Exploring the causes and repair measures of early cracks in prefabricated bridges

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Abstract: The study aims to explore the causes of early cracks in prefabricated bridges and propose repair measures. The study designs a test first. Analysis of the mix proportion and uneven shrinkage of concrete shows that, in concrete, the ratio of air content to water-binder is a quadratic parabola, the fly ash and water-binder ratio have a linear relationship, and slurry collection ratio and the water-binder ratio is inversely proportional. The test results suggest that the cracks of bridges are caused by the decrease of relative humidity in concrete. Afterward, some corresponding repair measures are put forward to safeguard the prefabricated bridges.

1. Introduction

In the deck construction of the prefabricated bridges, there are many schemes for the concrete construction of the deck, which can be roughly divided into two types: Cast-in-place and Prefabricated. The main construction steps of cast-in-place are: first, the protective formwork is erected at the construction site and then inset reinforcement to fix it; finally, the concrete is poured, and the concrete will be maintained and removed from the forms\textsuperscript{[1,2]}. Although the overall effect of this construction is good, it is slightly tedious and it takes a long time. If there is an emergency construction request, it is inevitable to delay the project delivery\textsuperscript{[3]}. Relatively speaking, using prefabricated concrete to cover the bridge deck avoids some defects of cast-in-place to a large extent, but there are also shortcomings. As the overall structure of the prefabricated bridge is composed of scattered segments, its mechanical performance is relatively weaker compared with the cast-in-place bridge, so it is not suitable to use in some earthquake-prone areas such as Sichuan, Guizhou and Yunnan in the construction process\textsuperscript{[4,5]}.

Wang Xuzhong(2021) The application advantages of prestress technology in the field of municipal highway bridge construction gradually appear. The application of this technology is conducive to improving the strength of the bridge structure, it takes into account the relationship between the whole bridge and the detail components, and ensures the bridge a high traffic service level\textsuperscript{[6]}. Teng et al. (2021) compared the crack detection performance (precision and calculation amount) under 11 feature extraction methods, which provided a basis for the rapid and accurate detection of cracks in concrete structures\textsuperscript{[7]}. Balzano et al. (2019) proposed a new healing system using pre-tensioned mixed tendons to seal the cementation content of cracks\textsuperscript{[8]}.

This paper mainly studies the prefabricated bridge, analyzes the early concrete cracks of prefabricated bridge, and understands the cracking time of concrete, the main form and characteristics by means of rural research. Based on this, through designed experiment, the paper discusses the reason of the early concrete cracks of prefabricated bridge caused by the mix parameters such as water-binder ratio, fly ash, gas content and aggregate-to-cement ratio, and also discusses the corresponding repair measures. The innovation of this study is to comprehensively consider the water binder ratio, fly ash...
replacement rate, air content, slurry ratio and other factors. It is hoped that the research of this paper can help solve the problems of early cracks in bridge construction and improve the safety of bridge in the future.

2. Research on crack of prefabricated bridge

2.1 Contraction test of prefabricated bridge

The concrete contraction test of the prefabricated bridge took 28 days from casting to completion. Since the concrete cannot be demoulded due to its low strength at the initial setting stage, the generation of early cracks on bridge deck will be greatly influenced by the fixed model in the initial setting stage [9]. Considered this factor and in order to effectively reduce influence of the mold constraints, we use flexible bellows. A major advantage of this kind of pipe is that its axial deformation ability is better than that of the radial direction. Fig. 1 is a schematic diagram of concrete crack deformation based on the bellows. When the radial deformation of the bellows is not taken into account, the length deformation of the bellows can be used to replace the volume deformation, as shown in Equation (1). Variables in the equation are shown in Figure 1 [10,11]. So in the early stage of concrete setting, the length deformation can be used to replace the volume deformation. The bellows used in the test is 100mm and length is 400mm, the deformation crack of concrete is detected by dial indicator[12].

\[ \Delta V = \frac{V_{ABCD} - V_{A_{BCD}}}{V_{ABCD}} = \frac{L_1 - L_2}{L_1} = \Delta L \]  

(1)

Fig. 1 Deformation diagram of concrete of prefabricated bridge

In the actual bridge construction process, the bridge deck must be maintained for three days after the concrete is poured, and the formwork can only be removed after three days. In this experiment, the actual environment should be fully simulated and as close to the actual construction site as possible. Therefore, the initial setting time of concrete in the experiment was set as 3 days. After 3 days, the bellows mold was removed and the concrete deformation was detected at the same time, and the detection interval of contraction deformation was 2 hours[13]. In order to eliminate interference of the friction resistance of bellows and the platform for the research results, the test platform was 5° upward, then the test platform was analyzed and made force balance with the friction resistance. What's more, there are three parallel specimens in each group, to improve the accuracy of test results [14]. The test will last 30 days in total. The temperature of this test is 25℃, the error is less than 1℃, and the relative humidity is 60%, the error is less than 2%.

According to the guidance of relevant literature, the deformation of the bridge deck concrete in this test is not only affected by the mold, but also by temperature. Therefore, to improve the accuracy of the research results, the temperature factor should also be taken into account. Formula (2) is the
formula that deformation caused by temperature change ($\varepsilon_T$).

$$\varepsilon_T(t) = \int_{T_0}^{T} \alpha dT$$  \hspace{1cm} (2)

In Formula 2: $\varepsilon_T$ represents the temperature deformation of concrete, $\alpha$ represents the thermal expansion coefficient (CTE) of concrete, $T$ is the real-time temperature of concrete at time $t$, and $T_0$ represents the temperature of concrete when it is poured on bridge deck [15]. According to relevant literature, the thermal expansion coefficient is not a fixed value, which changes with the time influence, and can be calculated according to Equation (3).

$$\alpha = 132 \exp\left(-\frac{0.3 t_{eq}}{d}\right) + 7$$  \hspace{1cm} (3)

$$t_{eq} = \int_{0}^{t} \exp\left(\frac{1}{R}(\frac{U_{at}}{293} - \frac{U_{at}}{273 + T})\right)dt$$  \hspace{1cm} (4)

$$U_a = (42830 - 43T) \exp((-0.00017T)t)$$  \hspace{1cm} (5)

In above formula, $t_{eq}$ represents the equivalent age of concrete, it is influenced by the temperature, and Equation (4) shows the influence result; $T$ represents the most appropriate temperature for bridge deck cure. $R$ represents the gas constant in concrete, and it is 8.314J/(mol·K) in standard situation. $U_{at}$ represents the activation energy generated by hydration reaction of cement at a certain temperature. $U_{atT}$ represents the activation energy generated by the reaction at $T$ temperature [16]. $U_a$ represents the function of time and temperature in this experiment, which can be approximately expressed by Equation (5). Formula (6) is the water-binder ratio; Formula (7) is fly ash substitution rate; Formula (8) is the gas content; Formula (9) is the aggregate-to-cement ratio.

$$y = 1100 e^{-3.2 \text{w/cm}}$$  \hspace{1cm} (6)

$$y = 0.8(\text{FA}) + 1$$  \hspace{1cm} (7)

$$y = -0.04(\text{AC})^2 + 0.35(\text{AC}) - 0.66$$  \hspace{1cm} (8)

$$y = 3.56 J^{-1.12}$$  \hspace{1cm} (9)

w/cm: water-binder ratio; FA: fly ash substitution rate; AC: gas content; J: aggregate-to-cement ratio.

On the basis of the original experiment, there are two more influence coefficients: gas content and aggregate-to-cement ratio. Now the experiment can fully reflect the influence of age, water-binder ratio, fly ash substitution rate, gas content and aggregate-to-cement ratio on the bridge deck concrete, then the causes of early cracks in prefabricated bridge can be obtained [17]. The influence of above mentioned factors on concrete contraction and deformation can be calculated by Equations(11)–Equations(15).

$$\varepsilon_{AS}(t) = \alpha \cdot (1 + \gamma) \cdot \eta \cdot \varepsilon_{28}(\text{w/cm}) \cdot \beta(t)$$  \hspace{1cm} (10)

$$\varepsilon_{28}(\text{w/cm}) = 1100 \exp[-3.2(\text{w/cm})]$$  \hspace{1cm} (11)

$$\beta(t) = 1 - \exp(qt^p)$$  \hspace{1cm} (12)

$$\gamma = a(\text{AC})^2 + b(\text{AC}) + c$$  \hspace{1cm} (13)

$$\alpha = 1 - k(\text{FA})$$  \hspace{1cm} (14)

$$\eta = n(J)^\mu$$  \hspace{1cm} (15)
time when the contraction strain occurs; $\gamma$ is the influence coefficient of gas content on concrete contraction strain; $AC$ represents the gas content, and $a$, $b$ and $c$ represent constants respectively, they all are related to the type of cementitious materials and air entraining agent; $\alpha$ is the influence coefficient of cement type and fly ash, $FA$ is the replacement rate of fly ash in bridge; $q$ and $p$ are constants, related to cement and fly ash; $\eta$ is the influence coefficient related to the aggregate-to-cement ratio, $m$ and $n$ are the constants of bridge aggregate and cementitious material; $t$ is the age of concrete.

2.2 Uneven contraction of concrete in prefabricated bridges

In practical engineering, the concrete is affected by the constraint of environmental conditions, which causes the uneven contraction and deformation of the concrete components on the same section and such uneven contraction deformation is often ignored by people [18]. In bridge, for example, for box girder, the large geometric size of the components and the different sizes in different positions may cause the contraction deformation of box girder in different places. Rate is not consistent with the influence of external environment, which will also cause the uneven contraction deformation of the whole box girder. During the contraction process, the small size of laboratory test specimens can be assumed to be uniform contraction. Strictly speaking, the early dry contraction of concrete components starts from the surface and develops from outside to inside, so the bridge concrete has uneven deformation [19]. Therefore, based on the expression of uniform contraction of concrete, it is more practical significant to test the uneven contraction of concrete components and analyze the contraction distribution to control early contraction cracks. This research will study the concrete contraction under different environments, mainly divided into single drying and integral drying, and discuss the influence of curing conditions on uneven contraction.

In order to fully reflect the uneven concrete contraction in the early and middle stage of prefabricated bridges, the platform structure size and the production of the test component should be considered in the test summary, the design size of the test component is 1m long, 0.5m wide and 0.2mm high. The tests were carried out after 5 hours when the initial setting of the concrete. The indoor environmental conditions were temperature 22.3℃~25.2℃ and relative humidity 59.5%~65.1%RH. The contraction under single drying and integral drying were both considered and compared the contraction results under single drying [20]. The unilateral constraint used in this paper are the most common in the process of bridge construction.

3. Analysis and optimization

3.1 Analysis of concrete mix design of prefabricated bridge

Fig. 2 shows the contraction change of prefabricated bridge within 30 days after initial setting.

![Fig. 2 The contraction change of prefabricated bridge within 30 days after initial setting.](image)

Based on the analysis of the changes in Fig.2, the influences of such parameters as age, water-binder ratio, gas content, fly ash substitution rate and aggregate-to-cement ratio on the early
contraction was obtained, and the corresponding regression curves was drawn as below Fig. 4.

![Graphs showing bar graphs for the parameters affecting contraction](image)

**Fig. 3 Bar of concrete parameters effect on contraction**
(a: Regression coefficient of water-binder ratio; B: The influence of gas content; C: The influence of fly ash substitution rate; D: Influence of aggregate-to-cement ratio)

Based on above graph changes and numerical regression, it can be concluded that the relation between gas content and water-binder ratio presents a quadratic parabola change, the fly ash is correlated linearly with water-binder ratio; the aggregate-to-cement ratio is inversely proportion to the water-binder ratio. It is also found that the concrete initial setting time of the prefabricated bridge occurs after the contraction strain, and the contraction deformation occurs in the next three days, and the dry contraction occurs in the next three days. These changes are basically consistent with the curing time of the bridge concrete in the actual engineering.

### 3.2 Analysis of uneven contraction in prefabricated bridge

In the study of early contraction deformation of prefabricated bridge in a dry environment, when the casting temperature is 19°C, the internal temperature of concrete becomes higher and higher over time due to the influence of hydration reaction. When the concrete was poured for one day, the internal temperature reached its maximum of 33.5 °C, the centra temperature of the concrete was 38 °C, and the bottom temperature was 36 °C. After the hydration reaction, the cement will gradually let heat out, so that the internal temperature of the concrete gradually decreases. After about 4 days, the internal, bottom and center temperatures of the concrete are basically consistent with the external environment, as shown in Fig. 4.
Fig. 4 Changes of Temperature and Humidity of bridge concrete
(a: Early temperature rise of single-sided prefabricated bridge concrete; b: Variation in humidity of single-sided prefabricated bridge concrete)

According to Fig. 4, it can be found that: uneven contraction strain and cracks are happened because after first contact with the external environment, the surface humidity is in dissipating. After the moisture-transfer ability of concrete declines, it will cause bridge inside contraction eventually lead to the generation of cracks, so the higher of the bridge is, the weaker moisture-transfer ability it has. Fig. 5 is the contraction strain in dry environment.

Fig. 5 Contraction strain of deck concrete under different conditions
(a: Contraction strain of bridge concrete under single dry; B: Contraction strain of bridge concrete under integral drying)

When the environment is dry, the concrete surface will exchange temperature and humidity with the outside world. From Fig. 5, it is obvious that there is no big contraction strain between the upper surface and the bottom surface of the deck concrete, which is between 9με and 19με. The reason for the contraction difference is that the deck is close to the bottom, so the humidity exchange is not as fast as that of the upper surface. Therefore, the minimum contraction strain occurs at the height of about 0.08m, but does not occur at the most central position. The maximum contraction difference of the concrete in dry conditions occurred seven days later after casting, which was nearly 35% less than that of the single-sided concrete in the same period. The contraction difference of the concrete itself is
also decreasing, so in order to better control the early crack on bridge deck, the single-side drying method can be used to reduce the contraction difference of the concrete.

4. Discussion
This study carried out experiments focus on the causes of cracks in early stage of prefabricated bridge (concrete mixture and uneven contraction), and propose suggestions to avoid the cracks rising in early stage of prefabricated bridge and guaranteed the safety of the prefabricated bridge: A. Improve the road and bridge design. Before design, to ensure the design rationality, a professional team can be sent to inspect the nearby environment according to the design requirements. B. Optimize the bridge construction process by cooling raw materials. When processing the bridge steel, a professional team must be on site and monitor the process. The process should be carried out strictly following the drawings. Perfect protection plan and surface protection should be carried out according to the actual casting requirements, and concrete temperature and humidity should be strictly controlled. C. Reasonable load control. The designers must investigate on-site before design. After making a comprehensive evaluation of the surrounding terrain and climate, the plan is determined to make the layout and load of the bridge meet the requirements.

5. Conclusion
In this paper, the object of the research is concrete of prefabricated bridge, based on the concrete mixture and uneven contraction experiment, the causes of early cracks are obtained. The results show that the relation between gas content and water-binder ratio is a quadratic parabola, fly ash and water-binder ratio have a linear relation, and the relation between slurry ratio and water-binder ratio is inversely proportional. It is also found that decrease of relative humidity in concrete is the direct factor that causes early contraction. The early contraction crack of concrete can be controlled by integral drying and single drying method. The safety of the bridge can also be guaranteed by improving the construction design of the road and bridge, reasonably optimizing the construction process of the road and bridge and reasonably controlling the load of the bridge. However, this study also has shortage, because the occurrence of early crack in bridge concrete is directly related to the average thickness of mortar. The thickness of mortar can not be determined in the design of concrete mix, so it should be further studied in the same type of research in the future.

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