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METHOD OF IMMEDIATE ESTIMATION OF CONCRETE STRENGTH

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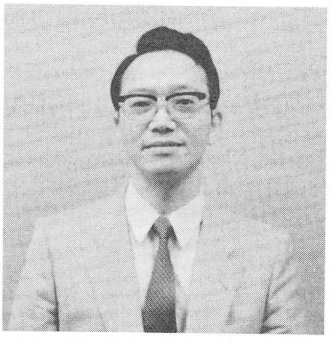

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SYNOPSIS

The method of immediate estimation of concrete strength using rapid hardening process is a method which can estimate concrete strength within about 1.5 hr after getting a sample from fresh concrete by means of compression test of rapidly hardened specimens. The rapidly hardened strength of specimens can be obtained by using the combination of the addition of accelerator and the high temperature curing. The strength of rapidly hardened mortar specimens which are obtained by wet-screening of concrete is clearly dependent on the water-cement ratio of concrete. Thus, there is a high correlation between the 28-day strength of concrete and the strength of rapidly hardened mortar specimen.
Practicability of this method was ascertained at the field test using a portable curing chamber and a small compression testing apparatus.

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1. INTRODUCTION

It seems to be one of the most urgent matters for concrete engineers to establish a rational method of an earlier estimation of concrete strength in relation to the inspection and quality control of concrete.
The three points which must be satisfied for the practical method of early determination of concrete strength are (1) rapidity for doing subsequent actions, (2) reliability of the test results, and (3) economy and simplicity of testing.
The method of immediate estimation of concrete strength using rapid hardening process is a method which can estimate concrete strength by means of compression test of rapidly hardened specimens within about 1.5 hr after getting a sample from fresh concrete(1).
The strength of rapidly hardened specimens can be obtained by using the combination of the addition of accelerating admixture and high temperature curing process.
This method has been confirmed to be an adequate method to fulfill the above-mentioned three points through the laboratory and field tests as described below.

2. PROCESS OF RAPID HARDENING

The mortar is obtained by wet-screening the fresh concrete using 5 mm sieve. The quantity of accelerator to add in the mortar is about 1 percent of mortar weight. After accelerator-mixed mortar is cast in the small mold , the specimen is cured in the chamber of 70 C 100 percent relative humidity in more than 50 minutes. The size of the rapidly hardened mortar specimen used in the figures of this paper is 4 cm x 4 cm x7.5 cm prism.
The cubic strength is obtained by compressing the 4 cm x 4 cm square portion of the longer sides immediately after finishing the high temperature curing. No capping is necessary for this specimen since the side surfaces of the specimen are used at the compression test.
A smaller mold, $\sqrt{10}$ cm x $\sqrt{10}$ cm x 5 cm, was devised later which produces 10 cm^2 compressive area. This mold is not only convenient for calculation of a test result but also advantageous to shorten the curing time due to rapid heat transfer.

3. PROPERTIES OF RAPIDLY HARDENED MORTARS

The relation between compressive strength and water-cement ratio was obtained experimentally at the curing time of 1.5 hr, 3 hr, and 4.5 hr as shown in Fig. 1. The accelerator used in the experiment was market-sold one and was named here as PR1. The main components of the accelerator are sodium aluminate and sodium carbonate.
Fig. 2 shows the same results expressed in terms of the relation of strength and curing time. From these results, the increase of strength of the mortars is very large and the mortars reach fairly stable condition within few hours.
This extremely rapid strength acquisition is completely due to the effect of the combination of accelerator and high temperature curing.
Furthermore, the strength of rapidly hardened mortar at each curing time is linearly dependent on the cement-water ratio of the mortar.

Fig. 3 shows an experimental result concerning the effect of accelerating admixture (PR1) varying the content from 0 to 6 percent of cement weight. In this figure, rather insensitive effect due to the change of quantity of accelerator on the strength of mortar can be seen when the quantity of accelerator exceeds about 3.5 percent of cement content.
This phenomenon is considered to become an important background of the method of immediate estimation of concrete strength since the content of cement in the concrete to be tested is generally different for each mix proportion.

Influences of elapsed time from the mixing of concrete, difference of the ratio of sand-cement content, and the inclusion of air-entrained or water-reducing admixture are also examined and these influences are found to be sufficiently small compared with the difference of water-cement ratio of the mortar.
For instance, the strength of rapidly hardened mortar is affected little by the elapsed time from the mixing as shown in Fig. 4.

However, in cases of inclusion of 2 percent cement weight of sugar or inclusion 3 percent cement weight of water-reducing admixture, the rapidly hardened mortar could not gain any strength even at 4.5 hr curing. Therefore, this method can detect the defective concrete which includes

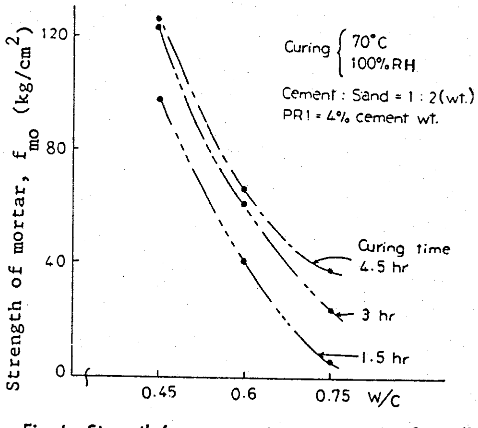

Fig. 1—Strength f_{mo} versus water-cement ratio of rapidly hardened mortars

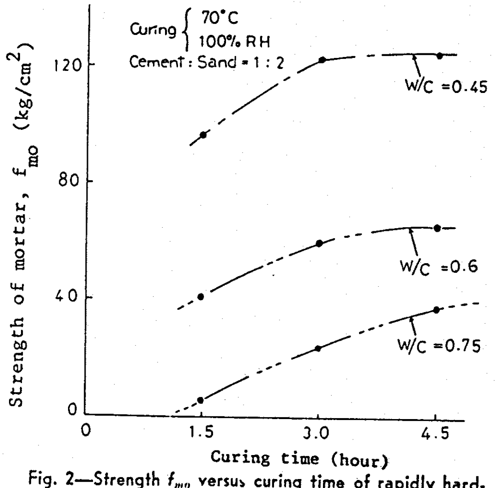

Fig. 2—Strength f_{mo} versus curing time of rapidly hardened mortars

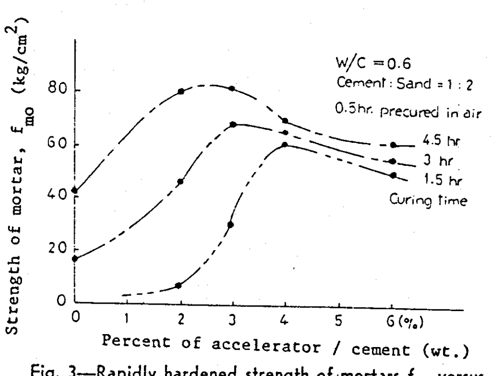

Fig. 3—Rapidly hardened strength of mortars f_{mo} versus quantity of accelerating admixture PR1 added as the percent of cement weight

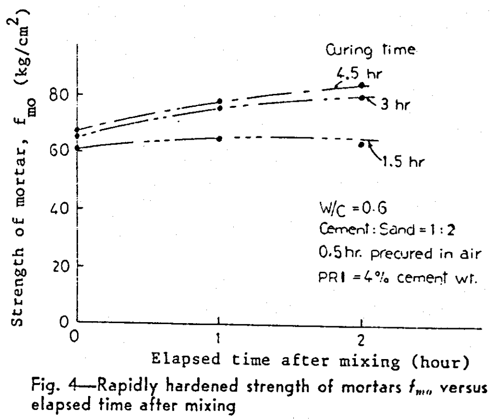

Fig. 4—Rapidly hardened strength of mortars f_{mo} versus elapsed time after mixing

harmful materials such as sugar, a large amount of admixtures, and so on.

4. AERATION OF CEMENT AND IMPROVEMENT OF ACCELERATOR

When cement is stored in the condition of high temperature and moist condition ,it is easily aerated, that is, hydrated and cabonated. It is known that slight or moderate aeration does not affect the strength of ordinary concrete.
However,the strength of rapidly hardened mortar was found to be influenced greatly by the aeration of cement.
Therefore, to increase the reliability and accuracy of the rapid estimation of the concrete strength, the effect of aeration of cement must be eliminated.
As the aeration of cement is caused by the carbonation at the surface of cement particles, high alkaline substances are considered to be effective to remove the carbonation of the surface of cement particles(2).
To analyze the influence of aeration and the effect of high alkaline substance on the rapidly hardened mortar, an experiment was done by changing the kind and quantity of high alkaline substances ,the water-cement ratio, and the rate of aeration of cement.
High alkalies used in this experiment were sodium hydroxide and potassium hydroxide. Aeration of cement was done in the atmosphere of 20 C 80 percent relative humidity through 2 days.

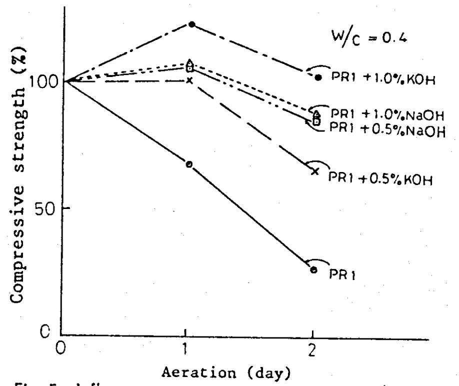

Fig. 5—Influence of the aeration of cement on the compressive strength of rapidly hardened mortar, and the effect of the improvement of accelerator ($W/C = 0.4$, curing time = 1.5 hr)

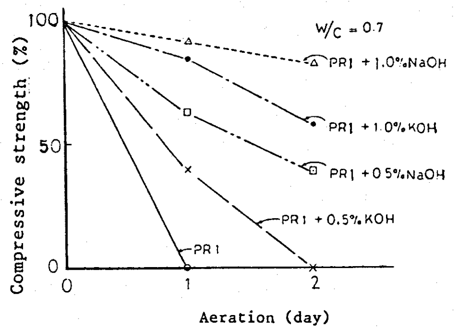

Fig. 6—Influence of the aeration of cement on the compressive strength of rapidly hardened mortar, and the effect of the improvement of accelerator ($W/C = 0.7$, curing time = 1.5 hr)

Fig. 5 shows the experimental result of the change of the strength of rapidly hardened mortar having water-cement ratio of 0.4 at the age of 1.5 hr.
In this figure, rapidly hardened mortar made with the accelerator "PR1" shows definite strength decline with respect to the rate of aeration, and that sodium hydroxide and potassium hydroxide are quite effective to eliminate the influence of aeration of cement.
Fig. 6 shows the similar result in the case of a water-cement ratio of 0.7.
The strength decline of rapidly hardened mortar having 0.7 water-cement ratio is more distinctive than the case of 0.4 water-cement ratio.
The effectiveness of high alkalies is quite clear in these figures as was expected.
The 28-day strength of ordinarily cured mortar made of cement as similarly aerated as above was examined. As the result, it was 78 percent of the strength of the mortar made of fresh cement in the case of 2-day aeration and 0.7 water-cement ratio.
Therefore, to correspond with the strength decline of ordinary concrete made with aerated cement, sodium hydroxide of 1 percent cement weight in addition

to the accelerator(PR1) is considered to be suitable for improvement of accelerator against the influence of aeration with reference to Fig. 5 and Fig. 6.

5. FORMULATION FOR THE ESTIMATION OF CONCRETE STRENGTH

The 28-day strength of standard specimen f'_{c28} is generally expressed by the function of cement-water ratio C/W as follows:

$$f_c'{}_{28} = k_1 \frac{C}{W} + k_2 \qquad (1)$$

where k_1 and k_2 are constants.
The strength of the rapidly hardened mortar f_{mo} the mortar of which is mixed as mortar proper is as follows:

$$f_{mo} = m_{o1} \frac{C}{W} + m_{o2} \qquad (2)$$

where m_{o1} and m_{o2} are constants.
The rapidly hardened strength of wet-screened mortar f_m which is affected by a wet-screening process is expressed in terms of the rapidly hardened strength of mortar proper f_{mo} having the same water-cement ratio as follows:

$$f_m = a_1 f_{mo} + a_2 \qquad (3)$$

where a_1 and a_2 are constants.
Combining the Eq. (1), (2), and (3), the following estimation formula can be derived to estimate the 28-day strength of concrete by knowing the rapidly hardened strength of mortar wet-screened from the particular concrete.

$$f_{c28} = \frac{k_1}{a_1 m_{o1}} f_m + k_2 - \frac{a_1 m_{o2} + a_2}{a_1 m_{o1}} k_1 \qquad (4)$$

where k_1, k_2, m_{o1}, m_{o2}, a_1, and a_2 are determined by experiments.
However, k_1, k_2, a_1, and a_2 can be assumed nearly as fixed values regardless of the change of materials. Therefore, Eq. (4) can be easily established by only giving the values of m_{o1} and m_{o2} in Eq. (2).
This means that an approximate estimation formula of Eq. (4) including material peculiarities can be promptly obtained by only testing the several rapidly hardened mortars of some different water-cement ratios.

6. VERIFICATION OF THE METHOD

Reliability and accuracy of this method were examined by comparing the estimated strength with actual one.
An improved accelerator (hereafter called as PR2) which consists of 80 percent PR1 and 20 percent sodium hydroxide in weight is used. The quantity of PR2 to add is one percent of mortar weight.
Variables used in this experiment were brand of cement, kind of admixture, water-cement ratio, and workability of concrete.
Since the air content in concrete affects the strength of concrete as well as water-cement ratio, a portion of the quantity of air in concrete larger than 2.5 percent was substituted as the volume of water in Eq. (1) to eliminate the effect of air content in the expression of concrete strength. By using this scheme, strength of concrete is expressed as a function of only equivalent water-cement ratio W'/C regardless of air-entrained concrete or plain concrete.

Here, W' is an equivalent water content which accounts a portion of air content as same volume of water.

The characteristics of concretes examined in this experiment are 25 mm maximum size of aggregate, 7 to 20 cm slump, and 3.8 to 5.8 percent air content.

Fig. 7 is the test result of the relationships between 28-day cylinder strength of concrete and the equivalent cement-water ratio . As seen in this figure, the expression using equivalent cement-water ratio is considered to be appropriate for obtaining a linear relationship. The coefficients in the Eq. (1) can be determined by using least square method as shown in Fig. 7.

In the same way, strength of rapidly hardened mortar is expressed by using equivalent cement-water ratio as shown in Fig. 8.

The wet-screening effect as expressed in Eq.(3) was determined in this experiment as follows:

$$f_m = 0.94\, f_{mo} + 7 \ (\text{kgf/cm}^2) \qquad (5)$$

To combine the relation of Fig.7, 8, and Eq.(5) the formula of estimation of 28-day concrete strength at 1.5 hr expressed by Eq.(4) can be obtained as follows:

$$f_c{}'_{28} = 3.77\, f_{m1.5h} + 93 \ (\text{kgf/cm}^2) \qquad (6)$$

where f'_{c28} : estimated strength of the concrete of 28-day by 1.5 hr test
$f_{m1 \cdot 5h}$: strength of rapidly hardened wet-screened mortar tested at 1.5 hr curing.

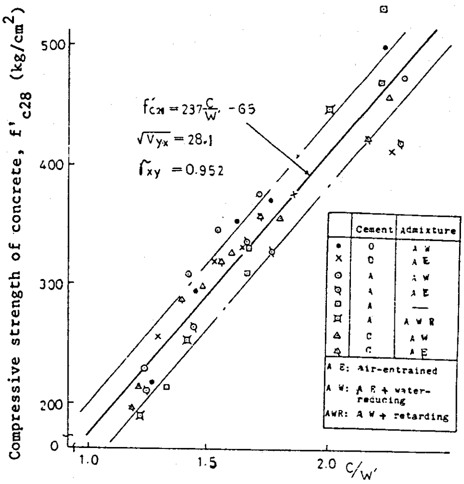

Fig. 7—Experimental result of the 28-day compressive strength of concretes $f_c{}'_{28}$ versus equivalent cement-water ratio C/W'

Fig. 9 shows the experimental result of the relationships of the actual 28-day strength and the strength of 1.5 hr rapidly hardened wet-screened mortar where calculated formula of Eq.(6) is shown for comparison with the

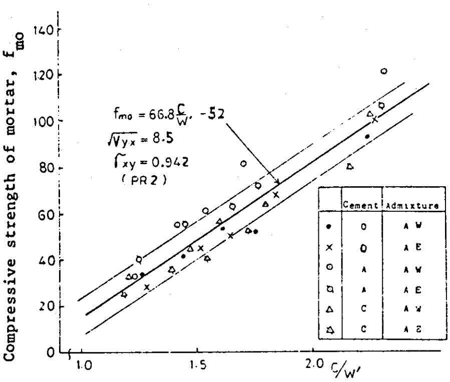

Fig. 8—Experimental result of the 1.5 hr compressive strength of rapidly hardened mortars f_{mo} versus equivalent cement-water ratio C/W'

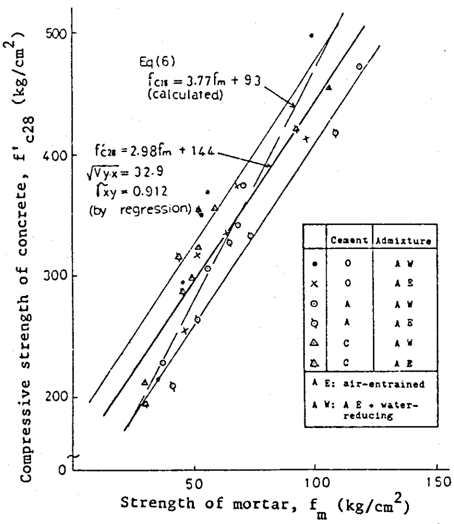

Fig. 9—28-day compressive strength of concretes $f_c{}'_{28}$ versus 1.5 hr compressive strength of wet-screened rapidly hardened mortars f_m

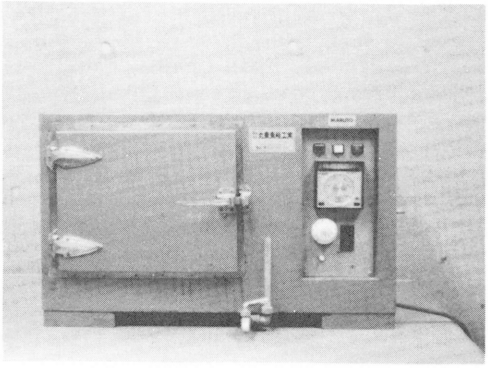

Fig. 10 - Portable curing chamber

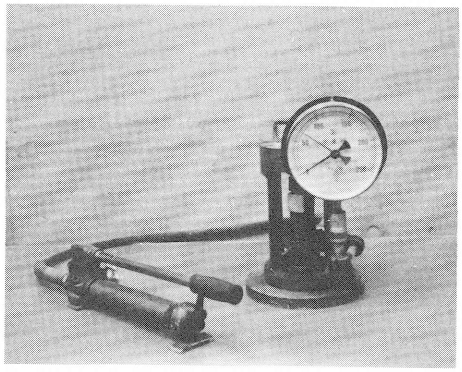

Fig. 11 - Portable compression testing machine

least square formula from the test result. Here, coefficient of correlation is 0.912 and the correlation between the strength of concrete and the rapidly hardened mortar is quite high although the data includes different brands of ordinary portland cement, different air-entraining admixures, and so on.
The coefficient of variation of the ratio of estimated values calculated by Eq.(6) to the actual values is about 10 percent. This coefficient of variation is about 7 percent when calculated individually for the brand of cement and admixture used.

7. PORTABLE TEST APPARATUS AND IMPROVEMENT OF THE METHOD

A portable curing chamber and a manual compression testing machine were designed and manufactured as shown in Fig. 10 and Fig. 11 to apply this method at actual construction sites.
Since it is desired to know the test result as soon as possible, shortening of curing time was studied
By utilyzing $\sqrt{10}$ x $\sqrt{10}$ x 5 (cm) small specimens, 50 minutes of curing at 80 C temperature was found to be adequate to get reliable test data.
In this case, the required time of testing from getting concrete sample to estimating concrete strength can be reduced to about 1 hour.

8. CONCLUSION

(1) The rapid strength increase of mortar was obtained by combining the accelerator and high temperature curing. The strength of rapidly hardened mortar was found to be determined by the water-cement ratio of the mortar.
(2) Though the strength of rapidly hardened mortar was remarkably affected by the rate of aeration of cement, addition of sodium hydroxide to market-sold accelerator was found to be quite effective to eliminate the influence of the aeration of cement.
(3) The 28-day strength of concrete was estimated only after 1.5 hr curing with coefficient of variation of about 10 percent regardless of the brand of cement and admixture. This coefficient was about 7 percent when calculated for the concrete made of same brand of cement and admixture.
(4) As this method is based on the strength test of the hydrated specimens, deffective concretes such as the concrete including harmful materials for hardening or the concrete made with defective cement can be definitely detected

within about 1.5 hr from getting sample from the fresh concrete.
By using the improved method, this time is about 1 hour.
(5) Portable test aparatus are available for this method. This means that the inspection of concrete at construction sites using this method can be executed easily and economically.

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