Comparison of calculating methods and applications of different concrete maturity

Da-jiang Geng1,a; Ning Dai2,b; Xue-sheng Jin1,c; En-xin Miao3,d

1 China Construction 4th Engineering Bureau 6th Co., Ltd, Shanghai 201100, China
2 Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Cao An highway, 4800, 201804 Shanghai, China
3 China Construction 4th Engineering Bureau Co., Ltd, Shanghai 201100, China

aemail: gdj1410704@alumni.tongji.edu.cn; bemail: 1710512@tongji.edu.cn;
cemail: 273959903@qq.com; demail: 97658201@qq.com

Abstract. Concrete maturity theory has great potential in practical engineering. In this paper, the calculation and application of the concrete maturity are presented based on the qualitative analysis and quantitative calculations. Firstly, the maturity calculations are summarized by the methods of direct calculation and equivalent age calculation, as well as a theoretical discussion of the advantages and disadvantages of each calculation method. Secondly, the main methods of compressive strength and elastic modulus predicted by the concrete maturity are also summarized, and the calculation accuracy of the main calculation methods is compared with the published test results. Finally, based on actual engineering project, the research on concrete maturity is prospected to clarify the further research direction. The results show that the calculation methods of concrete maturity consist of direct calculation method and equivalent age calculation method, and the equivalent age calculation method is more reasonable in theory. Considering the wide range of construction temperature, the Freiesleben-Hansen equivalent age equation and exponential function prediction equation are recommended to predict the strength and elastic modulus of concrete.

1. Introduction
Generally, the compressive strength and elastic modulus of concrete are easy to obtained under indoor standard curing conditions, while the conditions of engineering site are obviously different with those of indoor standard curing conditions. Hence, there is inevitable error for the concrete strength parameters obtained under indoor standard curing conditions to guide on-site engineering. Considering that the maturity of concrete is a function of time and temperature in the case of sufficient moisture, if the compressive strength and elastic modulus of concrete are reasonably modified with maturity, the accuracy of concrete strength parameters used for on-site engineering can be improved to a certain extent. Therefore, this paper concentrates on literature analysis, qualitative analysis and quantitative comparison methods to study the calculation and application of concrete maturity, so that better predict the strength parameters of concrete and guide engineering practice.

The compressive strength and elastic modulus of concrete are generally used in engineering practice. While in actual calculation, the maturity of concrete is firstly calculated, and then the...
required concrete indexes are predicted based on the maturity. At present, many researches have been
done on the maturity prediction of concrete performance indexes. However, some of the researches are
not systematic and objective. For example, most of the calculation methods were verified by their own
test results, without verifying by others. In addition, most results were verified by the indoor testing
results at constant temperature, which is significantly different from the actual engineering. To this
end, three parts of the calculation and application of concrete maturity, that are maturity calculation,
maturity application and research prospects are discussed based on qualitative analysis and
quantitative calculation methods in this study, so that use the concrete strength parameters predicted
by maturity to put forward engineering suggestions.

2. Maturity calculation
The calculation methods of concrete maturity include: direct calculation method and equivalent age
indirect calculation method.

2.1. Direct calculation
Basically, the higher the curing temperature and the longer the age of concrete, the greater the maturity
should be. The initial maturity calculating formula was based on this understanding, and the
corresponding Nurse-Saul maturity equation [1] is

$$M = \sum_{0}^{t} (T - T_0) \Delta t = \int_{t_0}^{t} (T - T_0) \, dt \tag{1}$$

Where, $M$ is maturity $(^\circ \text{C} \cdot \text{d})$, $T$ denotes temperature changes with time, $T_0$ stands for reference
temperature, at which the concrete stops hydrating and generally valued $-10^\circ \text{C}$, while the value
of concrete mixed with antifreeze is $-15^\circ \text{C}$ [2].

The derivative of time of eq. (1) in both sides is

$$\frac{dM}{dt} = (T - T_0) \tag{2}$$

There is an assumption in eq. (1) that the development speed of maturity over time is proportional
to temperature. While concrete cured at indoor standard temperature, according to eq. (1), the maturity
should linearly change with time, and their relation is curvilinear. Therefore, the assumption in Nurse-
Saul maturity (eq. (1)) is unreasonable.

Considering that it is easy to determine the temperature changes with time, the value of the
reference temperature $T_0$ has greater impact on the value of maturity in eq. (1). Regarding the value
of reference temperature, researches show that the value of reference temperature is significantly affected
by the temperature range of the curing environment, the type of cement, admixture the curing method
[3-4].

In order to characterize the influence of temperature and cement type on the hydration rate, based
on the Nurse-Saul maturity, De and Tegelaar [5] proposed a modified maturity calculation formula

$$M = \int_{t_0}^{t} T \cdot C^{0.17-1.245} \, dt \tag{3}$$

Where, $C$ is a parameter related to the type of cement, which can be valued according to the
literature [6], generally the value ranged in $[1.00, 1.65]$. Similarly, the derivative of time of eq. (3) in
both sides is

$$\frac{dM}{dt} = T \cdot C^{0.17-1.245} \tag{4}$$

Obviously, the changing rate of maturity over time is related to temperature, which behaves a non-
linear relationship. In other words, the relationship between cement hydration rate and temperature is
non-linear. Therefore, compared with eq. (1), the modified maturity calculation formula can simultaneously consider the influence of cement type and temperature on the cement hydration rate, which should be more reasonable in theory. However, this formula is not suitable for negative temperature conditions since it will result in negative maturity, which is obviously unreasonable.

2.2. Equivalent age indirect calculation method

Because the Nurse-Saul maturity was empirically established, the physical meaning of the calculated maturity is not clear. For this reason, Rastrup, E. [7] proposed the concept and calculation method of equivalent age that supposing the concrete age under real temperature history is transformed into an age under a fixed temperature (constant, such as 20°C), the same type of concrete at same mix ratio should share the same strength when the transformed age is equivalent. The equation of equivalent age is

\[ t_e = \int_0^t k(T) \gamma \, dt = \int_0^t \frac{k(T)}{k_r} \, dt \]  

(5)

Where, \( t_e \) means the equivalent age (d), \( k(T) \) represents the hydration reaction rate (1/d) of concrete at a temperature \( T \), \( k_r \) denotes the hydration reaction rate (1/d) at a contrast temperature \( T_r \), the equivalent coefficient \( \gamma = k(T)/k_r \). Obviously, the key to calculating the equivalent age in eq. (5) is the calculation of the hydration reaction rate \( k(T) \) and \( k_r \), as presented in the following equation [8,9]

\[ k(T) = A \cdot \exp \left( -\frac{E_a}{RT} \right) \]  

(6)

Where, \( A \) represents the hydration reaction parameter, \( E_a \) is the apparent activation energy of cement (kJ/mol), \( T \) denotes the Kelvin temperature (K), and \( R \) means the gas constant (valued 8.314J/(mol·K)).

Substituting eq. (6) into (5), considering the conversion of Kelvin temperature and Celsius temperature, then

\[ t_e = \int_0^T \exp \left[ -\frac{E_a}{R} \left( \frac{1}{T+273.15} - \frac{1}{T_r+273.15} \right) \right] \, dt \]  

(7)

When using eq. (7) to calculate the equivalent age, the gas constant \( R \) is a constant, and the contrast temperature \( T_r \) is a constant (20°C for European standards and 23°C for North American standards). The temperature \( T \) is easy to be measured, the apparent activation energy \( E_a \) has greater influence on the calculated value of equivalent age. Hence, it can be regarded as a function of the degree of hydration. Theoretically, the degree of hydration or apparent activation energy should be a function of time and temperature. The classical functional expressions of apparent activation energy \( E_a \) are shown in Table 1.

| Author          | Expression                                      | Remarks                                      |
|-----------------|-------------------------------------------------|----------------------------------------------|
| Freiesleben-Hansen [8] | \[ E_a = \begin{cases} (33.5 + 1.47(20 – T)) \text{kJ/mol} & T \leq 20°C \\ 33.5 \text{kJ/mol} & T > 20°C \end{cases} \] | Ignored the time influence |
| Kim, J. K. [10] | \[ E_a(t,T) = (42830 - 43T)e^{-0.00017Tt} \] | \( t_0 \) denotes the time of final set of concrete (d) |

Equation considered the influences of time and temperature
Rilem [11] \[ \frac{E_c}{R} = \begin{cases} 4000 & T \geq 20^\circ C \text{ Portland cement} \\ 4000 + 175(20 - T) & 20^\circ C < T \leq 30^\circ C \text{ Portland cement} \\ 175 & T < 20^\circ C \text{ Slag cement} \end{cases} \] Ignored the time influence

CEB-FIP [12] \[ \frac{E_{eb}}{R} = 4000 \] Suitable for ordinary Portland cement, ignored the time influence

ASTM [13] \[ \frac{E_{eb}}{R} = 5000 \] Suitable for type I cement without any admixtures. Ignored the influences of time and temperature

Considering that the equivalent age calculation method in eq. (7) is complicated, Rajesh simplified it and obtained following expression [14]

\[ t_e = \int_{t_0}^{t_e} \exp(\beta(T - T_r)) dt \] (8)

Where, \( \beta \) is the temperature influence factor (1/°C).

According to the expression of Nurse-Saul maturity equation in eq. (1), when \( T_0 = -10^\circ C \) and concrete at a constant curing temperature \( T=30^\circ C \) for 1d, the maturity \( M \) was 40°C·d. While at a constant temperature \( T=2^\circ C \) for 3.3333d, the maturity \( M \) reached 40°C·d. It is obvious the both maturities obtained in different cases are the same. Theoretically, both concrete strengths at a same grade and a same type ought to be the same. However, the concrete strength at second curing condition was higher than the first one, which do not agree with the calculation results. Guo, C. [15] also found the similar phenomenon, a same type and grade concrete cured at different temperature history. Even though both maturities obtained by the Nurse-Saul maturity equation were the same, their strengths were different. Which attributes to the assumption of the development speed of maturity over time is proportional to temperature in the Nurse-Saul maturity equation.

As to the same composition of concretes made of the same cement, as long as the degrees of hydration are the same, the strengths should be the same. Obviously, the equivalent age calculation method based on eq. (7) and (8) fairly meet this requirement. According to the qualitative analysis, the equivalent age model may be more reasonable.

3. Maturity application

According to above analysis, many maturity calculation methods have been effectively established, which is generally aimed at engineering application. Generally, indexes used in engineering application mainly involves in elastic modulus, compressive strength, etc. The key to maturity application is to establish a precise relationship between concrete indexes and maturity.

3.1. Calculation of compressive strength

3.1.1. Calculation formula

The formula of predicting strength using concrete maturity in the early time was a logarithmic form [16]

\[ S = a + b \log(M) \] (9)

Where, \( S \) represents the compressive strength of concrete (MPa), \( a \) and \( b \) are fitting constants. According to eq. (9), when the maturity \( M \) increases, theoretically, the compressive strength also increases. Particularly, when \( M \) approaches infinity, the compressive strength also approaches infinity, which is obviously inconsistent with the facts. In order to deal with this question, researchers proposed hyperbolic and exponential concrete maturity prediction strength formulas [17], which are
\[ S = \frac{M}{p + qM} \]  
\( \quad \) (10)

\[ S = p \exp\left( -\frac{q}{M} \right) \]  
\( \quad \) (11)

Where, \( p \) and \( q \) are fitting parameters, and the corresponding hyperbolic and exponential ultimate strengths are \( 1/q \) and \( p \), respectively. In addition, researchers have also proposed many calculation formulas of maturity prediction strength, as shown in Table 2. Actually, the application of these formulas in actual engineering is extremely limited.

| Author       | Expression | Remarks                                      |
|--------------|------------|----------------------------------------------|
| Li, Q. F. [18] | \[ S = \begin{cases} 10.76M^{0.331} & M \leq 840\degree C \cdot d \\ 27.4M^{0.1923} & M \geq 840\degree C \cdot d \end{cases} \] | Suitable for ordinary Portland cement. Unable to solve the problem of tending to infinity. |
| Li, Q. F. [18] | \[ S = \begin{cases} 2.32M^{0.559} & M \leq 840\degree C \cdot d \\ 27.4M^{0.1923} & M \geq 840\degree C \cdot d \end{cases} \] | Suitable for slag Portland cement. Unable to solve the problem of tending to infinity. |
| Zhao, Y. P. [19] | \[ \frac{S}{S_{28}} = \begin{cases} 0.26\ln M - 0.65 & M \leq 560\degree C \cdot d \\ 0.13\ln M + 0.18 & M \geq 560\degree C \cdot d \end{cases} \] | \( S_{28} \) is the strength cured for 28days under the standard condition. Unable to solve the problem of tending to infinity. |

Many existing test results showed that the early curing temperature of concrete significantly affects the later strength. While the maturity calculated according to the Nurse-Saul maturity equation (1) and logarithmic strength prediction equation (9) cannot reflect this effect. One suggestion is to predict strength by combining with the equivalent age, which are [20-22]

\[ \frac{S}{S_u} = \frac{k(t_e - t_0)}{1 + k(t_e - t_0)} \]  
\( \quad \) (12)

\[ \frac{S}{S_u} = \frac{\sqrt{k(t_e - t_0)}}{1 + \sqrt{k(t_e - t_0)}} \]  
\( \quad \) (13)

\[ \frac{S}{S_u} = \exp\left( -\left( \frac{\tau}{t_e} \right)^\alpha \right) \]  
\( \quad \) (14)

Where, \( S_u \) represents the strength when the concrete reaches the limit of hydration degree, \( k \) is the goodness of fit constant, \( \tau \) denotes the time normalization parameter, and \( \alpha \) means the goodness of fit constant. Obviously, according to eq. (12) and (13), if the final setting time \( t_0 \) is the same for the same type and mix ratio, only when the equivalent age \( t_e \) is the same, the concrete strength ought to be the same. When the equivalent age \( t_e \) is equal to the final setting time \( t_0 \), the concrete strength \( S \) becomes zero. If the equivalent age \( t_e \) tend to infinity, the concrete strength \( S \) tends to \( S_u \), which is theoretically consistent with the actual situation. Equation (14) also satisfies that when the equivalent age \( t_e \) tends to infinity, the concrete strength \( S \) tends to \( S_u \). While the most obvious difference between eq. (12), (13) and (14) is the form of expression. As eq. (12) assumes that the relationship between strength and equivalent age is a linear hyperbolic function, and the relations in eq. (13) and (14) are linear hyperbolic function and parabolic hyperbolic, respectively. Obviously, according to the qualitative analysis, eq. (12), eq. (13) and (14) are more reasonable than eq. (9).
3.1.2. Comparison and analysis of formula calculation accuracy
Since the temperature ranges of concrete in different seasons are different in actual engineering, it is important to analyze the calculation accuracy of different maturity calculation methods and different strength prediction methods at different temperatures, so that facilitate practical engineering applications. Generally, the calculation methods of maturity or equivalent age mainly include formula (1), formula (3) and (7), and the strength prediction method mainly includes formula (9) to formula (14), and the comprehensive prediction method is finally adopted in this paper. More details can be seen in Table 3.

Table 3. Summary of forecast methods.

| Prediction method number | Formula of maturity or equivalent age calculation | Formula of strength prediction |
|--------------------------|-----------------------------------------------|-------------------------------|
| 1                        | Eq. (1)                                        | Eq. (9)                       |
| 2                        | Eq. (3)                                        | Eq. (9)                       |
| 3                        | Eq. (1)                                        | Eq. (10)                      |
| 4                        | Eq. (3)                                        | Eq. (10)                      |
| 5                        | Eq. (1)                                        | Eq. (11)                      |
| 6                        | Eq. (3)                                        | Eq. (11)                      |
| 7                        | Eq. (7)                                        | Eq. (12)                      |
| 8                        | Eq. (7)                                        | Eq. (13)                      |
| 9                        | Eq. (7)                                        | Eq. (14)                      |

In past five years, many experimental studies have been conducted on the strength evolution law of concrete [23-33]. To enhance the objectivity of comparative work, the calculation accuracies of various prediction formulas are compared based on the existing test results.

(1) Negative temperature (-10°C~0°C)
Since the original experimental data provided by Qiu, Y. [32] and Duan, Y. [33] are relatively comprehensive, their test results are used for the calculation of maturity and strength prediction at negative temperature. The seven calculational formulas are used to compare the calculation and experimental results at constant negative temperature and variable negative temperature, which is shown in Fig. 1. Considering that formula (3) is inapplicable for the negative temperature situation, hence the corresponding prediction method 2, method 4 and 6 are not involved in the comparison. Specifically, when the apparent activation energy $E_a$ is required in the calculation, the first formula in Table 1 can be adopted. When eq. (1) is used to calculate the maturity, the reference temperature $T_0$ is set -10°C. Therefore, when the curing temperature reaches -10°C, the maturity calculated by eq. (1) is zero, which cannot be used to predict the strength. As a result, the results in Fig. 1(d) do not involve the results from method 1, method 3 and 5.
(a) Constant negative temperature -3°C

(b) Variable negative temperature at -3°C (5°C, 3°C, and 1°C are cured in sequence for 12h and then -3°C is cured)

(c) Variable negative temperature at -5°C (10°C curing for 1d and keep -5°C curing)
Fig. 1 Comparison of strength prediction methods under negative temperature

As shown in Fig. 1(a), at a constant negative temperature of -3°C and an age of 128 days, the method 1, method 3 and 5 are the equations corresponding to the Nurse-Saul maturity equation, with the calculation result of method 3 being the best and correspondence to a hyperbolic strength prediction method. While in the case of a constant negative temperature and a long age, the combination method of the Nurse-Saul maturity equation and the hyperbolic strength (combination I) has high accuracy in predicting concrete strength. The method 7, method 8 and 9 are the equations corresponding to the equivalent age calculating method of Freiesleben-Hansen, with the calculation result of method 9 being the best and correspondence to an exponential function strength prediction method. In addition, in the case of a constant negative temperature and a long age, the combination method of the Freiesleben-Hansen and the exponential function strength (combination II) has high accuracy in predicting concrete strength, which is much higher than that in the combination method of the Nurse-Saul maturity equation and the hyperbolic strength.

According to Fig. 1(b), in the case of middle age with variable negative temperature, both the combination method of the Nurse-Saul maturity equation and the exponential strength (combination III) and combination II have high calculating accuracy in predicting concrete strength, and the accuracy of the former is higher than the latter.

According to Fig. 1(c) and 1(d), in the case of variable negative temperature and short age, both the combination method of the Nurse-Saul maturity equation and the logarithmic strength (combination IV) and combination II have high calculating accuracy in predicting concrete strength, and the accuracy of the latter is higher than the former.

In general, when using the Nurse-Saul maturity equation to predict the concrete strength under negative temperature conditions, the hyperbolic, exponential, and logarithmic strength prediction equation are suggested to be adopted in the condition of long age, middle age and short age, respectively. However, when using the equivalent age equation of Freiesleben-Hansen, the exponential strength prediction equation is suggested to be used regardless of the age.

(2) Low positive temperature (0°C~20°C)

In the case of low positive temperature, since the original experimental data provided by Xu et al. (2020) and Qiu, Y. (2016) are comprehensive, their test results are used for the calculation of maturity and strength prediction. The nine calculational methods presented in Table. 3 are used to compare the calculation and experimental results at constant low positive temperature and variable low positive temperature, which is shown in Fig. 4. When the curing temperature keeps 0°C, the maturity calculated by eq. (3) is zero. As a result, the predicting method 2, method 4 and 6 eventually get invalidated.
Table 4. Comparison of strength prediction methods at low positive temperature.

| Temperature | Fitting goodness $R^2$ |
|-------------|------------------------|
|             | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 | Method 8 | Method 9 |
| Constant 0°C| 0.9967   | /        | 0.9964   | /        | 0.9817   | /        | 0.9946   | 0.9922   | 0.9968   |
| Constant 10°C| 0.9148  | 0.9148  | 0.9328   | 0.9328   | 0.9770   | 0.9770   | 0.9677   | 0.8973   | 0.9950   |
| Constant 20°C| 0.9613  | 0.9613  | 0.9997   | 0.9997   | 0.9776   | 0.9776   | 0.9891   | 0.9803   | 0.9988   |
| Changes around 20°C | 0.9804 | 0.9863 | 0.9979 | 0.9977 | 0.9742 | 0.9743 | 0.9905 | 0.9786 | 0.9972 |

Seeing from Table 4, at a constant temperature of 0°C, both the combination I and IV have high accuracy in predicting concrete strength. While at a constant temperature of 10°C, the combination III has high accuracy in predicting concrete strength, which is still lower than that of the combination II. Both the combination I and II have high accuracy in predicting concrete strength at a constant temperature of 20°C, with the accuracy of combination I higher than combination II. Concrete cured at variable temperature of 20°C, the method 3 and 4 have the highest calculating accuracy, followed by method 9, which indicates concrete at variable low positive temperature. Both combinations of I and II are the better prediction method.

(3) Positive temperature (20°C~60°C)
In the case of positive temperature, the experimental results by Xu, J. [23] and Qiu, Y. [32] are used to verify the accuracy of strength predicting method. Since there is no test result of variable positive temperature exceeding 20°C at present, the concrete strength cured at conditions of constant 35°C, constant 50°C and 60°C are verified in this paper. As shown in Table 5.

Table 5. Comparison of strength prediction methods at low positive temperature.

| Temperature | Fitting goodness $R^2$ |
|-------------|------------------------|
|             | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 | Method 8 | Method 9 |
| Constant 35°C| 0.9444  | 0.9444  | 0.8913  | 0.8913  | 0.9669  | 0.9669  | 0.9763  | 0.9098  | 0.9892  |
| Constant 50°C| 0.9047  | 0.9047  | 0.9232  | 0.9232  | 0.9649  | 0.9649  | 0.9935  | 0.9457  | 0.9987  |
| Constant 60°C| 0.8934  | 0.8934  | 0.9505  | 0.9505  | 0.9955  | 0.9955  | 0.9787  | 0.8672  | 0.9990  |

Obviously, seeing from Table 5, both the combination I and combination II have the highest accuracy in predicting concrete strength regardless of the curing temperature of constant 35°C, 50°C or 60°C.

Based on the results of negative temperature (-10°C~0°C), low positive temperature (0°C~20°C) and positive temperature (20°C~60°C), it is applicable for combination II to predict concrete strength at all temperature conditions.

3.2. Calculation of elastic modulus

3.2.1. Calculation formula
In addition to strength, the common concrete performance index is the elastic modulus. Compared with the strength predicting experiment, there are fewer experimental results related to elastic modulus prediction [34,35]. Similar to the method of strength prediction, the prediction method of elastic modulus mainly includes the establishment of the relation between elastic modulus and maturity or relation between elastic modulus and equivalent age. Correspondingly, the calculating method is the same as the nine methods in Table 3, where the strength is replaced by the elastic modulus.
3.2.2. Comparison and analysis of accuracy of formula calculation

As shown in Table 6, the fitting goodness of all methods are compared when the elastic modulus is predicted according to the nine methods in Table 3.

Table 6. Comparison of strength prediction methods at low positive temperature.

| Temperature | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 | Method 6 | Method 7 | Method 8 | Method 9 |
|-------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Constant 20℃ | 0.9756   | 0.9756   | 0.9271   | 0.9271   | 0.8567   | 0.8567   | 0.8828   | 0.9690   | 0.9778   |
| Variable 50℃ | 0.9835   | 0.9839   | 0.9284   | 0.9288   | 0.8716   | 0.8720   | 0.8810   | 0.9734   | 0.9843   |
| Constant 60℃ | 0.9197   | 0.9197   | 0.9766   | 0.9766   | 0.9544   | 0.9544   | 0.9617   | 0.9512   | 0.9716   |

According to Table 6, the combination method of equivalent age equation of Freiesleben-Hansen and exponential function-type elastic modulus method has the highest accuracy in predicting the elastic modulus of concrete at constant 20℃ and variable 20℃. While in the case of constant high temperature (60℃), the combination method of Nurse-Saul maturity equation and hyperbolic elastic modulus has higher accuracy in predicting the elastic modulus of concrete, followed by the combination method of equivalent age equation of Freiesleben-Hansen and exponential functional elastic modulus, but the difference in fitting goodness between the two combinations is merely 0.005.

4. Research Outlook

Much achievement has been made on the theory and application of concrete maturity by researchers, but the application in actual engineering is relatively limited. Some recommendations are made for the following research.

1. Most concrete maturity calculation methods developed based on the assumption of 100% of curing humidity. However, the change in curing humidity significantly affects the hydration reaction rate of cement, and hence the maturity is changed. It is of great importance to develop the calculation formula of maturity based on the concrete tests at various curing humidity [36].

2. With the continuous development of new types of concrete such as lightweight concrete, recycled concrete and high-performance concrete, whether the existing maturity calculation methods applies to these new concretes or not, it remains needing to be tested and verified [37]. Correspondingly, how to use maturity to judge the performance indexes of the new concrete is also an urgently problem for research.

3. Since conducting indoor tests is costly whatever in time or expense, it is recommended to conduct numerical simulation to verify the maturity after experimental verification [38].

4. In order to meet the requirements for the real estate market, rapid construction (e.g., five-day one-story) has become rather common. At present, the concrete of the calculations of connection node between formwork and concrete structure, and the compression deformation of each floor were assumed to be completely hardened and reached strength limit. Nevertheless, concrete in actual engineering generally takes a long time to reach the ultimate strength. Hence, it is unsafe to use the ultimate strength to verify the concrete strength when the actual strength does not reach the ultimate value. As a result, it is meaningful to establish a constitutive model of concrete considering the maturity and apply the constitutive model to finite element calculations [39,40].

5. Concluding remarks

In this study, the importance of concrete maturity in engineering is considered. The maturity calculation methods of concrete are summarized by literature induction, theoretical qualitative analysis and quantitative calculation. The calculating accuracy of maturity in predicting compressive strength
and elastic modulus are compared, and some future research suggestions are pointed out. The conclusions are as follows:

1. The calculation methods of concrete maturity include direct calculation method and equivalent age calculation method. Theoretically, the equivalent age calculation method should be more reasonable.

2. Since the wide range of on-site construction temperature, it is recommended to use the combination of equivalent age equation of Freiesleben-Hansen and exponential function strength to predict the concrete strength, and the combination of equivalent age equation of Freiesleben-Hansen and exponential function elastic modulus to predict the elastic modulus of concrete.

3. It is suggested to conduct experiments and numerical simulations to establish a concrete maturity calculation method considering the curing humidity. The existing research results can be used to infer the performance indexes of the new type of concrete. The constitutive model of concrete considering maturity is also suggested to be considered so that the maturity theory a play greater role in the finite element calculation of engineering.

Acknowledgments
The Program of China Construction (No. CSCEC4B-2020-KT-25) and High-Tech Program of China Construction 4th Engineering Bureau (No. CSCEC4B-2020-KT-25) are greatly appreciated for providing financial support for this research.

References
[1] Saul, A. (1951). Principles underlying the steam curing of concrete at atmospheric pressure. Magazine of Concrete Research, 2(6), 127-140. doi: 10.1680/macr.1951.2.6.127
[2] JGJ/T104-2011, (2011). Winter construction regulations for construction engineering. Beijing, China Construction Industry Press, 000(011), 140-141.
[3] Ge, Z. (2005). Predicting temperature and strength development of the field concrete. Ames: Iowa State University.
[4] Kim T. (2004). Concrete maturity: A quantitative understanding of how early-age temperature affects the maturity concept. Boulder: University of Colorado at Boulder. doi: 10.1016/S0008-8846(00)00481-6
[5] De. V. R., Tegelaar, R. (1998). Gewichtete Reife des Betons. Beton, 48(11), 674-678.
[6] CUR-RECOMMENDATION. (1986). Determining the strength of young concrete on the bases of weighted maturity. Gouda: The Dutch Centre for Civil Engineering, Codes and Specifications,
[7] Rastrup, E. (1954). Heat of hydration in concrete. Cement Concrete Reseach, 6(17), 127-140.
[8] Freiesleben, H. P., Pedersen, J. (1977). Maturity computer for controlled curing and hardening of concrete. Nordisk Betong, (1), 19-34.
[9] Brown, T. L. Lemay, H., Bursten, B. E. (2009). Chemistry: The Central Science. Prentice Hall. doi:10.1016/S0140-6736(02)79752-3
[10] Kim, J. K., Han, S. H., Lee, K. M. (2001). Estimation of compressive strength by a new apparent activation energy function. Cement and Concrete Research, (31), 217-225. doi: 0.1016/S0008-8846(00)00481-6
[11] Anonymous. TCE1. (1997). A diabatic and semi-adiabatic calorimetry to determine the temperature increase in concrete due to hydration heat of the cement. Materials & Structures, 30(8), 451-464. doi: 10.1007/BF02524773
[12] CEB -FIP MODEL CODE 1990. (1990) Comite Euro-international du Beton. London: Thomas Telford.
[13] ASTM. (2011). Standard practice for estimating concrete strength by the maturity method: ASTM C1074—2011. Pennsylvania: West Conshohocken.
[14] Rajesh, C. T., Nicolas, C. (1991). Rate constant functions for strength development of concrete. Materials Journal, 88(1), 74-83.
[15] Guo, C. (1989). Maturity of concrete: method for predicting early-stage strength. Aci Materials Journal, 86(4), 341-353.
[16] Plowman, J. M. (1956). Maturity and the strength of concrete. Magazine of Concrete Research, 8(22), 13-22. doi: 10.1680/macr.1956.8.22.13
[17] Kee, C. F. (1977). Relationship Between Strength and Maturity of Concrete. ACIJ, 54(12), 196-203.
[18] Li, Q. F. (2002). New Theory on Concrete. Concrete, (10), 12-15.
[19] Zhao, Y. P., Sun, Y. L., Yu, T., Yu, J. H. (2009). Test Study on Concrete Strength Growing Rules in Winter at Cold Area. Bulletin of the Chinese Ceramic Society, 28(4), 854-858. doi: 10.16552/j.cnki.issn1001-1625.2009.04.039
[20] Carino, N. J. (1984). The Maturity Method: Theory and Application. ASTM Journal of Cement and Concrete, 6(2), 61-73. doi: 10.1520/CCA10358J
[21] Knudsen, T. (1980). On particle size distribution in cement hydration. Paris: Editions Septima.
[22] Hansen, P. F, Pedersen, E. (1985). Curing of concrete structures. Switzerland: Draft DEB-Guide to Durable Concrete Structures.
[23] Xu, J., Zhu, R., Zhan, Y. J., Zhu, M. T., Li, X. K. (2020). Experimental Study on Strength Evolution of Concrete Structures Under Different Strength Grades and Curing Conditions. Building Construction, 42(12), 2314-2317. doi: 10.14144/j.cnki.jzsz.2020.12.034
[24] Dai, J. P., Wang, Q. C., Qu, S., Duan, Y., Xie, Z. G. (2018). Strength Prediction Model of Low Temperature Curing Concrete Based on Maturity Theory. Journal of Materials Science and Engineering, 36(02), 263-267.
[25] Ma, Y. Ma, L., Pan, B. L. (2019). Research on Prediction of Early Concrete Strength Based on Maturity Method. Highway Transportation Technology (Application Technology Edition), 15(05), 1-4.
[26] Yang, W. J., Deng, C. L., Yang, H. C., Wang, S. L. (2019). Comparison of prediction models at home and abroad for mechanical properties of concrete. Building Structure, 49(S1), 697-700. doi: 10.19701/j.cnki.1001-4179.2019.01.144
[27] Feng, S. X. (2018). The influence of setting agent and curing temperature on the development of concrete strength. Highway Transportation Technology (Application Technology Edition), 14(09), 141-143.
[28] Song, Y. T., Hu, J., Hu, J. B., Qin, M. Q. (2017). Use of maturity method to estimate compressive strength of marine concrete. New Building Materials, 44(09), 15-18.
[29] Zhu, X. L., Ding, J. T., Cai, Y. B. (2016). Prediction of mechanical properties of anti-abrasion concrete based on equivalent age method. Yangtze River, 47(23), 97-101. doi: 10.16232/j.cnki.1001-4179.2016.23.020
[30] Li, J., Cao, D. W., Han, S. (2016). Application Analysis of Maturity Integral Calculation Method for Cement Concrete. Transport Research, 2(06), 60-66. doi: 10.16503/j.cnki.2095-9931.2016.06.010
[31] Liu, G. (2016). Study on the equivalent method of concrete age based on electrical resistivity. China Three Gorges University.
[32] Qiu, Y. (2016). Maturity method to predict the strength of concrete in winter construction. Harbin Institute of Technology.
[33] Duan, Y. (2016). Study of concrete strength under constant minus-temperature and varied minus-temperature and calculation formula optimization of early strength of concrete. Lanzhou Jiaotong University.
[34] Hou, D. W., Zhang, J., Chen, H. Y., Liu, W. (2012). Development of strength and elastic modulus of concrete under moisture and drying curing conditions. Journal of Hydraulic Engineering, 43(02), 198-208.
[35] Zhu, R., Xu, J., Zhan, Y. J. (2020). A New Model for Predicting Elastic Modulus of Lightweight Concrete with Singly Mixed Fly Ash Based on Maturity Theory. Building Construction, 42(11), 2108-2110+2116. doi: 10.14144/j.cnki.jzsz.2020.11.026
[36] Wang, T., Wang, X. L. (2017). Maturity of Early Strength of Concrete Slab. Bulletin of the Chinese Ceramic Society, 36(05), 1783-1789. doi: 10.16552/j.cnki.issn1001-1625.2017.05.056

[37] Peng, C. Y. Zhang, X. P., Yu, B., Peng, J. Y., Jiao, C. J. (2020). Study on maturity of recycled-fine-powder concrete based on equivalent age. Concrete, (01), 22-26.

[38] Lv, F. Y., Meng, X. L., Li, B., Jia. J., Wang, B., Liu. C. Y. (2019). Simulation of the Maturity of New Cast Concrete After Overwintering. Journal of Water Resources and Architectural Engineering, 17(05), 123-127.

[39] Geng, D. J., Guo, P. J., Zhou, S. H. (2018). Implicit numerical integration of an elasto-plastic model for structured clays. Chinese Journal of Theoretical and Applied Mechanics, 50(01), 78-86.

[40] Geng, D. J., Dai, N., Guo, P. J., Zhou, S. H., Di, H. G. (2021). Implicit numerical integration of highly nonlinear plasticity models. Computers and Geotechnics, 132, 103961. doi: 132(2), 103961. 10.1016/ j.compgeo.2020.103961