Influential Mechanism of Pore Water Pressure on the Compressive Strength of Concrete

Ying Cui, Weifeng Bai, Yongjie Zheng, Haotian Han and Linai Liu

ABSTRACT

The expression of effective stress principle suitable for the micro-structural features of saturated concrete is established. The theoretical equation of pore water pressure coefficient under three-dimensional stress state is proposed. By this model, the compressive strength of concrete under different confining pressures is predicted, and the influential mechanism of pore water pressure on the strength of concrete under complicated stress states is investigated. The results indicate that the existence of pore water pressure changes the loading path of the matrix’s true stress in the principal stress space, therefore it modifies the compressive strength when the stress state of the concrete reaches its limit.1

INTRODUCTION

Concrete is the composite material mixed by water, aggregate, cement and so on. It has the heterogeneity meso-structure, and exhibits the complex macroscopic nonlinear mechanical behavior. There are a lot of micro-cracks between aggregate and mortar interface. The porosity of ordinary concrete is generally less than 8% to 10%, and will be filled with pore water in the external water environment[1]. It has a significant impact on the mechanical properties of concrete due to the existence of pore water. Lots of test results[2] show that the tensile and compressive strength of concrete will decrease with the growth of internal humidity, and the strength of saturated concrete is lower than the strength of dry concrete in triaxial compression test. In this paper, the expressions of effective stress and the pore water pressure

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coefficient for saturated concrete is proposed, which could be used to explore the strength reduction mechanism. In this paper, stress and pore water pressure are to be positive under pressure.

Figure 1. Sketch map for effective stress principle of saturated concrete.

**EFFECTIVE STRESS PRINCIPLE FOR SATURATED CONCRETE**

As shown in fig.1, the ideal model of saturated concrete is composed of the non-defective concrete matrix and spherical pores, each pore is filled with water. Make the isolation body by section a-a. When it bears pressure $\sigma$ at two ends, the equilibrium condition can be written as follow:

\[ A = A_s + A_v \]  \hspace{1cm} (1)

\[ \sigma\Lambda = \sigma_s A_s + uA_v \]  \hspace{1cm} (2)

Figure 2. Stress state of the saturated concrete.
where, \( A_s \), \( A_v \) is the cross-sectional area corresponding to the whole, the concrete matrix and the pores; \( \sigma_s \) is the normal stress to the matrix, \( u \) is the pore water pressure.

considering \( A_s / A >> 0 \), introduce the porosity \( n \), the expression can be written as:

\[
    n = \frac{A_v}{A} = \frac{V_v}{V}
\]

\[
    \sigma = \sigma_s (1 - n) + nu = \sigma' + nu
\]

where, \( V_v, V \) is the volume corresponding to the concrete matrix and the whole; \( \sigma' \) is the mean stress to \( A \). The tensor form can be written as follow:

\[
    \sigma_{ij} = \sigma_{ij} (1 - n) + nu \delta_{ij} = \sigma'_{ij} + nu \delta_{ij}
\]

where \( \delta_{ij} \) is the Kronecker operator.

**PORE WATER PRESSURE COEFFICIENT FOR SATURATED CONCRETE**

Assume the saturated concrete in a certain stress increment status (\( \Delta \sigma_1 > \Delta \sigma_2 > \Delta \sigma_3 \)), as shown in fig.2. It could be divided into two parts, spherical stress and deviatoric stress, the expression can be written as:

\[
    \Delta \sigma_m = \frac{1}{3}(\Delta \sigma_1 + \Delta \sigma_2 + \Delta \sigma_3)
\]

\[
    \Delta u = \Delta u_B + \Delta u_A
\]

where \( \Delta \sigma_m \) is the spherical stress increment; \( \Delta u \) is the total pore water pressure increment; \( \Delta u_B, \Delta u_A \) is the pore water pressure increment due to the spherical stress increment and deviatoric stress increment, respectively.

In term of the formula (4) and (5), it can be written as:

\[
    \Delta u_B = B \Delta \sigma_m = \frac{C - C_s}{n(C_v - C_s)} \Delta \sigma_m
\]
\[ \Delta u_A = 0 \] (9)

where \( B \) is the pore pressure coefficient relative to \( \Delta \sigma_m \); \( C_s \), \( C_v \), \( C \) is the volume compressibility corresponding to the concrete matrix, the pore water and the composite. The formula \( \Delta u_A = 0 \) indicates the deviatoric stress increment part has no contribution to the pore water pressure, and ignores the shear contraction phenomenon of concrete. Hence \( \Delta u \) can be written as:

\[ \Delta u = \Delta u_B = B \Delta \sigma_m = \frac{C - C_s}{n(C_v - C_s)} \Delta \sigma_m \] (10)

In particular, at the axisymmetric stress state \( (\Delta \sigma_1 > \Delta \sigma_2 = \Delta \sigma_3) \), \( \Delta u \) can be further expressed as:

\[ \Delta u = B[\Delta \sigma_3 + \frac{1}{3}(\Delta \sigma_1 - \Delta \sigma_3)] \] (11)

EXAMPLES AND VERIFICATION

The rationality of this proposed model was validated by predicting the compressive strength of concrete under different confining pressures. The influence mechanism of pore water pressure on the strength was discussed. The parameters of each phase in concrete are shown in Table I. The parameters of the pore pressure of dry and saturated concrete are shown in Table II, and the range of \( n \) is from 0.1 to 0.5.

In example, the uniaxial compressive strength of the ideal concrete matrix (n=0) was signed as \( f_c' \), the other stress-related variables were the relative values to \( f_c' \). The loading processes are assumed to start from the initial hydrostatic pressure state, \( \sigma_1^0 = \sigma_2^0 = \sigma_3^0 = N \), where \( N \) is the confining pressure. The loading paths were in the compression meridian plane of stress space. The Willam-Warnke model with five parameters was adopted, using the proposed parameters in references [4].
TABLE I. PROPERTIES OF THE THREE PHASES OF CONCRETE [3].

<table>
<thead>
<tr>
<th>Phase</th>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>K/GPa</td>
<td>27.91</td>
</tr>
<tr>
<td></td>
<td>G/GPa</td>
<td>18.45</td>
</tr>
<tr>
<td>Water (20°C)</td>
<td>K/GPa</td>
<td>2.20</td>
</tr>
<tr>
<td></td>
<td>G/GPa</td>
<td>0</td>
</tr>
<tr>
<td>Air</td>
<td>K/GPa</td>
<td>0.00015</td>
</tr>
<tr>
<td></td>
<td>G/GPa</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE II. PARAMETERS OF THE PORE PRESSURE OF CONCRETE.

<table>
<thead>
<tr>
<th>State</th>
<th>Item</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>K/GPa</td>
<td>22.56 18.20 14.58 11.52 8.90</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.27 1.43 1.64 1.91 2.29</td>
</tr>
<tr>
<td>Saturated</td>
<td>K/GPa</td>
<td>23.31 19.46 16.18 13.35 10.89</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.17 0.19 0.21 0.23 0.27</td>
</tr>
</tbody>
</table>

Figure 3. The relationship between matrix’s true stress path and ultimate strength in compressive meridian plane \((n=0.1, \Delta \sigma_1 : \Delta \sigma_2 : \Delta \sigma_3 = 1 : 0 : 0)\).

Figure 4. The relationship between matrix’s true stress path and ultimate strength in compressive meridian plane \((n=0.3, \Delta \sigma_1 : \Delta \sigma_2 : \Delta \sigma_3 = 1 : 0 : 0)\).
In fig. 3 – fig. 4, it showed the relationship curves between the loading path of matrix’s real stress and failure strength, corresponding to the ideal concrete, dry concrete and saturated concrete, in the loading path \((n=0.1, 0.3, N=0~0.5, \Delta \sigma_1: \Delta \sigma_2: \Delta \sigma_3 =1:0:0 )\). \(\rho_c\) is the deviatoric stress component. For the ideal concrete \((n=0)\), the true stress of the matrix is the total stress, the intersection of the stress path with the compression meridian line denotes the strength limit state. For the concrete specimens with void defects, in the dry condition, its pore is filled with air. Under the same total stress loading path, the real stress path of matrix in the meridional plane offset to the right roughly parallel, leading to the degradation of the corresponding nominal compressive strength. In the saturated condition, due to the existence of pore water pressure, it would eventually lead to the nominal compressive strength less than the dry state when reach the strength state. With the increasing of porosity, the offsets would be more significant.

In fig. 5, it showed the results in the loading path \((n=0.3, N=0~0.5, \Delta \sigma_1: \Delta \sigma_2: \Delta \sigma_3 =1:0.1:0.1 )\).

![Figure 5. The relationship between matrix’s true stress path and ultimate strength in compressive meridian plane \((n=0.3, \Delta \sigma_1: \Delta \sigma_2: \Delta \sigma_3 =1:0.1:0.1 )\).](image)

**CONCLUSIONS**

The existence of pore water pressure has a significant impact on the mechanical properties of the saturated concrete. In this paper, the effect of pore water pressure on the compressive strength of saturated concrete was discussed by the point of effective stress. The strength of saturated concrete is determined by both the confining pressure and the pore water pressure. The existence of water pressure in pore changes the loading path of the matrix’s true stress in the principal stress space.
Therefore, the compressive strength of saturated concrete would be decreased under different stress state compared with the dry concrete, which is influenced by the initial hydrostatic stress, pore ratio and loading path.

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