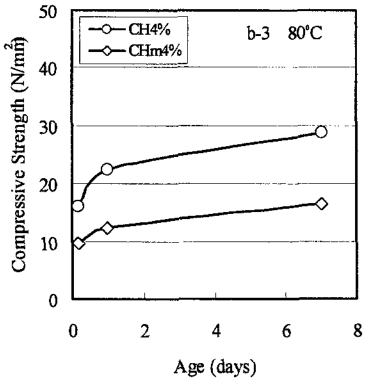

Fig.6 Comparing Compressive Strength with Commercially Available Calcium Hydroxide (CHm4%)

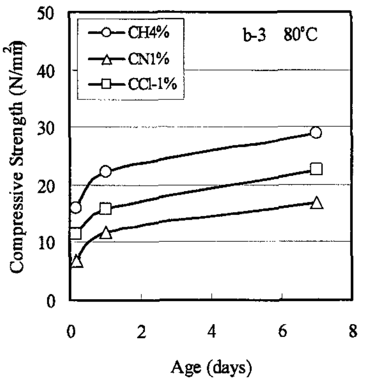

Fig.7 Comparing Compressive Strength with Other Accelerators (CN1%, CCl-1%)

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