

Curing planning method based on cement hydration analysis - Consideration of compatibility with productivity and low carbonization-

セメントの水和解析に基づく養生計画立案手法
ー生産性および低炭素化との両立に関する検討ー

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概 要

コンクリートの養生は、要求される性能を有するコンクリート構造物を構築するために非常に重要な作業工程である。養生の重要性は広く認識されているものの、合理的な養生計画手法は存在しないというのが一般的な認識である。このような背景から、筆者らは「セメント水和解析に基づく養生計画手法」を提案してきた。この手法では、養生によって達成されるセメントの水和を解析によって予測し、要求される性能を確保するための目標水和率が得られるように養生期間を算定する。一方、コンクリート工事の生産性向上が課題となっている中、性能を確保するための養生期間を求めるだけでは不十分である。そこで、生産性と性能の両方を考慮した養生計画手法を検討した。さらに、カーボンニュートラルの実現には、低炭素セメントの利用拡大が急務となっている。低炭素セメントは強度発現が遅いため養生期間を延長する必要がある、生産性の低下が懸念される。

以上の背景から、生産性と低炭素化の両立を考慮した養生計画の立案手法を検討した。検討の結果、設計材齢を適切に設定することで、生産性との両立が可能であることを示した。そこで、養生期間を制御するための設計材齢の算出方法を検討し、算出した設計材齢に基づいて配合を修正する方法を検討した。その結果、算出した設計材齢と圧縮強度および物質移動抵抗の算定式から、生産性と性能を両立する配合を修正できることが示された。そして、低炭素セメントを使用する場合でも、設計材齢を適切に設定することで、低炭素化と生産性向上を両立した養生計画を立案できることが示された。また、様々な条件下での具体的な計算例を示し、提案する養生計画方法によれば低炭素化と生産性・性能を両立できることが示された。

1. INTRODUCTION

Curing of concrete is a very important work process for constructing a concrete structure with the required performance^{1),2),3)}. The authors have proposed “Curing planning method based on cement hydration analysis”^{4),5)}. The proposed method is based on the original purpose of curing and calculates the curing period from the viewpoint of sufficiently promoting cement hydration. That is, the curing period is calculated so that the hydration rate calculated by the cement hydration analysis reaches the target hydration rate for satisfying the required performance of concrete. Based on the investigations so far, it has been confirmed that it is possible to formulate a curing plan rationally according to the structural conditions, concrete conditions and construction environmental conditions⁵⁾.

On the other hand, in the construction industry, improving productivity has become an important issue. In particular, it has been pointed out that the productivity of concrete works is low, and efforts to improve the productivity of concrete works have been studied from various viewpoints. Securing the curing period to ensure performance may also be one of the reasons why the productivity of concrete works has not improved. In addition, there is an urgent need to expand the use of low-carbon cement for carbon neutrality. There are

concerns that low-carbon cement may require a long curing period due to the high content of admixtures such as ground granulated blast furnace slag BFS and fly ash FA, which deteriorates initial strength development.

As mentioned above, it is not enough to find the curing conditions for securing the performance, and in the future, it is required to develop a curing planning method that aims at both productivity improvement and low carbonization. By applying the proposed “Curing planning method based on cement hydration analysis”, it is considered possible to find a method to achieve both productivity improvement by shortening the curing period and ensuring the performance of the structure.

From the above background, the purpose of this study is to develop a curing planning method that considers both productivity improvement, low-carbonization and performance securing. In this paper, we first introduce “Curing planning method based on cement hydration analysis”. Next, we will introduce the specific methods of curing planning methods that consider both productivity and low-carbonization and ensuring performance. In addition, we present examples of curing plans under various conditions, and show that it is possible to rationally formulate a curing plan that takes into account both productivity and low-carbonization and performance assurance.

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2. CURING PLANING METHOD BASED ON CEMENT HYDRATION ANALYSIS

2.1 Basic concept

In the proposed method, the hydration rate of cement is analytically predicted, and a curing plan is formulated so as to satisfy the target hydration rate. Here, the target hydration rate is the hydration rate that should reach in order to satisfy the required performance of concrete. First, after setting the boundary conditions according to the curing method and construction environmental conditions, the moisture distribution in the structure during the curing process and after curing is predicted by moisture migration analysis. Hydration analysis is performed based on the obtained moisture distribution, and the hydration rate of cement in each part of the structure is calculated. Then, the validity of the curing method and curing period is confirmed by comparing the hydration rate obtained by hydration analysis with the target hydration rate.

2.2 Cement hydration analysis program

For cement hydration analysis, the thermodynamic coupled analysis system DuCOM for Structural Design^(6,7) will be used. DuCOM is a finite element analysis program that can trace the formation process of concrete up to the start of service and the progress of deterioration in the environment after service on the time-space axis for any material, mixture proportion, and environmental conditions. Considering the mass transfer and temperature change in the one-dimensional field from the surface of the structural member toward the inside, it analyses by coupling the basic model of the hydration reaction of cement, the formation of pore structure, and the water retention and transfer model. It is possible to track the hydration rate of each site. In other words, DuCOM can track the water content in the depth direction of the member by analyzing the moisture supply and retention behavior during the curing process and the moisture dissipation behavior after curing. Furthermore, in the hydration exothermic model, the reduction in heat generation rate due to the reduction in free water (hydrate precipitation space) is formulated by reducing the opportunity for contact between the reaction surfaces of cement particles and free water. Therefore, it is possible to analyze the hydration considering the effect of the hydration state during and after curing on the progress of hydration. Here, the hydration rate is the ratio of the accumulated calorific value calculated by the hydration exothermic model to the final calorific value. The cumulative calorific value is calculated for each of the four types of cement minerals (C_3S , C_2S , C_3A , C_4AF) and admixture (ground granulated blast furnace slag, fly ash)⁽⁸⁾. Furthermore, considering the cumulative calorific value and mineral composition, the average hydration rate is calculated by Eq. (1) as the hydration rate⁽⁹⁾.

Hydration rate =

$$\frac{\sum \text{Cumulative calorific value}}{\text{Final calorific value}} \times \text{mineral composition} \quad (1)$$

In DuCOM, curing conditions and environmental conditions after curing can be set by giving boundary conditions for the inflow and outflow of heat and water, that is, thermal boundary conditions and moisture boundary conditions. Moisture boundary conditions basically give the relative humidity of the air in contact with the concrete surface, that is, the relative humidity of the space between the concrete surface and the curing material.

2.3 Setting the basic conditions for calculating the required curing period

In calculating the required curing period, it is necessary to set the basic conditions shown below.

(1) Setting the design age that defines the target

Hereinafter, the material age that defines the target hydration rate is referred to as “**design age**”. It is appropriate to set the design age as the age when evaluating the performance of concrete, and the hydration rate reached at that age as the target hydration rate. For example, compressive strength is generally evaluated at the age of 28 days. Therefore, in this case, the design age is 28 days, and the target hydration rate is the hydration rate achieved when the standard underwater curing is performed for 28 days.

(2) Setting the achieved age

In order to calculate the required curing period, it is necessary to determine when the target hydration rate will be achieved (hereinafter referred to as “**the achieved age**”). Although there is a possibility that hydration will progress even after the start of service due to the water supply effect of rainfall, there are many uncertainties, so we should not expect this effect when formulating a curing plan. Therefore, it is essential to satisfy the required performance before the start of service. Since it would be complicated to set for each member with different construction times, it is appropriate to set the achieved age to 91 days to half a year on the safe side.

(3) Setting the evaluation depth

After curing, water escapes from the concrete surface, so the water content varies depending on the depth from the surface. Therefore, it is necessary to determine to what depth from the surface (hereinafter referred to as **evaluation depth**) the hydration rate is to be evaluated. When setting the evaluation depth, the performance required for concrete. In addition, it is necessary to consider the cover of reinforcing bars and the dimensions of the structure. It is checked whether the average value of the hydration rate at the set evaluation depth satisfies the target hydration rate.

2.4 Concept of calculating the required curing period

Figure 1 shows the concept of the required curing period. This figure shows an example in which the design age is 28 days, and the achieved age is 91 days. The black solid line indicates the hydration rate in the case of standard underwater curing for the entire period, and the target hydration rate is the hydration rate (broken line) at the age of 28 days. The solid red line shows the progression of hydration upon exposure to air after a certain period of wet curing. As shown in the figure, the hydration rate reached the target hydration rate at the age

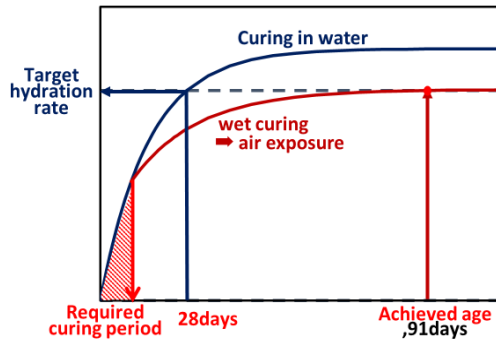


Figure 1. Concept of the required curing period³⁾

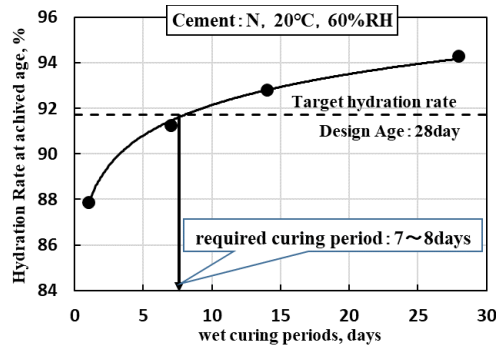


Figure 2. Relationship between the wet curing period and the hydration rate³⁾

of 91 days. So, this wet curing period is the required curing period.

2.5 Method of calculating the required curing period

Hydration analysis is performed with various curing periods, and the hydration rate at the achieved age is calculated for each curing period. Next, regarding the relationship between the curing period and the hydration rate, the curing period that satisfies the target hydration rate is the required curing period. **Figure 2** shows the relationship between the water curing period and the hydration rate at the achieved age. The dashed line indicates the target hydration rate, and it can be seen that curing for 7 days or more is necessary to satisfy the target hydration rate. Therefore, the required curing period is calculated to be 7 days.

3. BASIC CONCEPT FOR ACHIEVING BOTH PRODUCTIVITY AND PERFORMANCE

3.1 Shortening the required curing period by adjusting the design age

Figure 3 shows an example of calculating the required curing period. In this example, with a design age of 28 days, the required curing period is calculated to be about 7 days at an ambient temperature of 20°C and about 25 days at 10°C. When the ambient temperature drops below 10°C, the progress of hydration of cement is delayed, indicating that long-term curing is necessary to ensure the performance of concrete. By shortening the design age to 21 or 14 days, the target hydration rate is lowered and the required curing period is shortened¹⁰⁾. Therefore, even in a low-temperature environment, it is possible to shorten the curing period by appropriately

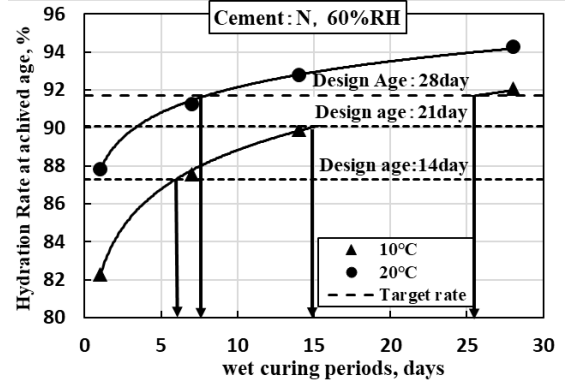


Figure 3. Relationship between the wet curing period and the hydration rate at the achieved age¹⁰⁾

setting the design age. Specifically, by shortening the design age, a mixture with a low water-cement ratio can be selected, and the required performance can be satisfied without extending the curing period.

3.2 Adjusting method for design age

In previous research, we evaluated the influence of various factors on the required curing period and showed that the required curing period can be calculated appropriately using the equation shown below^{11),12)}. C_p is the required curing period and can be calculated by multiplying the required curing period C_{p0} of the standard conditions by the influence coefficient for each factor.

$$C_p = \alpha_c \cdot \alpha_m \cdot \alpha_t \cdot \alpha_r \cdot \alpha_d \cdot \alpha_{temp} \cdot \alpha_{RH} \cdot C_{p0} \quad (2)$$

α_c : Influence coefficient for cement type

α_m : Influence coefficient for water-cement ratio

α_t : Influence coefficient for design age

α_r : Influence coefficient for achieved age

α_d : Influence coefficient for evaluation depth

α_{temp} : Influence coefficient for environmental temperature

α_{RH} : Influence coefficient for environmental humidity

Here, the standard conditions are as follows. Cement type: Ordinary Portland cement, Water cement ratio: 50%, Evaluation depth: 5 cm, Design age: 28 days, Achieved age: 91 days, Environmental conditions: Temperature 20°C, Humidity 60% RH

From the above calculation equation, it is also possible to select the conditions so that the curing period is appropriate for productivity. It is rational to consider setting the design age when considering the construction plan. Specifically, it is possible to suppress the extension of the required curing period by adjusting the coefficient α_t related to the design age in **Eq.(1)**. It is also possible to adjust the design age so that the required curing period is appropriate. Here, in past research¹⁰⁾, a equation for calculating the influence coefficient α_t for the design age t_d has been obtained.(See **Figure 4**). The equation is expressed in **Eq.(3)**.

$$\alpha_t = 0.0834 \cdot \exp(0.0883 \cdot t_d) \quad (3)$$

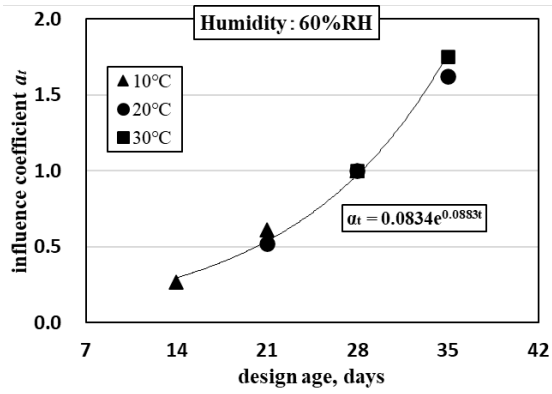


Figure 4. Relationship between the influence coefficient and design age¹⁰⁾

From the Eq.(3), the design age t_d for shortening the curing period can be calculated by adjusting the influence coefficient α_t .

$$t_d = \frac{\ln(\alpha_t / 0.0834)}{0.0883} \quad (4)$$

3.3 Mixture proportion correction method

The previous chapter showed how to adjust the design age t_d to shorten the required curing period. Strictly speaking, it is necessary to design the mixture proportion so that the required performance can be obtained at the adjusted design age. However, it is not rational to design a mixture proportion for each adjusted design age. In this section, we will study a realistic method of mixture proportion correction.

(1) Development of equations for calculating compressive strength and mass transfer resistance

Here, the required performance includes compressive strength and mass transfer resistance. Therefore, the mixture proportion of concrete will be corrected to satisfy these performances at the adjusted design age. For this purpose, equations for calculating compressive strength and an equation for mass transfer resistance, which use a material age and a parameter of mixture proportion as variables, will be developed. Here, the cement-water ratio or the water-cement ratio was adopted as a parameter of mixture proportion.

(2) Investigation of mixture proportion correction method

From the adjusted design age, compressive strength, and mass transfer resistance calculation equation, we will consider a correction method so that the mixture proportion satisfies the performance.

3.4 Development of equations for calculating compressive strength and mass transfer resistance

(1) Test outline

Three types of cement commonly used for structures, ordinary portland cement(N), blast furnace cement type B(BB) and fly ash cement type B(FAB) were used. And blast furnace cement type C(BC) as low carbon cement were used. Here, the mixing ratio of blast furnace slag is 70%. The water-cement ratio was set

at three levels of 40, 50 and 60%. The curing conditions were standard underwater curing ($20 \pm 2^\circ\text{C}$), and compressive strength tests were conducted at ages of 7, 14, 28 and 91 days. The surface layer air permeability coefficient (Trent method) was measured. The specimen was a cube with 200 mm sides. Standard underwater curing periods were 3, 7, and 28 days, and after curing the specimens were placed in a constant temperature and humidity chamber at 20°C and 60% RH, and the surface air permeability of the four sides was measured at the age of 91 days.

(2) Derivation of compressive strength calculation equation

In order to make it possible to correct the mixture proportion from the design age, it is better to use the material age t and the cement-water ratio C/W as variables. It is also known that the compressive strength has a linear relationship with the logarithm of the material age and a linear relationship with the cement-water ratio. Therefore, a linear expression of the logarithm of the material age t used, and the coefficient of the expression was a linear expression of C/W . The compressive strength calculation equation is as follows.

$$f'c = (A1 \cdot C/W + B1) \ln(t) + A2 \cdot C/W + B2 \quad (5)$$

The equation for calculating the compressive strength of each cement is shown below.

• N :

$$f'c = (1.13C/W + 3.61) \ln(t) + 22.9C/W - 26.5 \quad (6)$$

• BB :

$$f'c = (1.13C/W + 6.35) \ln(t) + 22.7C/W - 36.7 \quad (7)$$

• FAB :

$$f'c = (1.84C/W + 2.65) \ln(t) + 17.9C/W - 25.3 \quad (8)$$

• BC :

$$f'c = (3.05C/W + 4.56) \ln(t) + 9.59C/W - 21.0 \quad (9)$$

(3) Derivation of Surface Permeability Calculation Equation

Figure 5 shows the relationship between the hydration rate of the surface layer and the surface air permeability coefficient. Since it is used for mixture proportion correction, the calculation equation must be a function of material age t . Therefore, through hydration analysis using DuCOM, the relationship between material age and hydration rate in standard underwater curing was determined. Based on this relationship, the hydration rate at the time of surface layer permeability measurement was converted to material age. The obtained material age is called the equivalent material age.

Figures 6 show the relationship between the equivalent material age and the surface air permeability coefficient. Since the logarithm of the material age and the logarithm of the surface layer permeability coefficient are in a linear relationship, the equation for calculating the surface layer permeability coefficient is as follows.

$$\log(kT) = (A1 \cdot W/C + B1) \cdot \log(t) + A2 \cdot W/C + B2 \quad (10)$$

The equation for calculating the surface permeability of each cement obtained is shown below (See Figure 6).

$$\begin{aligned} \bullet \text{ N} : \log(kT) &= (-0.00419 W/C - 0.9294) \log(t) \\ &\quad + 0.02278 W/C - 0.5828 \quad (11) \end{aligned}$$

$$\begin{aligned} \bullet \text{ BB} : \log(kT) &= (-0.01152 W/C - 0.4329) \log(t) \\ &\quad + 0.04739 W/C - 2.5549 \quad (12) \end{aligned}$$

$$\begin{aligned} \bullet \text{ FAB} : \log(kT) &= (-0.02814 W/C + 0.2362) \log(t) \\ &\quad + 0.06932 W/C - 3.0120 \quad (13) \end{aligned}$$

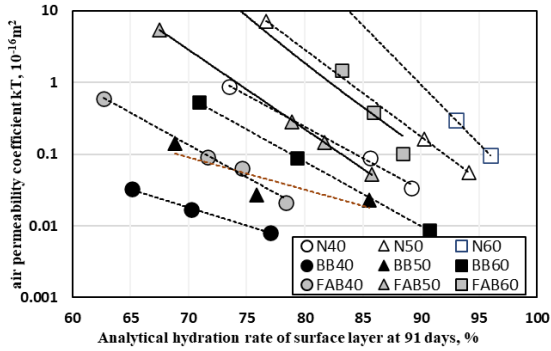


Figure 5. Relationship between the hydration rate of the surface layer and the air permeability coefficient

$$\begin{aligned} \bullet \text{ BC} : \log(kT) &= (-0.04701 W/C + 1.280) \log(t) \\ &\quad + 0.1209 W/C - 5.784 \quad (14) \end{aligned}$$

3.5 Development of equations for calculating compressive strength and mass transfer resistance

(1) Consideration from the perspective of ensuring compressive strength

The following equation is substituted into the compressive strength calculation equation with the premium factor and the design strength $f'ck$.

$$f'c = \alpha \cdot f'ck \quad (15)$$

The premium coefficient α shall be calculated by the following equation.

$$\alpha = \frac{1}{1 - 1.645 V / 100} \quad (16)$$

Here, V: coefficient of variation (%)

By substituting the design age t_d and design strength $f'ck$ (Eq.(15)) calculated from Eq.(4) into the compressive strength calculation equation (Eq.(5)), the water-cement ratio W/C can be calculated.

$$W/C = \frac{A1 \cdot \ln(t_d) + A2}{\alpha \cdot f'ck - B1 \cdot \ln(t_d) - B2} \quad (17)$$

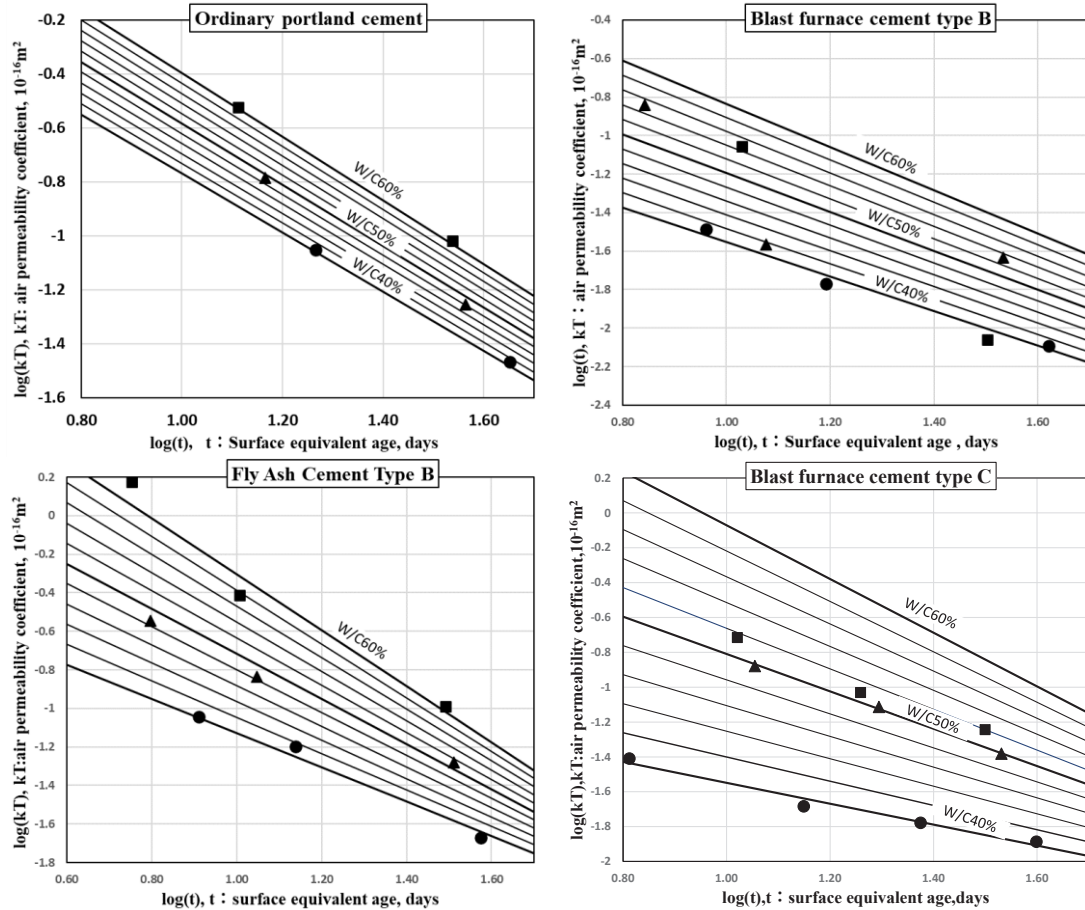


Figure 6. Relationship between the surface equivalent age and the air permeability coefficient

Since it is practical to change the nominal strength in general construction work, the nominal strength is calculated as the compressive strength of the calculated water-cement ratio at a material age of 28 days.

Nominal strength

$$= \{(A1/(W/C)+B1) \cdot \ln(28)+A2/(W/C)+B2\} / \alpha \quad (18)$$

(2) Consideration from the perspective of securing mass transfer resistance

It is ideal to give a specific surface air permeability coefficient in the same way as for compressive strength. However, it is difficult to set on a clear basis. Therefore, the following procedure was used to examine the method of correcting the mixture proportion.

1) Estimation of the water-cement ratio of the original mixture

From the design strength f'_{ck} and the compressive strength equation (Eq.(5)), estimate the water-cement ratio W/C_0 of the original mixture.

$$W/C_0 = \frac{A1 \cdot \ln(28) + A2}{\alpha \cdot f'_{ck} - B1 \cdot \ln(28) - B2} \quad (19)$$

2) Estimation of the surface permeability coefficient of the original mixture

Estimate the surface layer air permeability coefficient kT_0 of the original mixture from the calculated water-cement ratio W/C_0 of the original mixture and Eq. (10).

$$\log(kT_0) = (A1 \cdot W/C_0 + B1) \log(28) + A2 \cdot W/C_0 - B2 \quad (20)$$

3) Calculation of W/C

Calculate the W/C that secures the same surface permeability coefficient kT_0 as the original mixture at the design age t_d using Eq. (10).

$$W/C = \frac{\log(kT_0) - B1 \cdot \log(t_d) - B2}{A1 \cdot \log(t_d) + A2} \quad (21)$$

4) Calculation of nominal strength

Calculate the nominal strength from the calculated W/C (Eq. (18)).

$$\text{Nominal strength} = \{(A1/(W/C)+B1) \cdot \ln(28)+A2/(W/C)+B2\} / \alpha \quad (22)$$

4. EXAMPLES OF CALCULATIONS

4.1 Method of shortening to arbitrary curing period

Consider shortening the curing period to an arbitrary period. Here, for the sake of simplification, let us consider a case where the curing period is shortened to an arbitrary period under standard conditions. The influence coefficient α_t for an arbitrary curing period C_{popt} is as follows.

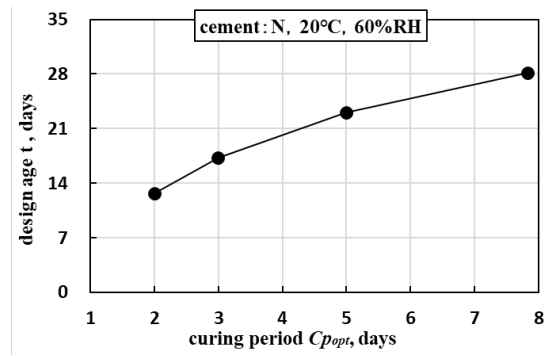


Figure 7. Relationship between the curing period and design age

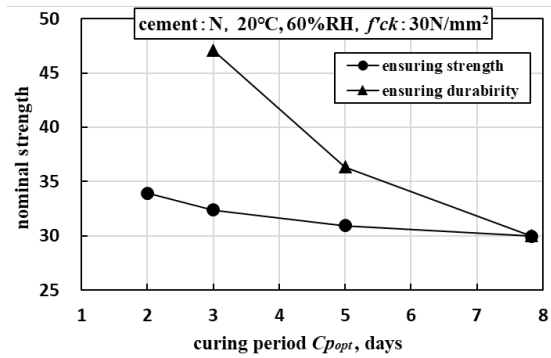


Figure 8. Relationship between the curing period and nominal strength

$$\alpha_t = \frac{C_{popt}}{C_{p0}} \quad (23)$$

The design age t_d for an arbitrary curing period C_{popt} can be calculated from the above Eqs. (3) and (4). Figure 7 shows the relationship between curing period and design age. From the calculated design age, the nominal strength can be calculated in the same procedure as above. Figure 8 shows the calculation results of the nominal strength. It can be said that it was shown that the correction of the nominal strength for shortening the curing period to an arbitrary period can be reasonably calculated. In the case of securing compressive strength, the correction of nominal strength is about 5 or less, but in the case of securing durability, the calculation result shows that a large correction of nominal strength is necessary. This indicates that it is necessary to secure an appropriate curing period without shortening the curing period when ensuring durability is required.

4.2 Examination of compatibility between low carbonization and productivity

The most effective way for low carbonization of concrete is to increase the blending ratio of fine mineral admixtures such as granulated blast furnace slag and fly ash. However, due to the high content of admixtures such as ground granulated blast furnace slag BFS and fly ash FA the initial strength development deteriorates, so that the curing period needs to be extended. It is necessary to further increase the blending ratio for low

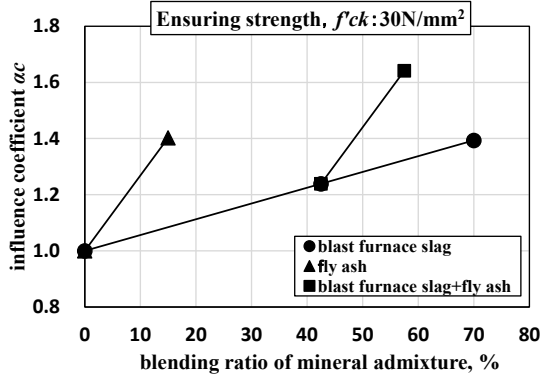


Figure 9. Relationship between the blending ratio of admixtures and the correction factor of cement type

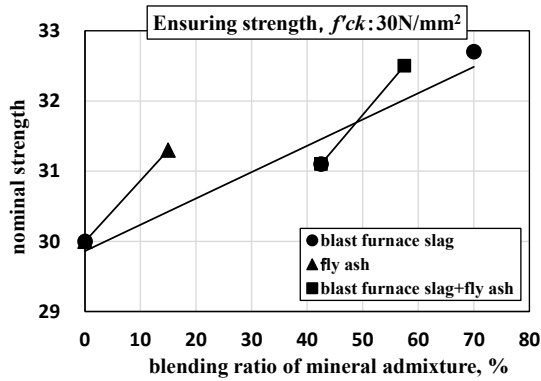


Figure 10. Relationship between the blending ratio of admixtures and the nominal strength

carbonization, and there is concern that productivity will decrease due to the extension of the curing period. Here, a method of ensuring productivity even when using low-carbon cement, that is, a method of not extending the curing period, will be examined. As the blending ratio of the blended admixture can be increased, the carbon content can be reduced. As in the previous studies, we consider the case where the curing period is constant when only the type of cement is changed under the standard conditions. In order to keep the curing period constant regardless of the type of cement, the influence factor α_t for the design age is calculated as follows.

$$\alpha_t = \frac{1.0}{\alpha_c} \quad (24)$$

Here, in the case of blended cement, the influence coefficient for the type of cement can be expressed as a function of the blending ratio of the admixtures. **Figure 9** shows the relationship between the blending ratio of the admixtures and the influence factor for the type of cement. In addition, the calculation equation of the influence factor for cement type is shown below.

$$\alpha_c = 0.005619 \cdot BS + 0.02682 \cdot FA + 1.0 \quad (25)$$

Here, BS: Blending ratio of ground granulated blast furnace slag (%), FA: Blending ratio of fly ash (%)

It is possible to calculate the nominal strength for keeping the curing period constant by the same procedure as the previous studies. **Figure 10** shows the calculation results of the nominal strength. Even when low carbon cement is used, it is possible to calculate the nominal strength for the same curing period as for ordinary cement. As described above, it was confirmed that the correction value of the nominal strength for securing the performance without extending the curing period can be reasonably calculated even when using blended cement to achieve low carbonization. In other words, it was confirmed that the nominal strength correction value for ensuring both low carbonization and productivity can be reasonably calculated.

5. CONCLUSIONS

Based on the Curing planning method based on cement hydration analysis, we investigated for the purpose of developing "Curing planning method considering both low carbonization and productivity". The obtained results are as follows.

- (1) We proposed a curing planning method based on cement hydration analysis. In the proposed method, the target hydration rate that should be achieved in order to satisfy the target performance of concrete is set, and the curing period is calculated so that the cement hydration rate reaches the target hydration rate.
- (2) When calculating the required curing period, we must appropriately set the age that defines the target hydration rate (design age), the age at which the target hydration rate should be achieved (achieved age), and the depth from the surface to be evaluated (evaluated depth).
- (3) It was shown that the curing period for ensuring performance can be shortened rationally by shortening the design age.
- (4) An equation for calculating compressive strength and an equation for surface air permeability coefficient were derived using material age and a parameter of mixture proportion as variables, and a method for calculating nominal strength for securing performance from the corrected value of design age was shown. In other words, a method for rationally calculating the nominal strength correction value for achieving both productivity and performance was shown.
- (5) It was confirmed that the nominal strength for shortening the curing period to an arbitrary period can be reasonably calculated.
- (6) It is possible to reasonably calculate the nominal strength for a certain period even when using low-carbon cement with a high blending ratio of admixtures such as ground granulated blast furnace slag and fly ash. In other words, we were able to develop a curing planning method that considers both low-carbonization and productivity.

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