Modeling the effect of temperature on strength development for cast-in-place box girder

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Abstract: In this paper, winter construction of cast-in-place box girder of Rongwu Expressway Project is taken as the research object. By analyzing the internal temperature field development data of box girder concrete structure and using MIDAS FEA finite element software, the simulation results are similar to those in the field. The development of concrete internal temperature field at ambient temperature 0°C and -10°C is calculated. The strength prediction of cast-in-place box girder concrete structure at lower internal temperature was carried out by using the maturity model established in laboratory test. With the decrease of ambient temperature, the internal temperature of cast-in-place box girder concrete structure decreases. The lower temperature of concrete in box girder is the edge part of the two flank plates, the windward side and the combined part of old and new concrete. Based on the maturity theory established earlier, the 5d tensile strength of different parts was calculated. Under 0°C and -10°C conditions, the minimum strength of the edge of cast-in-place box girder concrete wing plate is 47 MPa and 41.2 MPa, the minimum strength of the junction of new and old concrete is 50.5 MPa and 50.3 MPa and the minimum strength of the windward side is -52.2 MPa and 51.2 MPa respectively. The edge of the wing plate and the interface of new and old concrete should pay special attention to the protective insulation measures.

1. Introduction
Rongwu Expressway is Rongcheng to Wuhai Highway referred to as Rongwu Expressway. It is an important part of the peripheral backbone expressway network of "four vertical and three horizontal" in Xiongan New Area. It is of great significance for the Xiongan New Area to play the leading and demonstrative role of the first batch of pilot projects for the construction of a transportation power. Affected by the construction period, the construction of the hanging basket of the project should run through the whole northern winter period. Winter in North China is cold and dry. The construction in winter not only affects the personnel allocation, mechanical operation and production efficiency, but also makes it difficult to maintain the prestressed cast-in-place beam concrete in the cold environment. Concrete is easy to be subjected to early freezing, which leads to the deterioration of its mechanical properties and durability and seriously affects the quality of engineering construction. The results show that the hydration force of cementitious materials in concrete changes significantly with the ambient temperature. The strength of concrete is closely related to curing age and temperature. It is generally believed that the strength of concrete is a function of the product of curing age and temperature which
reflects the mathematical formula of hydration process and temperature of cementitious materials in concrete which is the commonly used theory of concrete maturity. The maturity theory can be used to calculate the development of concrete strength at different temperatures, but the temperature of different parts will not be consistent in the field curing process. If the temperature of the selected point is not appropriate, the local concrete strength will be too low to be detected. In this paper, Midas FEA finite element simulation software as a tool based on the preliminary monitoring by changing different working conditions to establish a relatively close to the entity model. The low temperature was found by simulating the internal temperature field distribution of mass concrete. Combined with the maturity theory, the strength of different parts is calculated to guide the smooth construction of the project.

2. Maturity theory and model building

2.1. Strength development law of cryogenic concrete based on maturity theory

In this paper, the relative tests were carried out for the mixing ratio of cast-in-place box girder concrete in Rongwu high-speed at 5℃, 10℃ and 20℃ for the mold temperature and curing temperature. The theoretical calculation formula of maturity and concrete strength is established, as shown in Table 1, Table 2, Table 3 and Figure 1.

| Curing temperature /℃ | 1d | 2d | 3d | 7d |
|-----------------------|----|----|----|----|
| 5                     | 17.8 | 31.4 | 37.8 | 48.2 |
| 10                    | 25.6 | 35.8 | 44.8 | 51.6 |
| 20                    | 34.5 | 42.3 | 48.9 | 58.1 |

| Curing temperature /℃ | Maturity / (℃*h) |
|-----------------------|------------------|
| 1d                    | 2d | 3d | 7d |
| 5                     | 480 | 960 | 1440 | 3360 |
| 10                    | 600 | 1200 | 1800 | 4200 |
| 20                    | 840 | 1680 | 2520 | 5880 |

Cement is P.O52.5 ordinary Portland cement provided by Laishui Jinyu Jidong Environmental Protection Technology Co., Ltd. Fly ash for shandong huaneng dezhou power industrial company production of F class II grade fly ash. The slag is S95 granulated blast furnace slag produced by Hebei Qianjin Metallurgical Technology Co., Ltd. Fine aggregate for sand mining in zhangjiakou fu tai mining co., LTD production of medium sand II area. Coarse aggregate is gravel produced by Laishui County Shunhe Building Materials Co., Ltd. Superplasticizer is a polycarboxylic acid superplasticizer produced by Subot Co., Ltd.
Figure 1 The fitting formula of maturity and concrete strength

In Fig. 1, F is the compressive strength and M is the maturity. According to the figure, the relationship between concrete strength and maturity can be seen in Equation (1) below.

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f = 59.46e^{-\frac{551.79}{M}}
\]  

(1)

2.2. Simulation of internal temperature field of box girder

The winter insulation of this project is the template resistance wire and rock wool. Covered with an electric blanket. The cavity of the box girder is heated by steam and hot air cannon. Windproof cloth shall be used to cover the whole compartment on the windward side. In the early stage of this paper, a large number of temperature measurement data were collected based on repeated groping tests and adjusting temperature measurement points for the entity monitoring data of cast-in-place box girder concrete structures. The internal temperature field of cast-in-place box girder concrete structure under the condition above 0°C was deduced by using the finite element simulation software. The simulation of determining the value of relevant boundary parameters is shown in Figure 2 and Figure 3 below. The lower temperature of the cast-in-place box girder is the end of the cast-in-place box girder and the end positions of the two flank plates.

Figure 2 Temperature point layout

Figure 3 Temperature field distribution

According to the winter temperature statistics of the project location over the years, two working conditions of the average ambient temperature of 0°C and -10°C are selected. The finite element numerical model is modified by using the temperature monitoring data of the project site and the internal temperature field distribution of cast-in-place box girder concrete structure is simulated under the ambient temperature of 0°C and -10°C. The strength development of typical parts of box girder is predicted by maturity theory.

3. Prediction of temperature field and concrete strength of cast-in-place box girder under different working conditions

3.1. Development of temperature field of box girder and prediction of concrete strength at ambient temperature of 0°C

The working conditions were selected as follows: the ambient temperature was 0°C, the mold insertion temperature was 20°C, the electric blanket was heated for 3 days, the removal time of the end template was 1.5 days and the template was heated for 5 days.
3.1.1. Temperature field distribution of box girder concrete

Aiming at the low temperature inside the box girder, a typical point is selected to analyze its temperature development by finite element numerical simulation. The selected points are shown in Figure 4 and Figure 5. The temperature measuring points are selected as the contact point between the upper end face of the box girder and the air 4, the side end point of the wing plate 6, the contact point between the lower end face of the box girder and the air 11, and the contact point between the lower end face of the box girder and the old concrete 13.

It can be seen from the above figure that the lower temperature field distribution of box girder is at each end face especially the side end of the wing plate where the temperature of the whole girder body is lower and the temperature drops rapidly which should be protected.

3.1.2. Strength prediction of concrete

The maturity and strength of selected points at ambient temperature 0℃ are shown in Table 4 and Table 5. The slow development of lateral edge strength should be the focus of attention.

| Point | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Maturity /°C·h | 2399.8 | 4537.2 | 5064.8 | 5037.8 | 5235.7 | 2601.1 | 2323.2 | 5314.9 | 3862.5 |
| Maturity /°C·h | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |

| Point | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Compressive strength /MPa | 47.4 | 52.8 | 53.5 | 53.5 | 53.7 | 48.2 | 47.0 | 53.8 | 51.7 |
| Compressive strength /MPa | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |

3.2. Development of temperature field of box girder and prediction of concrete strength at ambient temperature of -10℃

The working conditions were selected as follows: the ambient temperature was 0℃, the mold insertion temperature was 20℃, the electric blanket was heated for 3 days, the removal time of the end template was 1.5 days and the template was heated for 5 days.
3.2.1. Temperature field distribution of box girder concrete

Aiming at the low temperature inside the box girder, a typical point is selected to analyze its temperature development by finite element numerical simulation. The selected points are shown in Figure 6 and Figure 7. The temperature measuring points are selected as the contact point between the upper end face of the box girder and the air 4, the side end point of the wing plate 6, the contact point between the lower end face of the box girder and the air 11, and the contact point between the lower end face of the box girder and the old concrete 13.

It can be seen from the above figure that the temperature field distribution of box girder is lower at each end face especially at the side end of the wing plate where the temperature of the whole girder body is lower and the temperature drops faster. When the ambient temperature is -10°C the side end of the wing plate has been below 0°C for about 2 days which should be protected.

3.2.2. Strength prediction of concrete

The maturity and strength of selected points at ambient temperature -10°C are shown in Table 6 and 7. As the ambient temperature decreases, it can be seen from the above table that the strength of the end and side end of the cast box girder further decreases.

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Maturity /°C*h | 1494.1 | 4071.2 | 4727.9 | 4707.2 | 4948.8 | 1745.5 | 1789.0 | 5038.1 | 3978.5 |
| Maturity /°C*h | 1494.1 | 4071.2 | 4727.9 | 4707.2 | 4948.8 | 1745.5 | 1789.0 | 5038.1 | 3978.5 |

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| Compressive strength /MPa | 41.2 | 52.1 | 53.1 | 53.0 | 53.3 | 43.5 | 43.8 | 53.5 | 51.9 |
| Compressive strength /MPa | 51.6 | 51.2 | 53.2 | 50.3 | 55.3 | 55.7 | 55.9 | 55.9 | 55.4 |

It can be known from the predicted values of maturity and strength above. The concrete strength at the end of the cast-in-place box girder and the end of the wing plate is the lower of the whole box girder. With the decrease of ambient temperature, its strength decreases, so the conservation measures should be strengthened. In particular, the wing at the end of the side for the lowest strength should be focused on protection.
3.3. Improvement measures

According to the above simulation prediction, the strength of the end of cast-in-place beam body and the side end of the wing plate is low. In particular, the side end of the wing plate is the lowest temperature part of the whole beam body because of its thin-walled structure. The following suggestions are put forward for the above problems:

1) in view of the problems of slow temperature rise and low strength at the side end of the cast-in-place box girder concrete wing plate, it is suggested to strengthen the heat preservation and curing of the end of the wing plate such as covering the quilts and heating the internal embedded resistance wire, etc. and strengthen the monitoring of the temperature of the end concrete.

2) according to the simulation analysis and strength prediction results, when the ambient temperature is lower than 0°C the concrete strength of the end of the newly poured box girder concrete structure is lower in the range of 0.4m. It is suggested that the embedded resistance wires should be heated and cured in the range of 0.6m when the ambient temperature is lower than 0°C and the reasonable spacing of the embedded resistance wires should be determined through tests. At the same time, the site personnel should take insulation measures such as covering the quilt or other insulation measures and should strengthen the monitoring of the temperature of the concrete in this part.

3) heating and heat preservation measures to ensure the concrete temperature to improve the early strength of great significance should strictly follow the heat preservation and heating measures in place to ensure the heating and curing time

4. Conclusion

The theoretical model of concrete strength and maturity was established with the curing temperature of 5°C, 10°C and 20°C as 5°C, 10°C and 20°C in laboratory tests. Through field verification, the model has strong correlation with field concrete curing strength. Through the analysis of a large number of monitoring data and finite element software, the distribution of temperature field inside concrete is calculated. According to the low temperature, the strength value of concrete under different working conditions (0 and -10) is calculated. With the decrease of ambient temperature, the strength of the wing edge, the junction of old and new concrete and the part of the windward side are lower. At the edge of the wing plate, the junction of old and new concrete and the part of the windward side, the corresponding improvement measures are put forward to provide guidance for similar projects.

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