A Damage Model of Concrete under Freeze-Thaw Cycles

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Abstract: The frost durability of concrete is considered from structural engineering points of view. Specific failure process is analyzed and a damage model is established, which can describe the deterioration of concrete during the whole freeze-thawing process. The model is verified by test data. The parameters of model can explain the effect of pore structures or water to binder ratio on frost durability of concrete.

Key words: concrete; frost durability; damage model; parameters of model

1 Introduction

Phenomena in different durability degradation processes of concrete are almost similar; the inner structures of concrete loosening, the flaws enlarging and cracks opening and accumulating[1]. These are similar to failure phenomena of concrete under loads. Therefore, the durability degradation process of concrete could be described with some mechanical methods. If a mechanical model is set up, the concrete durability, and then the durability degradation process could be quantitatively investigated using model’s parameters.

The frost durability of concrete under freeze-thaw is chosen as the research subject. A damage model is proposed to analyze the frost durability degradation process of concrete with damage theories. In this paper, the model is verified by test data. The results indicated that the model is correct and its parameters can express the feature of the durability degradation.

2 Damage Model of Concrete under Freeze-Thaw

The loss rate of dynamic elastic modulus of concrete is regarded as the damage variable $D^{[2]}$:

$$D = 1 - \frac{E'_d}{E_d}$$

where $E_d$ is the dynamic elastic modulus (DEM) of concrete before freeze-thaw, $E'_d$ is the dynamic elastic modulus after concrete has gone through several freeze-thaw cycles.

The frost durability deterioration of concrete could be divided into two phases: the initial damage phase and the damage propagation phase. It can be expressed separately:

1. When $0 \leq N \leq N_c$ (the first phase, that is, the initial damage phase):

$$D = 1 - \exp\left[-\frac{k_1 T_{f}^{2}}{3 E'_{d}} N \right]$$ (1)

where $k_1$ is a material constant.

2. When $N_c \leq N \leq N_u$ (the second phase, that is, the damage propagation phase):

$$D = 1 - \left[(1 - D_c)^2 - \frac{k_2 T_{f}^{2}}{E} (N - N_c) \right]^\frac{1}{2}$$ (2)

where $k_2$ is also a material constant, $N_c$ the sudden mutation point and $D_c$ the damage at the point.

3 Results and Analyses

3.1 Test results of freeze-thaw cycles

In Ref[3], the frost durability of common concrete, high strength concrete, and high performance concrete (HPC) has been investigated. Fig. 1 shows the test results of concrete specimens under slow-freezing cycles.

It is evident that the frost durability of HPC is better than that of the common concrete of same strength grade. The DEM loss of HPC is slower. Before 150 cycles, DEM loss rate of high strength concrete D-60 is lower than 5% and there is no failure phenomenon on their surface. After 270 cycles, the cracks appear and develop rapidly, which makes the concrete specimens of D-60 fail. The cause of sudden failure of high strength concrete is the opening of micro-cracks. The closed micro-pores led by the MA202 can reduce the opening of micro-cracks and slowly release the energy accumulated during freeze-thaw cycles. This explains why H-60 did not fail suddenly.

3.2 Model verification and data analysis

Experimental data were adopted to evaluate and veri-
fy the frost durability damage model proposed. According to the procedures of concrete test and prescription of GBJ82-85, let \( T = \) the average cycle periodicity: \( T = 8 \) h for slow-freezing and \( T = 3 \) h for quick-freezing.

Based on experimental results in Fig. 1, the sudden mutation points of specimens can be assumed as below: \( N_{c(D-40)} = 100, N_{c(D-60, H-40)} = 150 \) and \( N_{c(H-60)} = 300 \).

The following equations can be derived from equations (1) and (2):

\[
 k_1 = \frac{3E^2\ln(1-D)}{TN_{\text{max}}} \\
 k_2 = \frac{E[1 - D_1^2] - (1 - D)^2}{T\sigma_{\text{max}} (N - N_c)} 
\]

Based on the above hypothesis, \( \sigma_{\text{max}} = f_1 \), \( (\sigma_{\text{max}} = 2.25N/mm^2, E = 325000 N/mm^2 \) for D-40 and H-40; \( \sigma_{\text{max}} = 2.95 = 2.95 N/mm^2, E = 36000 N/mm^2 \) for D-60 and H-60), \( k_1 \) and \( k_2 \) around the sudden mutation points can be calculated and the means can be got:

<table>
<thead>
<tr>
<th>Mix</th>
<th>D-40</th>
<th>D-60</th>
<th>H-40</th>
<th>H-60</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_c )</td>
<td>100</td>
<td>150</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>( k_1 )</td>
<td>61.53</td>
<td>4.40</td>
<td>17.36</td>
<td>3.40</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0007</td>
<td>-</td>
</tr>
</tbody>
</table>

From lower to higher, \( k_1 \) values of different concrete are arranged in the same order as the actual frost durability from better to worse. \( k_1 \) values of H-40 and H-60 are smaller than those of D-40 and D-60, respectively, which reveals that the pore structure is one of the factors that may affect \( k_1 \). In the first phase of frost durability deterioration of concrete, the damage of D-60 is not localized, but the one of D-40 is localized. \( k_1 \) value of D-60 is nearly the same as that of H-60. It indicates that the value of \( k_1 \) is related with the concrete strength to some extent when damage is not localized. \( k_1 \) value of D-40 is much higher than that of H-40. It indicates that the value of \( k_1 \) is controlled only by the pore structure when damage is localized.

From lower to higher, \( k_2 \) values of different concrete are arranged in the same order as the actual frost durability from better to worse in the second phase. (Although the damage accumulation of H-60 has not developed into the second phase when 300th cycle, its \( k_1 \) value must be lower than that of H-40). \( k_2 \) values of D-40 and D-60 are nearly the same. This fact reveals that in the second phase the increment of concrete strength has no evident advantages in resisting freeze-thaw damage. Despite of lower concrete strength, \( k_2 \) value of H-40 is smaller than that of D-60 due to better pore structure introduced by air-en trainer and water reducer. Therefore, \( k_2 \) value is closely related to the pore structure parameters, such as the air content, pore spacing and so on.

Comparing values derived from the model in this paper with the test data, it can be found that the model is able to accurately forecast the damage evolution in the whole freeze-thawing process.

### 3.3 Improved Loland model and verification

As the mark of damage localization, the sudden mutation point and its position definitely have a guiding significance to improve the frost durability in practical engineering. However, in practice there are usually no enough data to estimate the position of the sudden mutation point. In order to solve this problem, an improved Loland model is introduced.

Revisit the Loland model as the following:

\[
 D = D_0 + C\varepsilon \beta \\
 \beta = \frac{\lambda - E_1/E_0}{1 - D_0 - \lambda} \\
 C = \frac{1 - D_0 - \lambda}{E_1^\varepsilon} \\
 \lambda = \frac{\sigma_1}{E_0\varepsilon_1} \\
 \varepsilon_1 = \sigma_1/A_1 \\
 D_0—\text{the initial damage. According to the actual process of freeze-thaw cycles and the definition of damage variables, } D_0 \text{ is equal to zero. } \varepsilon—\text{the maximum strain before damage localization. The value of } \varepsilon_1 \text{ can be got from the mono-axial tensile test of concrete. For common concrete, the value of } \varepsilon_1 \text{ is about } 65\% \text{ of the ultimate strain; for the high strength concrete, it is about } 80\% \text{ of the ultimate strain. } E_0—\text{the initial elastic modulus. } E_1—\text{the secant modulus when strain is } \varepsilon_1. \text{ For the common concrete, } E_1 \text{ is about } 80\% \text{ of } E_0; \text{ for the high strength concrete, it is about } 85\% \text{ of } E_0. \text{ It can be assumed that the damage level is } D_1 \text{ (sudden mutation point), when the concrete strain caused by the freeze-thaw stress reaches } \varepsilon_1 \text{ in a certain cycle. From the revised Loland model, the damage of the sudden mutation point can be got: } D_1 = 0.2 \text{ (for D-40 and H-40); } D_1 \text{ is }
\]