Creep of Fly Ash Concrete under Sulfate Attack Based on Consolidation Theory and Damage Theory

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Abstract. This paper focuses on the creep characteristics of fly ash concrete corroded by sulfate. Firstly, based on the existing research, combined with the creep consolidation theory of concrete, the creep prediction model of fly ash concrete suitable for corrosive environment is analyzed. Secondly, through the analysis of the progress of sulfate corrosion of fly ash concrete, the concept of damage degree in damage theory is introduced to establish the creep calculation model of sulfate corrosion of fly ash concrete. Finally, the calculated value of the model is compared with the test value. The results show that the calculated value of the model is in good agreement with the experimental data and are consistent with the creeping growth trend.

Keywords. Fly ash concrete, creep, sulfate attack, consolidation, damage.

1. Introduction

As one of the important contents of the research on the time-varying characteristics of concrete materials, creep has always been valued by researchers. Although the creep of concrete is considered in most national design codes, further research is needed to accurately predict and control the creep and its influence on structural performance. Especially for the problem of concrete creep under the actual environment, although there have been relevant reports [1], most of them are qualitative analysis, and the quantitative research on creep and its influencing factors is still very insufficient.

Sulfate corrosion resistance is a hot issue in the study of concrete durability. The results show that the concrete forms of sulfate attack concrete are as follows: the sulfate ion is transmitted to the concrete through various ways and reacts with the hydration products of cement or crystalizes and precipitates directly in the concrete, resulting in the expansion, cracking, peeling and other phenomena of the concrete, accelerating the deterioration of the durability of the structure, and ultimately causes the structure to lose its bearing capacity and integrity [2].

Aiming at the creep characteristics of fly ash concrete under sulfate corrosion, this paper firstly analyzes the creep prediction model of fly ash concrete suitable for corrosive environment based on the existing research and combining with the creep consolidation theory of concrete. Secondly, through the analysis of the progress of sulfate corrosion of fly ash concrete, the concept of damage degree in damage theory is introduced to establish the creep calculation model of sulfate corrosion of fly ash concrete. Finally, the calculated value of the model is compared with the experimental value, and the applicability of the model built in this paper is proposed.
2. Creep Model of Fly Ash Concrete Based on Consolidation Theory

At present, B3 model [3], ACI209R model [4] and GL2000 model [5] are widely used to calculate the creep of ordinary concrete at home and abroad. Different from ACI209R model and GL2000 model, B3 model is based on the theory of concrete consolidation, and more calculation parameters are introduced into creep calculation model, and the parameters in the calculation formula have exact physical significance. At the same time, B3 model also considers the influence of creep parameters, which makes every creep parameter uncertain. Therefore, an uncertain coefficient $\gamma$ can be added before each coefficient of $q_1$-$q_4$ in the partial calculation formula of B3 model, thus a creep calculation formula meeting the actual situation can be obtained. A large number of experiments show that the uncertainty coefficient $\gamma$ follows a normal distribution with a mean value of 1. Wang [6] through a large number of creep test analysis and research shows that: the physical meaning of each parameter in B3 calculation model formula is clear, and the result calculated by this model is more consistent with the theoretical calculation value; and B3 model is well considered, which is closer to the actual situation compared with other model calculations. Therefore, the creep model of fly ash concrete is suitable to be based on B3 model.

Literature [7] established a modified B3 fly ash concrete creep model based on consolidation theory by analyzing and calculating a large number of experimental data [8-10] by domestic and foreign scholars. The specific calculation formula in the model is as follows

$$C(t, t_0, t') = q_1 + \gamma_2 q_2 Q(t, t') + \gamma_3 q_3 \ln[1 + (t - t')^n] + \gamma_4 q_4 \ln(t / t')$$  \hspace{1cm} (1)

In the equation (1), $q_1$ is the instantaneous deformation elastic coefficient, $q_2$ is aging viscoelastic coefficient and $q_3$ is non aging viscoelastic coefficient; $q_4$ is the rheological coefficient, and its physical meaning and calculation formula are detailed in reference [3]. Three parameters of $\gamma_2$, $\gamma_3$ and $\gamma_4$ are introduced when considering the influence of fly ash. Among them, $\gamma_2$ represents the influence coefficient considering the colloidal content and strength of fly ash cement, $\gamma_3$ represents the influence coefficient of water binder ratio, and $\gamma_4$ represents the influence coefficient of aggregate colloidal ratio. The expressions of $\gamma_2$-$\gamma_4$ are as follows:

$$\gamma_2 = 0.829 + 0.713 f_{cm28}^{3.532} \cdot b^{1.834}$$ \hspace{1cm} (2)

$$\gamma_3 = 3.546 - 14.808 (w / b)^{2.167}$$ \hspace{1cm} (3)

$$\gamma_4 = 0.995 + 0.04(a / b)^{0.643}$$ \hspace{1cm} (4)

In the equations (2-4), $f_{cm28}$ is the strength of fly ash concrete at 28 days, $b$ is the mass of cementitious material in unit volume concrete, $w / b$ is the water cement ratio, and $a / b$ is the mass ratio of aggregate and cementitious material.

The regression process is quite complex and the parameters are various, but R square of the regression consistent degree in equations (2-4) are not less than 0.8. Therefore, the regression results have good applicability, conform to the objective law and are in good agreement with the development trend of the creep of fly ash concrete.

3. Creep of Fly Ash Concrete Under Sulfate-Corroded

In the damage mechanics theory, the degree of mechanical degradation in materials is defined by the degree of damage. The expression is as follows:

$$D = \frac{A_c - \tilde{A}_c}{A_c}$$ \hspace{1cm} (5)
where \( D \) is the damage degree of fly ash concrete, \( A_c \) is the cross-sectional area of the fly ash concrete component when it is not eroded, and \( \overline{A} \) is the bearing area of the intact part of the fly ash concrete after being eroded.

In practice, it is very difficult to measure the bearing area of intact concrete, and there is no unified measurement standard. For this reason, some scholars put forward the principle of strain equivalence. The strain produced by the stress action when the material is undamaged \((D = 0)\) is equivalent to the strain produced by the stress action when the material is eroded \((D \neq 0)\). In the environment of erosion, the damage caused by the erosion of fly ash concrete is related to stress level, concentration of erosion solution and erosion time. Cao [11] obtained the damage variable formula of continuous load under sulfate erosion through experiments

\[
D = 1 - \exp\left[ a \times n^b \times (f_c^c)^d \times (\sigma / f_c)^e \times \phi \times t^f \right]
\]  

(6)

where \( n \) is the concentration of erosion solution (%), \( f_c \) is the compressive strength of fly ash concrete prism; \( \sigma / f_c \) is the stress level; \( \phi \) is the effective thickness of fly ash concrete component, \( \phi = 2V / S \); \( V \) is the volume of fly ash concrete component; \( S \) is the surface area of fly ash concrete component; \( t \) is the erosion time; \( a, b, c, d, e \) and \( f \) are the fitting regression coefficients.

For fly ash concrete members under sulfate attack, the average strain is equal everywhere on the concrete members when subjected to continuous load. Furthermore, the main effect on fly ash concrete components is the stress and strain of undamaged concrete. Thus, combined with the fly ash concrete creep model in the previous section, the fly ash concrete creep during the sulfate environment erosion can be expressed as

\[
\varepsilon_{\text{cr}}^{\text{sul}}(t) = \bar{\sigma}(t) \cdot J(\tau, t')
\]  

(7)

\[
\bar{\sigma}(t) = \frac{\sigma(t)}{1 - D}
\]  

(8)

\[
J(\tau, t') = q_1 + C_0(t, t_0)
\]  

(9)

\[
C_0(t, t_0) = \gamma_2 q_2 Q(t, t') + \gamma_3 q_1 \ln[(1 - \tau)^{0.1} + 1] + \gamma_4 q_1 \ln(t / t')
\]  

(10)

where \( \varepsilon_{\text{cr}}^{\text{sul}} \) represents the creep of fly ash concrete under single sulfate attack; \( \bar{\sigma} \) represents the effective stress; \( J(\tau, t') \) represents the creep function of fly ash concrete.

Since the sulfate corrosion test of fly ash concrete creep rare, therefore, according to a part of experimental data in [12] (four groups of 1-3, 2-1, 2-2, and 2-3). Using SPSS software, entering formula input data to fit the pending regression parameters. \( a = -2.663, b = 1.214, c = -1.248, d = 0.222, e = -0.369, f = 0.947 \), correlation coefficient \( R^2 = 0.857 \), are in good agreement.

4. Model Validation

The calculated values of the established fly ash concrete creep model under a single sulphate erosion environment (5% concentration, 15% stress level) were compared with the experimental data (group 1-1, group 1-2) not used for fitting in literature [12] and the deviations were compared. Among them, the comparison results and deviation analysis between the calculated value of the modified model and group 1-1 (1% sulfate concentration, 15% stress level) in reference [12] are shown in figure 1 and table 1.
Figure 1. Comparison between the calculated values of the modified fly ash concrete model and the experimental values at 1% sulfate concentration and 15% stress level.

Table 1. Deviation between calculated value and test value of modified fly ash concrete model at 1% sulfate concentration and 15% stress level (%).

| Creep time (days) | 30  | 60  | 90  | 180 | 270 | 360 | 450 | 540 |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Deviation (%)    | 1.27| 6.22| 6.74| 6.87| 4.68| 4.41| 5.49| 8.57|

*deviation = |test value - revised model calculation value| / test value.

From figure 1 and table 1, it can be concluded that the calculated value of the creep model of fly ash concrete established in this paper is in good agreement with the test value, which can roughly reflect the development trend of creep. Within 0-90 days, the calculation maximum deviation of fly ash concrete is 6.22%; within 90-180 days, the calculation maximum deviation of fly ash concrete is 6.87%; within 180-450 days, the calculation maximum deviation first decreases and then increases to 5.49%; when creep develops to 540 days, the error is 8.57%.

From figure 2 and table 2, it can be concluded that the calculated value based on the B3 theoretical creep model of fly ash concrete is basically consistent with the test value, which can roughly reflect the development trend of creep. Within 0-90 days, the calculation maximum deviation of fly ash concrete is 4.21%; within 90-180 days, the calculation maximum deviation of fly ash concrete is 11.07%; within 180-450 days, the calculation maximum deviation gradually reduces to 3.17%; when creep develops to 540 days, the error is 2.15%.

Figure 2. Comparison of calculated values of modified fly ash concrete model with test values at 5% sulfate concentration and 15% stress level.
Table 2. Deviation between calculated value and test value of modified fly ash concrete model at 5% sulfate concentration and 15% stress level (%).

| Creep time (days) | 30  | 60  | 90  | 180 | 270 | 360 | 450 | 540 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Deviation (%)     | 2.27| 4.21| 3.78| 11.07| 4.53| 6.61| 3.17| 2.15|

\[ \text{deviation} = \frac{\text{test value} - \text{revised model calculation value}}{\text{test value}}. \]

It can be seen from figures 1-2 and tables 1-2 that factors such as fly ash content, sulfate solution concentration and stress level are taken into account in the creep model constructed, and the calculated value is roughly consistent with the test value curve, which conforms to the objective law.

5. Conclusion

The currently used concrete creep models, such as ACI209, GL2000, B3, etc., can not be used to predict the creep of fly ash concrete under sulfate corrosion. In this paper, based on the characteristics of clear physical meaning and modifiable parameters in B3 model, on the basis of analyzing the long-term deformation mechanism of sulphate corrosion fly-ash concrete, combined with the concrete damage theory, considering the factors of fly ash content and corrosion solution concentration The creep calculation model of fly ash concrete under sulfate corrosion is used, and the model is verified by the test data, which provides a certain engineering reference for the application of fly ash concrete in corrosive environment.

This article only conducted a preliminary study on the creep of fly ash concrete in a sulfate immersion environment, but the actual sulfate corrosion environment is various, including dry wet alternation, contact with salt soil erosion and so on, which needs further study.

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