Study on Applicability of Maturity Theory to Predict Concrete Compressive Strength under Non-standard Curing Condition

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Abstract: The curing temperature of the actual construction site, which has a greater impact on the concrete strength, often fails to meet the standard requirements. This paper studies the effect of curing temperature on concrete compressive strength from the perspective of maturity by designing four curing conditions including standard curing, high temperature curing in summer, low temperature curing in winter, and natural curing, using the artificial climate simulation room. The result shows that the relationship between compressive strength and maturity of concrete under the standard curing condition is basically in accordance with the hyperbolic model, which can be used to predict the compressive strength at different ages; however, when the curing temperature and the standard curing temperature are quite different, the hyperbolic model is no longer applicable; at this point, direct prediction of concrete compressive strength using maturity will lead to significant errors. Therefore, it is necessary to further establish a theoretical model of maturity that takes into consideration the effect of temperature in order to predict the compressive strength of concrete more accurately.

1. Introduction

It has been approved by researchers that temperature is one of the main factors affecting the strength of concrete. A. A. Ramezanianpour and V. M. Malhotra [1] have pointed out that high temperature curing is beneficial to higher strength in the early stage, but not in the long run. C. M. Aldea et al. [2] also pointed out that high temperature curing is not conducive to the long-term concrete strength by adopting the method of high temperature and high pressure curing and high temperature steam curing. Xie Youjun et al. [3] studied the development law of concrete strength under low temperature curing. Zhao Xinmin et al. [4] studied the development of concrete strength under positive and negative temperature changes. Cheng Zhiqing et al. [5] studied the early strength development of fly ash concrete under the low temperature condition. Wang Chuanxing et al. [6, 7] studied the strength of concrete under ultra-low temperature conditions. It can be found that both high temperature and low temperature have a great influence on the concrete strength.

The concept of maturity was first proposed by Nures and Saul in the mid-20th century [8,9], saying that the strength of concrete is mainly controlled by temperature and curing age. They also proposed the maturity calculation formula (Nures-Saul formula) and the idea of same maturity leading to basically the same concrete compressive strength. Later studies found out that the temperature affects the cement hydration rate to some extent. Since the Nures-Saul formula has a certain errors, the Arrhenius equation in the chemical reaction is introduced into it to bring out the concept of
“equivalent age”, which is an improvement for the maturity theory [10]. The present study on maturity is mostly based on conventional curing condition, but less on different temperature conditions, and there is little applicable result in this field.

This paper simulates the curing conditions in the actual engineering site by using the artificial climate simulation room, and studies the development law of concrete compressive strength by designing curing conditions under different temperatures. On this basis, this paper discusses the applicability of maturity theory under different temperatures.

2. Test process

2.1 Materials and mix ratio
This paper adopts P.O. 42.5 ordinary Portland cement, mixed sand, 5-20 mm artificial gravel, HQ-3 set retarding superplasticizer, which are all in compliance with the specifications. The mix ratio is shown in Table 1.

| Water-to-binder ratio | Cement/(kg) | Water/(kg) | Sand/(kg) | 5-20mm/(kg) | Sand ratio/(%) | Admixture/(%) |
|-----------------------|-------------|------------|-----------|-------------|----------------|---------------|
| 0.50                  | 400         | 200        | 756       | 924         | 45             | 2.5           |

2.2 Curing condition design
A total of four curing conditions are designed in this paper: the standard curing condition is performed in the concrete standard curing room; the non-standard curing condition is realized through the artificial climate simulation room, which can be programmed to accurately simulate the temperature and humidity test, see Figure 1. The specific curing conditions are shown in Table 2.

| No. | Curing conditions                  | Specific description                                                                 |
|-----|-----------------------------------|--------------------------------------------------------------------------------------|
| ①  | Standard curing                   | Age: 7 d; 14 d; 28 d; 56 d; 104d                                                    |
| ②  | High temperature curing in summer | Day: 35 °C; night: 20 °C; after 7 days of alternate curing, transfer to standard design to the designed age |
| ③  | Low temperature curing in winter  | Day: 15 °C; night: 5 °C; after 7 days of alternate curing, transfer to standard design to the designed age |
| ④  | Natural curing                    | Place the test block in an indoor laboratory with an average temperature of 11 °C and an average high temperature of 17 °C. |

2.3 Test content
Conduct compressive strength test on the concrete test block, which is a 150 mm cube standard block in accordance with the Hydraulic Concrete Test Procedure (SL 352-2006).
3. Result

3.1 Relationship between compressive strength and maturity under the standard curing condition

The formula for calculating the maturity $M_s$ is shown in equation (1):

$$M_s = \sum (T_i - T_0) t_i$$  (1)

$T_0$ is the reference temperature, which is taken as $-10$ °C.

The maturity and compressive strength values of different ages under the standard curing condition are shown in Table 3. The relationship between compressive strength and maturity can be reflected using a hyperbolic curve. The fitting formula is:

$$f_{cu} = \frac{M_s}{a + bM_s}$$  (2)

$a$ and $b$ are fitting parameters.

Transform Equation (2) by taking $Ms/f_{cu}$ as the ordinate and $Ms$ as the abscissa, then the two are in a linear relationship, as shown in the following formula:

$$\frac{M_s}{f_{cu}} = a + bM_s$$  (3)

For the fitting results, see Figure 2, in which $a=4.1967$, $b=0.02145$, and the correlation coefficient $R^2=0.9885$. It can be seen that the fitting result is satisfactory. According to the hyperbolic fitting model, the final compressive strength of concrete is 46.6 MPa, which is in line with its development law.

Table 3 The values of $M_s$ and $f_{cu}$ under the standard curing condition

| Maturity $/\degree\text{C} \times \text{d}$ | 140 | 280 | 560 | 1120 | 2080 |
|------------------------------------------|-----|-----|-----|------|------|
| Compressive strength /MPa               | 24.5| 29.8| 32.1| 36.4 | 44.0 |

![Figure 2: The fitting result](image)

3.2 Relationship between compressive strength and maturity under non-standard curing condition

The maturity and compressive strength values under the non-standard curing condition are shown in Table 4 and Figure 2. It can be seen from Figure 2 that the relationship between compressive strength and maturity under non-standard curing condition has deviated from the hyperbolic model, meaning that the hyperbolic theoretical model of concrete compressive strength and maturity established based on the standard curing condition is not applicable to the non-standard curing condition in this paper and the prediction will cause significant errors.
Table.4 The values of $M_s$ and $f_{cu}$ undering nonstandard curing conditions

| Curing method          | High temperature in summer | Low temperature in winter | Natural curing |
|------------------------|----------------------------|----------------------------|---------------|
| Maturity /°C×d         | 612                        | 510                        | 490           |
| Compressive strength /MPa | 38.5                      | 27.4                       | 24.2          |

3.3 Discussion
Non-standard curing condition varies in temperature or humidity compared to the standard curing condition. High temperature curing in summer should maintain humidity above 95% while keeping temperature higher than the standard curing 20 °C with an average temperature of 27.5 °C. The low temperature curing in winter should maintain humidity above 95% while keeping the temperature lower than the standard curing temperature with an average temperature of 10 °C. Natural curing maintains an average temperature of 14 °C and an average humidity between 60% and 70%. Thus it can be seen that the temperature is different under different curing conditions. Study shows that temperature has a significant influence on the compressive strength of concrete. As is generally believed, when concrete is cured with sufficient humidity, the increase in compressive strength is mainly controlled by temperature and time, and same maturity leads to the basically same strength. However, this paper points out that the above statement is not accurate when the curing temperature is quite different from the standard curing temperature. Therefore, it is necessary to further study the mechanism of how temperature influences the compressive strength of concrete.

4. Conclusion
This paper designs four conditions, including standard curing and non-standard curing in order to study the relationship between concrete compressive strength and maturity. The conclusions are as follows:
(1) Under the standard curing condition, the relationship between compressive strength and maturity of concrete basically conforms to the hyperbolic model, which can be used to predict the compressive strength at different ages;
(2) When the curing temperature is quite different from the standard curing temperature, the aforementioned hyperbolic model is no longer applicable; at this point, direct prediction of concrete compressive strength through maturity will leads to significant errors;
(3) Curing temperature has a great influence on the compressive strength of concrete; therefore, it is necessary to further establish a theoretical model of maturity taking into consideration the influence of temperature.

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