Study on Application of Blast-furnace Slag Cement Concrete to PC Girders Based on Evaluation of Shrinkage and Creep

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The application of blast-furnace slag cement concrete (BC) to PC girders is one good method to prevent ASR; however, its shrinkage and creep have not been evaluated. This paper summarizes the result of the compression creep tests executed, and shows that the shrinkage and creep of BC can be evaluated through conventional equations, usually used for normal cement concrete (NC). In addition, the analysis results indicate that even if BC is applied, the deflection and prestress loss of PC girder differ only a little from that of NC.

Keywords: blast-furnace slag cement concrete, creep, shrinkage, PC girders

1. Introduction

High-strength concrete has been used for PC girders because prestress force needs to be applied at an early age. Deterioration of PC girders caused by ASR has been found however, because of the large alkali content in high-strength concrete. The application of BC to PC girders is one good method to prevent ASR. However, the prediction formula of shrinkage and creep can be applied only to NC and early strength cement concrete in the Design Standards for Railway Structures (RC standards) [1]. This paper shows the evaluation of the curing, strength appearance, shrinkage and creep of BC, and the study on the application of BC to PC girders through compressive creep tests and 3D FEM.

2. The compression creep test outline

Table 1 outlines the specimens. There are differences in the replacement ratio of the blast-furnace slag, the load age (t'), the loading stress (σcp) and the volume to surface ratio (V/S). The compressive strength at 28 days of age (f'(28)) is aimed at being 40-N/mm² but the B7-d10-s59 is aimed at being 40-N/mm² at 7 days. Table 2 shows the concrete mixture. The W/B of BC is lower than NC because the strength appearance is later. Figure 1 shows the compressive strength of concrete (f'(t')). Figure 2 shows the relationship between the Young’s modulus and f'(t'). Figure 3 shows the situation of the compression creep test.

Table 1 Specimens’ outline

| CA | Name   | Slag (%) | t' (day) | σcp (N/mm²) | V/S (mm) | f'(28) (N/mm²) | σcp/f'(28) | E(t') (kN/mm²) | ε' (E(t')/σcp) × 10⁻⁶ |
|----|--------|----------|----------|-------------|----------|----------------|------------|----------------|----------------------|
| 1  | B14-d10-s40 | 60%      | 14       | 16.0        | 100      | 28.8           | 36.6       | 0.56           | 24.3 | 659 (780) |
| 2  | B28-d10-s40 | 60%      | 28       | 14.6        | 100      | 36.3           | 36.3       | 0.40           | 27.8 | 525 (619) |
| 3  | B28-d10-s20 | 60%      | 28       | 8.0         | 100      | 39.9           | 39.9       | 0.20           | 29.0 | 276 (293) |
| 4  | B28-d30-s20 | 60%      | 28       | 8.0         | 300      | 39.9           | 39.9       | 0.20           | 29.0 | 276 (282) |
| 5  | N14-d10-s40 | 0%       | 14       | 16.0        | 100      | 39.1           | 49.7       | 0.41           | 30.2 | 531 (552) |
| 6  | N28-d10-s40 | 0%       | 28       | 18.0        | 100      | 45.1           | 45.1       | 0.40           | 31.4 | 574 (563) |
| 7  | B7-d10-s59  | 60%      | 7        | 27.5        | 100      | 46.5           | 76.5       | 0.59           | 27.4 | 1004 (1043) |
3. Results of the compression creep test

3.1 Shrinkage strain

Figure 4 and 5 show the shrinkage strain of BC and NC. \( \varepsilon'_{\text{exp}}(t_0, t) \) is the measured value in the non-loaded specimens, and \( \varepsilon'_{\text{cal}}(t_0, t) \) is the calculated value by (1), (2). The unit cement content in (1), (2) is changed to the unit binder content in case of BC.

\[
\varepsilon'_{\text{cal}}(t, t_0) = \left[ 1 - \exp \left\{ -0.108(t - t_0)^{0.66} \right\} \right] \varepsilon'_{ab}
\]  
\(1\)

\[
\varepsilon'_{\text{cal}}(t, t_0) = \varepsilon'_{ab} + \varepsilon'_{\text{as}}(t, t_0)
\]  
\(2\)

where \( t_0, t \): the equivalent age of concrete when the drying starts and the drying is kept;

\( \varepsilon'_{ab} \): the final shrinkage strain of concrete;

\( \varepsilon'_{\text{as}}(t, t_0) \): the dry shrinkage strain of concrete during the period \( t_0 \) to \( t \); and

\( \varepsilon'_{\text{al}}(t, t_0) \): the autogenous shrinkage strain of concrete during the period \( t_0 \) to \( t \).

One reason for the difference between \( \varepsilon'_{\text{exp}}(t_0, t) \) and \( \varepsilon'_{\text{cal}}(t_0, t) \) is the effect of aggregate, because this relationship between BC and NC is the same. The difference in \( t_0 \) over 14 days of age only has a small effect on the difference in \( \varepsilon'_{\text{exp}}(t_0, t) \). \( \varepsilon'_{\text{exp}}(t_0, t) \) decreases with the increase in \( V/S \). Figure 6 shows the relationship between \( \varepsilon'_{\text{exp}}(t_0, t) \) and \( \varepsilon'_{\text{cal}}(t_0, t) \) of BC and NC. The area of \( \pm 0.5 \varepsilon'_{\text{cal}}(t_0, t) \) is also shown, in order to indicate the variation of about 50% in \( \varepsilon'_{\text{exp}}(t_0, t) \) against \( \varepsilon'_{\text{cal}}(t_0, t) \). \( \varepsilon'_{\text{exp}}(t_0, t) \) of BC can be also calculated with the same accuracy as NC by (1) and (2) which are applicable to NC, because all \( \varepsilon_{\text{cal}}(t_0, t) \) are within the variation.

### Table 2 Concrete mixture

| CA | \( c_{\text{max}} \) (mm) | Slump (cm) | Air (%) | W/B | \( s/a \) (%) | Unit weight (kg/m³) |
|----|----------------|--------|--------|-----|-------------|------------------|
| SE |                |        |        |     |             | \( W \) | \( C \) | \( BS \) | \( S \) | \( G \) |
| 1 ~ 4 | 20           | 12     | 4.5    | 0.52| 48          | 161            | 124            | 186         | 875       | 968       |
| 5, 6  | 20           | 12     | 4.5    | 0.62| 49          | 159            | 257            | 0           | 924       | 990       |
| 7    | 20           | 12     | 5.0    | 0.34| 45          | 159            | 186            | 279         | 758       | 956       |

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Fig. 1 Compressive strength

Fig. 2 Young’s modulus

Fig. 3 Test situation

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Fig. 4 Shrinkage strain of BC

Fig. 5 Shrinkage strain of NC

Fig. 6 Accuracy of prediction
3.2 The creep coefficient

Figure 7 and 8 show the creep coefficient of BC and NC. $\varphi_{\text{exp}}(t', t', t_0)$ is the calculated value by the measured value of the non-loaded and loaded specimen using (3), and $\varphi_{\text{cal}}(t', t', t_0)$ is the calculated value using (4) or (5). The unit cement content in (4), (5) is changed to the unit binder content when $\varphi_{\text{cal}}(t', t', t_0)$ of BC is calculated.

$$
\varphi_{\text{exp}}(t', t', t_0) = \frac{\varepsilon'_{\text{exp}}(t', t_0) - \varepsilon'_{\text{cal}}(t_0)}{\varepsilon'_{\text{cal}}(t_0)}
$$

(3)

$$
\varphi_{\text{cal}}(t', t', t_0) = \frac{1}{E_c} \left( 1 - \exp \left[ \frac{0.09(1 - t'/t_0^{0.5}) - 1}{E_c} \right] \right) = \frac{1}{E_c} \left( 1 - \exp \left[ \frac{0.09(1 - t'/t_0^{0.5}) - 1}{E_c} \right] \right)
$$

(4)

$$
\varphi_{\text{cal}}(t', t', t_0) = \frac{4W(1 - \text{RH}/100) + 350}{12 + f'_{c}^{2}(t')} \log (t - t' + 1). E_c
$$

(5)

where $t_0$, $t'$, $t$: the equivalent age of concrete when the drying starts, the loading starts and the drying is kept;

$$
\varepsilon'_{\text{exp}}(t', t_0): \text{the creep strain of concrete in the loaded specimen during the period } t_0 \text{ to } t;
$$

$$
\varepsilon'_{\text{cal}}(t', t_0): \text{the elastic strain of concrete in the loaded specimen when } t', t_0; \varepsilon'_{\text{cal}}(t, t_0): \text{the strain of concrete in the loaded specimen during the period } t_0 \text{ to } t;
$$

$$
\varepsilon'_{\text{exp}}(t', t_0): \text{the strain of concrete in the non-loaded specimen during the period } t_0 \text{ to } t;
$$

$\phi$: the final creep strain of concrete per unit stress; $W$: the unit water content (kg/m$^3$); and $\text{RH}$: the relative humidity (%).

$\varphi_{\text{exp}}(t', t_0)$ decreases with increase in $t'$ and the V/S. $\varphi_{\text{exp}}(t', t_0)$ of BC is larger than that of NC. As one of these reasons, it is inferred that the W/B of BC needs to be smaller than that of NC to achieve the same $f'_{c}$. Figure 9 shows the relationship between $\varphi_{\text{exp}}(t', t_0)$ and $\varphi_{\text{cal}}(t', t_0)$ of BC and NC, and also shows the variation area of $\pm 0.5\varphi_{\text{cal}}(t', t_0)$. $\varphi_{\text{exp}}(t', t_0)$ of BC can be also calculated with the same accuracy as NC by (4), (5) which are applicable to NC.

![Fig. 7 Creep coefficient of BC](image1)

![Fig. 8 Creep coefficient of NC](image2)

![Fig. 9 Accuracy of prediction](image3)

4. The deformation prediction of PC girders using 3D FEM Analysis

The deformation and prestress loss over 100 years of railway PC girders made from BC were analyzed by 3D FEM program. Figure 10 shows the analyzed PC box girder (post-tensioning, 45 m). Table 3 shows the analysis case. PC-N7 is the making from NC. $t'$ and the W/B are decided by reference to the design examples of general PC girders. PC-B14 is the making from BC. $t'$ and the W/B are decided by reference to the result of CASE 2 in the compressive creep test. Figure 11 shows the input shrinkage stain and creep coefficient, which are calculated by (1), (4). RH is set to 70 %, and $t_0$ is set to 3-day age. The girder weight (24.5 kN/m$^2$, 1-day age), the prestress (822 N/mm$^2$) and the track weight (7.5 kN/m$^2$, 1000-day age) are considered in the analysis.

Figure 10 shows the deformation and stress after 100 years. Figures 12 and 13 show the deflection and the PC wire stress. The deflection increases with prestress, and decreases with track weight. The PC wire stress at the edge decreases after it is prestressed, and on the other hand, that at the center decreases with prestress and increase with track weight.

The difference of the deflection between the 100-year PC-N7 and PC-B14 is small because the shrinkage and creep properties can be made almost the same if the conditions are changed in consideration of the difference of each level of strength.

![Fig. 10 Deformation and stress](image4)

![Fig. 11 Input shrinkage strain and creep coefficient](image5)

![Fig. 12 Deflection](image6)

![Fig. 13 PC wire stress](image7)

![Table 3 Analysis case](image8)

| CASE   | $f'_{c}$ (N/mm$^2$) | $f'_{c}(t')$ (N/mm$^2$) | Unit weight (kg/m$^3$) | $W/B$ | $t'(\text{day})$
|--------|---------------------|-------------------------|------------------------|-------|-----------------
| PC-N7  | 40                  | 34                      | 160                    | 320   | 0.48            | 7        |
| PC-B14 | 40                  | 28.8                    | 161                    | 124   | 186             | 0.52     | 14       |
5. Conclusions

The shrinkage and creep properties of BC can be calculated by the prediction formula for NC on the RC standards. The deflection and the prestress loss of 100-year age PC girders made from BC are almost the same as these of PC girders made from NC if the conditions are changed in consideration of the difference in strength appearance between NC and BC.

References

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