PREDICTION MODEL ON MECHANICAL STRENGTH OF MORTAR AT ULTRA LOW TEMPERATURE

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Abstract:

In this paper, strength development law of mortars with different water to cement ratios at ultra low temperature was analyzed using nonlinear least square method, and the prediction model on strength development of mortar at ultra low temperature was proposed. Based on the proposed prediction model, strength development laws of high strength mortar (HM) with different curing time and mortars with different moisture content and water to cement ratio of 0.31, 0.4, 0.5 and 0.6 at ultra low temperature were verified. The results show that the fitting coefficients are up to water to cement ratio. It is quantitatively verified that the influence of moisture content on flexural strength of mortar at ultra low temperature is higher than that on compressive strength. It is verified that given moisture content \( m \) and curing time of ultra low temperature \( t \), the prediction model of strength development of mortar can be expressed as

\[
\sigma_t = \sigma_o + (A(m - m_o)^2 + C)(1 - \exp\left(\frac{t}{B}\right)).
\]

Key words: strength; ultra low temperature; curing time; moisture content; prediction model

1 INTRODUCTION

Mechanical performance is one of the key properties of concrete. Mechanical performance of concrete at ultra low temperature is quite different from that at room temperature. Many researches focused on mechanical performance at ultra low temperature have been done. It can be concluded that concrete has higher strength at ultra low temperature. But these researches can hardly reach a consistent result on the strengthening mechanism and the strength development law at ultra low temperature [1-6]. Therefore, it is of great significance to study and establish prediction model on mechanical performance of mortar or concrete at ultra low temperature, especially for practical applications.

Compressive strength of concrete at ultra low temperature [7] can be expressed as

\[
\sigma_{cl} = \sigma_{co} + \Delta \sigma_c
\]

(1)

Where \( \sigma_{cl} \) represents compressive strength at ultra low temperature, \( \sigma_{co} \) represents
compressive strength of concrete at room temperature and $\Delta \sigma_c$ represents increase of compressive strength at ultra low temperature.

$$\Delta \sigma_c = \begin{cases} 
120 - \frac{1}{270} (T \cdot 180)^2 \cdot W, & 0\leq T\leq-120^\circ C \\
107 \cdot W, & T\leq-120^\circ C 
\end{cases}$$  \hspace{1cm} (2)$$

$T$ represents temperature and $W$ represents moisture content.

The tensile strength of concrete at ultra low temperature [7] can be expressed as

$$\sigma_T = 0.38 \cdot \sigma_c^2$$  \hspace{1cm} (4)$$

While, the strength increase of concrete at ultra low temperature can be expressed as in the literature [10],

$$\delta = \frac{\theta m}{12} \text{N/mm}^2$$  \hspace{1cm} (5)$$

Where $\delta$ represents strength increase, $\theta$ represents temperature and $m$ represents moisture content.

According to my early research [11,12], given moisture content $m$ and curing time of ultra low temperature $t$, the equation of strength development of mortar can be expressed as

$$\sigma_t = \sigma_0 + \Delta \sigma (\exp \frac{t}{B}) = \sigma_o + \Delta \sigma (\exp \frac{1}{B}) = \sigma_o + \Delta \sigma (1 - (\exp \frac{1}{B}))$$  \hspace{1cm} (6)$$

$$\Delta \sigma = A(m - m_c)^2 + C$$  \hspace{1cm} (7)$$

$$\sigma_t(m, t) = \sigma_o + (A(m - m_c)^2 + C)(1 - \exp(\frac{t}{B}))$$  \hspace{1cm} (8)$$

$m>0; \ t\geq0$; while $\sigma_o$ represents strength of mortar at room temperature and $A, B, C, m_c$ represent fitting coefficients.

Equation (8) can predict the strength development of mortars at ultra low temperature. However, it is still uncertain that whether this equation can be used when moisture and water to cement ratio of mortars varies. And the physical significance of fitting coefficients is unknown.

Therefore, this paper is aimed to analyze strength datum of mortars at ultra low temperature with water to cement ratio 0.31, 0.4, 0.5, 0.6 using nonlinear least square method and try to explain the physical significance of fitting coefficients. Strength of high strength mortar in different conditions (full saturated, saturated surface dry and oven dry) is fitted to verify the function relationship between curing time and strength at ultra low temperature. Finally, compressive and flexural strength development law of mortars at -110^\circ C suffering 7d ultra low temperature curing with water to cement ratio 0.4, 0.5, 0.6 respectively is studied to validate function relationship between strength and moisture content.

2EXPERIMENT

2.1 Raw materials and mix proportion
P.O 42.5 cement and natural river sand with its modulus 2.49 were used. Polycarboxylic acid superplasticizer with 30% solid content was adopted. The mix proportion of mortars is shown in table 1.

Table 1 The mix proportions of mortars

<table>
<thead>
<tr>
<th>Mortar types</th>
<th>Cement</th>
<th>Water</th>
<th>Sand</th>
<th>Superplasticizer%</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Strength Mortar, HM</td>
<td>1</td>
<td>0.31</td>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>Ordinary Mortar1, OM1</td>
<td>1</td>
<td>0.4</td>
<td>3</td>
<td>0.44</td>
</tr>
<tr>
<td>Ordinary Mortar2, OM2</td>
<td>1</td>
<td>0.5</td>
<td>3</td>
<td>/</td>
</tr>
<tr>
<td>Ordinary Mortar3, OM3</td>
<td>1</td>
<td>0.6</td>
<td>3</td>
<td>/</td>
</tr>
</tbody>
</table>

2.2 Experimental Methods
Firstly, four different kinds of mortars are cured for 28d at room temperature, then cured at ultra low temperature for 7d and tested. Detailed curing and testing methods at ultra low temperature and equipments such as ultra low temperature curing box, ultra low temperature incubator, thermocouples and data collector in this experiment are specified in the literature [11].

2.3 Experimental program
In this paper, mortars with different water to cement ratio 0.31, 0.4, 0.5, 0.6 were firstly cured in water at room temperature for 28d, then cured at ultra low temperature -110 °C for 7d and further tested for compressive and flexural strength at -110°C. High strength mortar with water to cement ratio 0.31 were cured in water at room temperature for 28d, Then respectively made into samples in the conditions of fully saturated, saturated surface-dry and oven dry, the corresponding moisture content is 5.9%, 4.5% and 0 respectively. The strength of HM in three conditions were cured at ultra low temperature -110°C for 0, 1, 2, 3, 17, 28 d respectively, while the testing value is compared with the calculating value from prediction model. Finally, three kinds of mortars with water to cement ratio 0.4, 0.5, 0.6 respectively were cured in water at room temperature for 28d, then made into samples with different moisture content and tested for compressive and flexural strength, while testing value of strength was compared with the calculating value from prediction model.

3 RESULTS AND DISCUSSION

3.1 The mechanical strength development model of mortar at ultra low temperature

Mechanical strength of mortar increases to a stable level after 7d curing at ultra low temperature. Therefore, in this experiment, mortars were cured at ultra low temperature for 7 d, and when curing time of ultra low temperature \( t \) in equation (8) is 7 d, the equation (8) is simplified into equation (7). Fitting results and coefficients of mortars with different water to cement ratio using prediction equation (7) were achieved, shown in Fig.1 and table2.
The diagrams show the relationship between moisture content and compressive strength or flexural strength for different materials and conditions, along with their respective fitting formulas and coefficients of determination ($R^2$). The formulas are:

(a) Compressive strength
\[ y = -0.7173x^2 + 7.038x + 45.632 \]
\[ R^2 = 0.9236 \]

(b) Flexural strength
\[ y = -0.1997x^2 + 2.9353x + 1.7348 \]
\[ R^2 = 0.85 \]

(c) Compressive strength
\[ y = -0.5223x^2 + 8.3626x + 16.677 \]
\[ R^2 = 0.9355 \]

(d) Flexural strength
\[ y = -0.185x^2 + 2.674x + 2.4738 \]
\[ R^2 = 0.8749 \]

(e) Compressive strength
\[ y = -0.2291x^2 + 7.1075x + 15.343 \]
\[ R^2 = 0.8927 \]

(f) Flexural strength
\[ y = -0.0623x^2 + 1.3903x + 4.1224 \]
\[ R^2 = 0.76 \]
In Fig.1, table2, the fitting coefficient A from fitting formula (7) stays minus, indicating that the increase of flexural and compressive strength of mortar at ultra low temperature has the maximum value and it firstly increases and then decreases with the increase of moisture content. The absolute value of A from different mortars decreases with the increase of water to cement ratio, indicating that moisture content highly affects on strength increase value, and the lower the water to cement ratio, the higher its influence is. A reflects the degree of influence of moisture content on strength of mortar at ultra low temperature and also determine the function curvature to great extent. Once four kinds of mortars with same moisture content, the strength increase at ultra low temperature is highly dependent on A.

Mortar is a kind of porous material and its porosity depends on water to cement ratio, curing conditions etc.. Normally, moisture content of mortar lies on pore characteristics such as pore size, pore structure and porosity. The interior pore water in mortar includes free water, capillary water and gel pore water. The freezing of free water and capillary water will bring expansion, causing stress on pore wall. The bigger the pore, the more serious the expansion due to freezing of pore water will be, resulting in higher stress from expansion. Therefore, when the stress is higher than tensile strength of the materials, damage will take place in the materials. So, the maximum value of compressive and flexural strength will be achieved with optimal moisture content $m_c$, while fitting coefficient C represents increase of strength at this point. As shown in Fig.2, $m_c$ is closely related to water to cement ratio and C increases with the increasing of water to cement ratio.

Coefficient B possibly relates to water to cement ratio and ultra low temperature conditions.
3.2 Prediction on mechanical strength of mortar with different curing time of ultra low temperature

The compressive strength of high strength mortar reaches 60Mpa at 28 days in normal temperature curing conditions. The relative value of $A$, $B$, $C$ for mortars with different moisture content $m_c$ is adopted in equation(8), strength at ultra low temperature will be obtained with different curing time $t$ at ultra low temperature. In Fig.2, It is demonstrated that nonlinear fitting method is adopted to analyze the calculated value from equation (8) and tested strength at ultra low temperature, while the relative error between calculated value and testing value is shown in table 3.
As shown in Fig.2, the tested value differs from calculated value and fitting curve of tested value does not totally coincide with that of calculated value, while the fitting law is similar and the correlation coefficient of HM is over 0.95 except oven dry HM. High correlation coefficient indicates the prediction model can predict mechanical performance of different mortars with different moisture content and curing time of ultra low temperature. In table 3, it is illustrated that relative error is below 20% except oven dry mortar, indicating the prediction model can be full of confidence to predict the mortar behavior at ultra low temperature. The relative error between tested value and calculated value of oven dry HM is considerable high because when the moisture is near 0, little pore water will be frozen, resulting in strength scatters at ultra low temperature.

3.3 Prediction on mechanical performance development of mortar with different moisture content at ultra low temperature

The strength at ultra low temperature stabilizes after 7d curing at ultra low temperature. Therefore, the increase of strength at ultra low temperature can be calculated with adsorption of equation (8) and the comparison of calculated value and
tested value is shown in Fig. 3 and Table 4.

Fig. 3 Relationship between moisture content and strength of mortars curried for 7 days at ultra low temperature
Table 4 Relative error between testing strength and calculating value at ultra low temperature with different moisture content (%)

<table>
<thead>
<tr>
<th></th>
<th>OM1</th>
<th>OM2</th>
<th>OM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_c$</td>
<td>11.18</td>
<td>-1.45</td>
<td>-1.86</td>
</tr>
<tr>
<td>$\Delta \sigma_f$</td>
<td>-1.05</td>
<td>-2.62</td>
<td>8.39</td>
</tr>
<tr>
<td>$\Delta \sigma_c$</td>
<td>-4.24</td>
<td>10.85</td>
<td>-6.62</td>
</tr>
<tr>
<td>$\Delta \sigma_f$</td>
<td>-9.18</td>
<td>-7.12</td>
<td>11.59</td>
</tr>
<tr>
<td>$\Delta \sigma_c$</td>
<td>-7.53</td>
<td>-7.57</td>
<td>-0.16</td>
</tr>
<tr>
<td>$\Delta \sigma_f$</td>
<td>-6.34</td>
<td>-11.46</td>
<td>-20.14</td>
</tr>
</tbody>
</table>

In Fig.3, it is demonstrated that the fitting curve of calculated value from the prediction model nearly coincide with that of tested value and the correlation coefficient is over 0.93; indicating the predicted value is quite close to tested value. The relative error of compressive and flexural strength between tested value and calculated value is below 10% and 20% respectively, quantitatively verifying that the influence of moisture content on flexural strength of mortar at ultra low temperature is higher than that on compressive strength.

4 CONCLUSION

1) For mortar with different water to cement ratio, given moisture content $m$ and curing time of ultra low temperature $t$, prediction model of strength development of mortar can be expressed as $\sigma_t = \sigma_o + (A(m - m_o)^2 + C)(1 - \exp(\frac{t}{B}))$.

2) There lies an exponential relationship between strength of mortar and curing time of ultra low temperature. The higher moisture content, the higher the correlation coefficient will be. Strength of mortar at ultra low temperature reaches a stable level after a certain curing time of ultra low temperature.

3) Given a certain curing time of ultra low temperature, there lies in a quadratic relationship between strength and moisture content of mortar. The fitting coefficients $A$, $m_o$, and $C$ is dependent closely on water to cement ratio.

4) It is quantitatively verified that the influence of moisture content on flexural strength of mortar at ultra low temperature is higher than that on compressive strength.

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