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Article

Study on the Effects of Innovative Curing Combinations on the Early Temperature Field of Concrete Box Girders

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Abstract: Box girder bridges are often subject to cracking due to wet temperature changes caused by the heat of hydration in the early stages; however, current studies do not provide an effective method for considering this effect. The reasonable temperature control of concrete box girders can prevent early concrete cracking and ensure concrete quality, but box girder temperature control becomes an important focus in construction. To fill this gap, a two-dimensional temperature field study was carried out for a large-span box bridge by the finite element method. The advantages and disadvantages of the two innovative combination curing methods and the early curing effects on the construction of a box girder in summer were investigated and analyzed based on the temperature field of the box girder under different curing methods, the time–history curves of the temperature at each key node of the box girder, and the time–history curves of the temperature difference between the inside and outside of the box girder. The research results show that the mold paste and automatic water spray method (Combination B method) is more suitable for the early curing of box girders in summer.

Keywords: automatic spray fog method; concrete curing; concrete box girder; formwork sticking method; innovative curing; natural curing; temperature field

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1. Introduction

In the actual construction process, there are often difficulties in the concrete curing in place for concrete box girder bridges. Although there are many kinds of curing methods used in the world, unreasonable curing methods will directly affect the quality of curing concrete and induce the emergence of bad-performance concrete. With the appearance of high-performance concrete, higher requirements are put forward for maintenance. The traditional maintenance technology can not reach the maintenance standard at all, and the specific maintenance method should be determined according to the actual situation of the bridge [1]. Hydration heat causes early wet temperature changes within the concrete structures, which induces temperature stress and the self-shrinkage deformation of the concrete, making early cracks appear easily [2]. The root cause of early cracks in concrete is that there is no reasonable way to maintain the concrete at the early stage of hardening, or the curing actions are not in place, because temperature and humidity are the key factors of concrete hardening [3].

Muhammad Nasir et al. (2017) [4], concrete specimens were poured at different temperatures and exposed to summer ambient conditions. The curing agent was found to be effective in reducing the shrinkage strain of all concrete by applying a water-based curing substance or by covering the specimen with a plastic sheet. Jiang Liu et al. (2020) [5], conducted large-scale temperature measurements and the finite element model analysis of a combined girder bridge. Based on the full validation of the finite element method, a comprehensive parametric study of the spatial and temporal distribution patterns of hydration temperature was carried out. Grzegorz Knor et al., 2019 [6], present a method for the numerical identification of the thermophysical properties of concrete during hardening. Xianzheng Yu et al. (2018) [7] numerically analyzed the main factors affecting the cracking of mass concrete in conjunction with engineering practice. Shi Changlong [8] investigated the variation law of curing conditions on the durability and strength of ultra-high-performance concrete based on experiments. Zhu Bofang [9] described the calculation method of temperature creep stress in temperature field of mass concrete structures and the engineering measures of controlling temperature to prevent cracks. H. Cifuentes et al. (2019) [10] proposed a general procedure based on a fracture mechanics model to analyze the level of cracking and structural safety of early-age reinforced concrete members. Miguel Azenha et al. (2009) [11] used a thermal–mechanical numerical model to simulate the early performance of concrete specimens. After a brief description of the model background, the numerical simulation results were compared with the experimental results. H. Cifuentes et al. (2018) [12] performed an analysis of the early cracking of rapidly hardening cement concrete. A.K.H. Kwan et al. (2017) [13] performed a two-dimensional early thermal cracking finite element analysis of concrete structures. Chadon Lee et al. (2016) [14] proposed a generalized rate constant model for predicting the compressive strength of early prestressed concrete. In their study, xiao-Yong Wang et al. (2018) [15] developed an integrated model for the hydration-strength optimization of cement–slag–limestone ternary blends. Based on the parametric analysis, the concrete strength iso-response curves were calculated. Zhenyang Zhu et al. (2020) [16] proposed a microscopic finite element method to accurately calculate the heat transfer between mortar and aggregate. The temperature field of concrete during vibration was accurately calculated by accurately describing the heat absorption characteristics of different parts of concrete during vibration.

The reasonable temperature control of concrete box girders can prevent early concrete cracking and ensure concrete quality, but box girder temperature control becomes an important focus in construction due to the summer climate. The key section of the box girder bridge was selected as the study object, and the finite element software was used to study the effect of different methods of concrete curing, such as natural curing methods, combination curing methods, etc. The temperature field of the box girder, the time curing curves of the temperature at each key node of the key section, and the time curing curves of the temperature differences between the inside and outside of the section at each location were analyzed under different curing methods to select the best early curing process for summer.

2. The Early Temperature Field Theory of Concrete

The instantaneous temperature at any point in the concrete at moment t is expressed as $T = f(x, y, z, t)$. The instantaneous temperature T at a moment is related to both the moment, t, and the spatial coordinates of the point [9]. Assuming that concrete is a homogeneous and isotropic material, the heat transfer within concrete using Fourier's theory is [9]:

$$q_x = -\lambda \frac{\partial T}{\partial x} \tag{1}$$

where λ is the thermal conductivity of concrete, and its unit is kJ/(m·h·°C), and q_x is the heat per unit area per unit time along the x-axis direction, and its unit is KJ/m^2.

According to the heat balance principle, there are:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{Q}{c\rho} \tag{2}$$

where a is the concrete temperature conductivity, $a = \frac{\lambda}{c\rho}$, and its unit is m^2/h.

Under adiabatic conditions, the hydration of concrete is simplified as the coagulation temperature rise, and the rate of the thermal rise can be expressed as:

$$\frac{\partial\theta}{\partial t} = \frac{Q}{c\rho} = \frac{Wq}{c\rho} \tag{3}$$

where θ is the adiabatic temperature rise of concrete, Q is the heat generated per unit volume of cement hydration in unit time, W is the amount of cement in a unit volume of concrete, q is the heat of hydration given off per unit weight of cement per unit time.

If the temperature is constant along the y and z directions, the three-dimensional temperature field problem is simplified to a one-way temperature field problem, and Equation (2) is transformed to:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} + \frac{\partial\theta}{\partial t} \tag{4}$$

3. Determination of Surface Heat Release Coefficient of Concrete Box Girder

During the simulation analysis of the temperature field of a box girder, the following basic assumptions are usually proposed about the material and the environment to simplify the calculation:

(1) Assume that the concrete material used for the box girders is homogeneous and continuously isotropic and that all nodes have the same thermal properties.

(2) The thermo-physical parameters of concrete (such as heat transfer coefficient, specific heat, surface exotherm coefficient, etc.) are assumed to be constant in conducting the whole simulation analysis.

(3) Under the same curing method, it is assumed that the surface exothermic coefficients are equal at any node location on the surface of the box girder.

(4) It takes a long time to pour the concrete of the same section of the box girder, and the surrounding environmental factors may change at any time. When the concrete is poured into the bottom and top slabs of the box girder, there must be a difference in temperature in the mold. So the initial temperature of the concrete is assumed to be the same when the same section is poured.

(5) For reinforced concrete members of the box girder, although the steel reinforcement has good thermal conductivity and will have some influence on the temperature field, the heat transfer still relies on concrete transfer, and the influence of steel reinforcement is small because the steel reinforcement is all wrapped in concrete. So it is assumed that the influence of steel reinforcement is ignored.

In this paper, the three-dimensional unsteady temperature field is studied as a two-dimensional temperature field. Because the longitudinal length of the box girder is much larger than that of the transverse dimension, the internal hydration heat conduction of the box girder is mainly carried out in its cross-section, while the longitudinal temperature change along the box girder is very small, so the longitudinal temperature change of the box girder is generally not considered.

The key section was selected as the research object, and the spatial model of the box girder of a large-span continuous rigid bridge was established using Midas/FEA according to the actual dimensions, shown in Figure 1. The six-facet unit with eight-node line heat transfer was selected to define the thermal performance parameters of the concrete material, and the thermodynamic boundary conditions were established. The solid model was selected with a cell size of 10 cm for free meshing, with 3824 cells and 5620 nodes. A total of eight nodes were chosen to study its temperature time variation curve and to investigate the temperature variation of the box girder structure. The calculation time was set to 168 h according to the actual curing situation on site. The finite element model of the 0# section in the middle of the box girder span is shown in Figure 1. The layout and numbering of the cross-sectional temperature measurement points are shown in Figure 2. The key nodes are N598 and N4067 (lower chamfer midpoint and surface), N815 and N227 (web midpoint and surface), N31 and N26 (the midpoint of the bottom plate and surface), and N137 and N180 (roof midpoint and surface) of the box girder structure, shown in Figure 2.

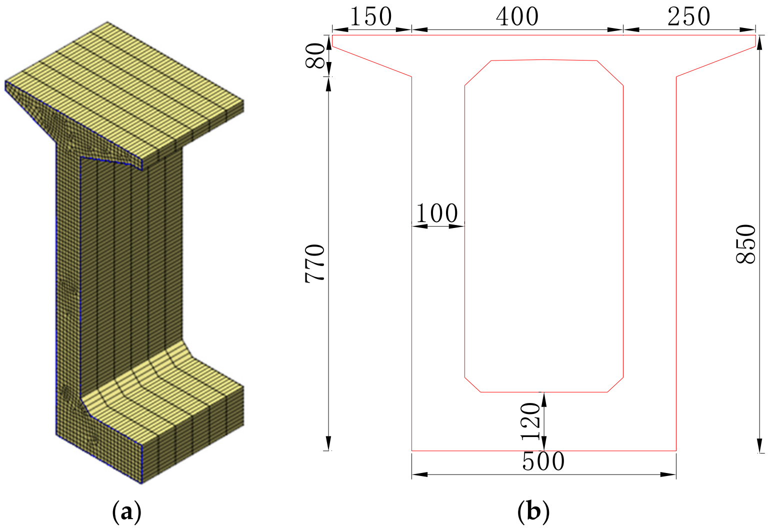

Figure 1. Finite element model and sizes of the concrete box girder. (**a**) Half of finite element model of concrete box girder. (**b**) Sectional sizes of box girder/cm.

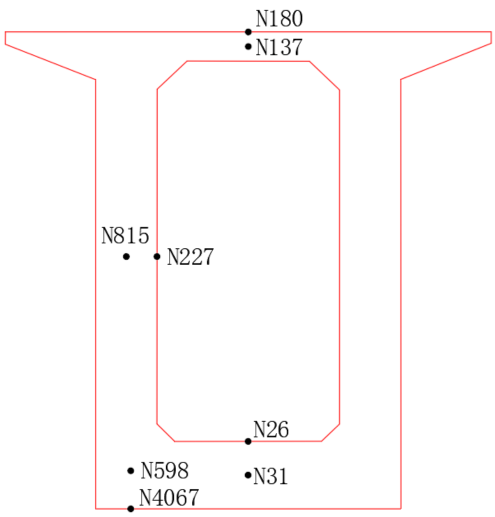

Figure 2. Location and quantity of temperature-measuring points in the mid-span section.

4. Innovative Methods of Concrete Curing for Box Girder Bridges

The common curing methods for box girder bridges in summer are the water sprinkling curing method, the wet cover curing method, etc. However, with the continuous innovation and improvement of various additives and admixtures, the quality of concrete has been substantially improved. Nevertheless, new problems have emerged one after another, such as cracking sensitivity and the self-shrinkage of concrete. The main reason is the unreasonable curing method and low curing efficiency. The traditional curing methods can no longer achieve better curing effects and cannot ensure the curing quality of concrete. With the improvement of technology, four kinds of early curing methods of box girder bridges, namely water spray curing, spraying conservation agent curing, mold paste curing, and conservation film curing, have been adopted. The following is a brief description of the respective curing methods and an analysis of the advantages and disadvantages in terms of effectiveness and economy.

(1) Automatic water spray curing method

Automatic water spray mist is a kind of water curing method, better than the traditional method of curing. The traditional method is manual sprinkling which has great arbitrariness and limitations, and may easily cause unreachable areas and uneven sprinkling, and the artificial sprinkler maintenance of the box girder web and bottom plate cannot be performed. However, automatic water spray mist curing is a set of curing systems that can automatically carry out water spraying, and it only needs to set the nozzle position and angle in advance. It is mainly composed of a water pump device, water pressure device, water pipe, nozzle, and water source, as shown in Figure 3.

Figure 3. Automatic water spray mist curing method.

Compared with the traditional curing process, the novelty advantages of automatic water spray curing are as follows:

(i) Conservation effect

High operability, easy installation of equipment, and simple operation of the system. Automatic spraying only needs to control the curing bracket and determine the nozzle sprinkling range and water spraying time, so it can automatically carry out water spraying curing to save manpower and avoid the arbitrariness of manual sprinkling. By controlling the nozzle position, it is easy to maintain the outside of the web and the bottom plates of the box girder and to avoid the blind area of manual water curing.

(ii) Economy

The curing system equipment cost is low, and the system equipment involves common supplies, consisting of a water pump, water pressure device, and water pipes. It can save manpower, reduce the cost of manual maintenance, reduce the generation of concrete cracks due to the good curing effect, reduce the cost of concrete repair, and enhance the durability and service life of the concrete. So, it is an economically objective effect in the long run.

(2) Spraying conservation agent curing method

A spraying curing agent belongs to a kind of sealing curing to achieve the curing purpose. A polymer material is sprayed on the concrete surface to form a dense film to isolate the concrete surface from the air and to reduce the water loss caused by water evaporation on the concrete surface.

Spray curing is essentially chemical curing. At a theoretical level, the sprinkling curing effect is better than the spraying curing effect. It is more water-saving and labor-saving in terms of using spraying during construction, especially for concrete structures where water sprinkling and moisturizing are difficult, and in areas with drought and water shortage, it can better achieve the curing effect. Moreover, concrete cannot be sprinkled until its final age, and the use of a conservation agent is a better choice. Spraying conservation agent curing is shown in Figure 4.

The evaporation decrease of water from concrete depends on the amount of spraying. The effective water retention rate can be more than 90%, giving better quality uniformity in concrete. It will fall off automatically after a month, and easy to operate. The method can save water resources. One kilogram of curing agent can be used for an area of 8–10 m^2, so 1 ton of curing agent can save about 2000 t of water.

(3) Mold paste curing method

The essence of the molding paste is permeable to cloth, which sticks the mold paste (permeable formwork cloth) to the inside of the formwork to remove excess moisture and air between the formwork and the concrete and to trap the concrete surface particles. When pouring the concrete, part of the water is stored in the molding paste, and the excess water flows out along the formwork, while the air bubbles escape through the molding paste. The air bubbles escape, reducing the trachoma on the concrete surface, while the water stored in the molding paste maintains the humidity of the concrete surface, which can reduce the generation of cracks and improve the quality and durability of concrete. The mold paste curing method is shown in Figure 5.

Figure 4. Spraying conservation agent curing method.

Figure 5. Mold paste curing method.

The advantages of the mold paste curing method include the following:

(i) Cruising effect

The molding paste has the characteristics of water storage and air permeability, which can substantially reduce the cracks on the concrete surface, improve the density of the concrete surface layer, and increase the strength and durability of the surface layer.

(ii) Economy

The molding paste can be used repeatedly to save costs. The formwork is easy to release, and there is no need to use a release agent, so the use of mold paste can increase the turnaround of the formwork.

(iii) Special attention

When using mold paste curing, a formwork with high stiffness should be chosen, ensuring that the molding paste is not easily deformed and makes the concrete surface flat. It is necessary to keep the formwork clean before sticking the film and to not cause wrinkles when sticking the formwork's cloth, which will affect the concrete surface's appearance and the curing effect. For formwork with a sticky formwork cloth, it is not necessary to spray the releasing agent again.

(4) Conservation film curing method

The conservation film curing method is also a kind of sealed curing, also known as the plastic film cover method, as shown in Figure 6. The plastic film has the function of moisturizing and heat preservation. The water in the concrete evaporates fast between the freshly poured stage and the final coagulation stage. As the water evaporates from the concrete by covering the concrete surface with a plastic film, it condenses back to the plastic film and continues to replenish the immature concrete, further improving the concrete conditions.

Figure 6. Conservation film curing method.

The method has the function of moisturizing and heat preservation, effectively inhibiting micro-cracks, and the moisturizing rate can reach 95%. Temperature conditions can also be improved by changing the film to different colors. For example, a light-colored film in summer can reflect part of the sunlight and reduce the absorption of heat. Dark-colored film is used in winter to increase the absorption of solar radiation and raise the temperature of the concrete surface. The in situ site is neat. The cost of the method is low, equivalent to 0.25 yuan/m^2.

After the film is covered, the film should be checked and protected at any time to avoid reducing the quality of early curing due to film damage. When the wind is strong, it may easily cause damage to the conservation film, so it is necessary to implement the anti-wind measures.

The introduction of four common curing methods—automatic water spray curing, mold paste curing, spraying conservation agent curing, and conservation film curing—is presented. The advantages and disadvantages of the four curing methods are compared at the level of curing effects and economic benefits.

Two innovative compound curing methods suitable for the concrete casting of box girders in summer are proposed.

Combination A of curing methods "mold paste method + natural curing method" is simplified as the Combination A method.

Combination B of curing methods "mold paste method + automatic water spray method" is simplified as the Combination B method.

5. Combination A Method

The conventional curing method for mass concrete is manual watering and wet sack covering. Before demolding (1–3 d concrete curing), the top surface of the top plate of the box girder and the top surface of the bottom plate is covered with a 1 cm wet sack, and water is sprinkled every 2 h during the day to keep the concrete surface moist. Other parts of the box girder are attached with 5 mm steel plates and no curing measures are taken. After demolding (4–7 d concrete curing), the bottom template remains close to the bottom plate of the box girder except for the bottom surface of the bottom plate and plays a supporting role. The other parts of the box girder are loosened from the steel template, and the top surface of the bottom plate and the top surface of the top plate are still covered with wet sacks, while the outer surface of the web and the bottom surface of the bottom plate are not maintained.

The Combination A method is the combination of the mold paste method and the natural curing method. Before the concrete is cast, a layer of permeable mold paste is glued to the outer surface formwork of the box girder. After demolding, the molding paste was removed together with the formwork, then a 1 cm wet sack was used to cover the top surface of the top plate of the box girder and the top surface of the bottom plate, water was sprinkled regularly by hand to keep the concrete surface moist, and no curing was done on the outer surface of the web and the lower surface of the bottom plate.

(1) Equivalent heat release coefficient

The selection of the convection coefficient is based on the calculation formula of the convective exothermic coefficient and equivalent convective exothermic coefficient [9]. When sprinkling with water for curing, the concrete surface temperature is equal to the water temperature, while air and water exist between the molding paste and the steel plates, so the equivalent exothermic coefficient of the film before demolding is $\beta_s = 40\ \mathrm{kJ}/(\mathrm{m}^2{\cdot}\mathrm{h}{\cdot}{}^\circ\mathrm{C})$.

As shown in Table 1. β_1 refers to the exothermic coefficient of the top surface of the top plate of the box girder, β_2 refers to the equivalent exothermic coefficient of the top surface of the bottom plate of the box girder, β_3 refers to the equivalent exothermic coefficient of the outer surface of the box girder, and β_4 refers to the equivalent exothermic coefficient of the inner surface of the box girder. Same below.

Table 1. Exothermic coefficients of box girder surfaces unit: $\mathrm{kJ}/(\mathrm{m}^2{\cdot}\mathrm{h}\cdot{}^\circ\mathrm{C})$.

Time	β_1	β_2	β_3	β_4
Before demolding	28.50	16.20	40.00	21.80
After demolding	28.50	23.90	65.95	23.90

The temperature field of the box girder using the Combination A method is shown in Figure 7. The time–history curves of temperature at each key node of the box girder using the Combination A method are shown in Figure 8, and the time–history curves of temperature differences between the inside and outside at each position of the box girder under the Combination A method are shown in Figure 9.

From Figures 8 and 9, the trends of each node's temperature on the age changes are roughly the same, and the temperature peak is reached at about 3 d. The peak temperature of the nodes in the middle of the bottom slab and the upper chamfers reaches 45.3 °C and 45.4 °C, respectively. The concrete node temperature is influenced by the ambient temperature, so the node temperature change shows a cyclic change. After demolding, the temperature curves appear as a "sudden change" phenomenon, and the surface of the concrete is in contact with the atmosphere, so the temperature decreases rapidly. The temperature difference between the inside and outside of the concrete box girder increases suddenly, and the temperature difference between the inside and outside of the lower chamfers and the bottom plate is the largest, up to 17.8 °C. Therefore, the concrete surface should be kept moist in the time after demolding.

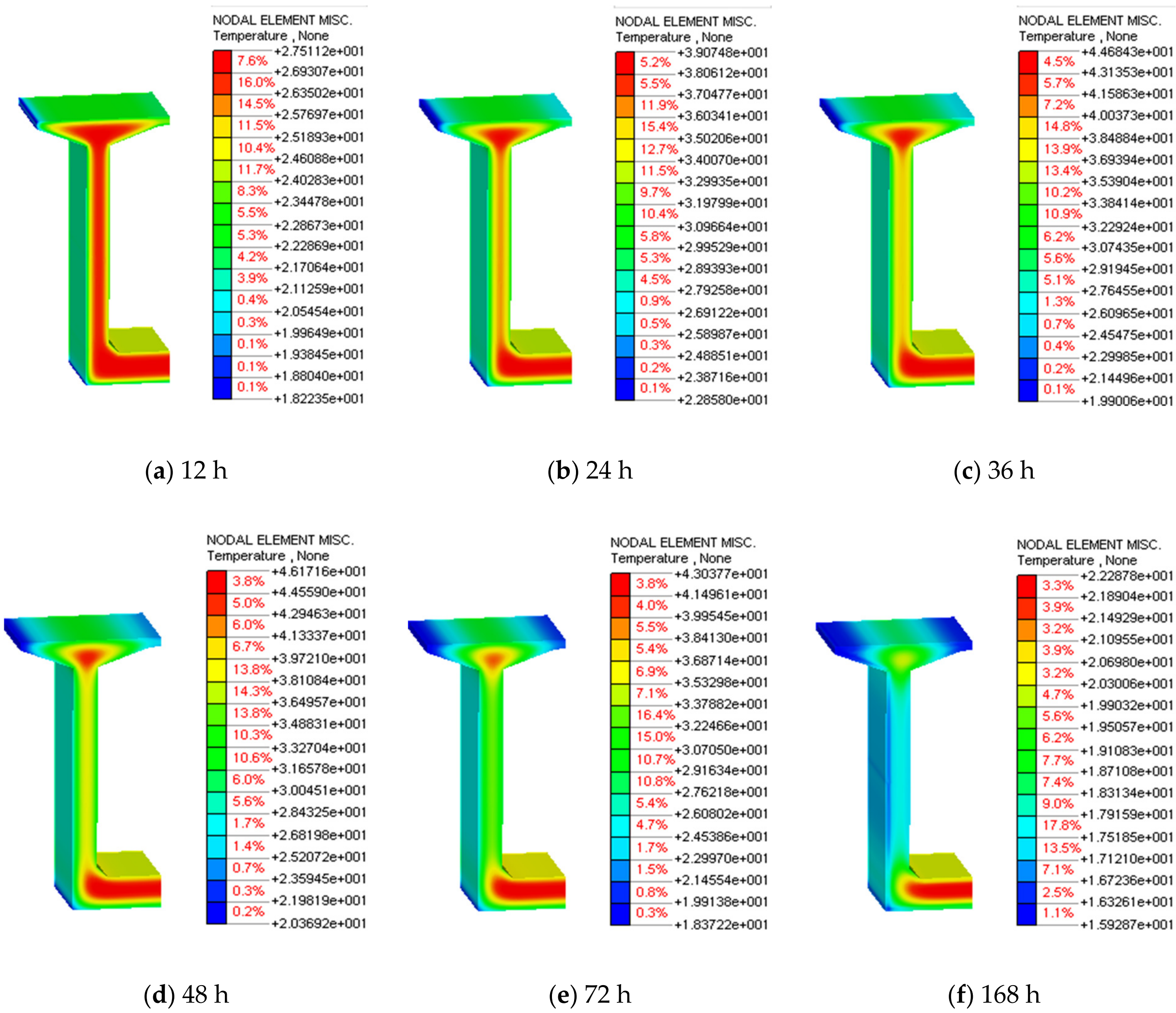

Figure 7. Temperature field distribution of the box girder at each key moment.

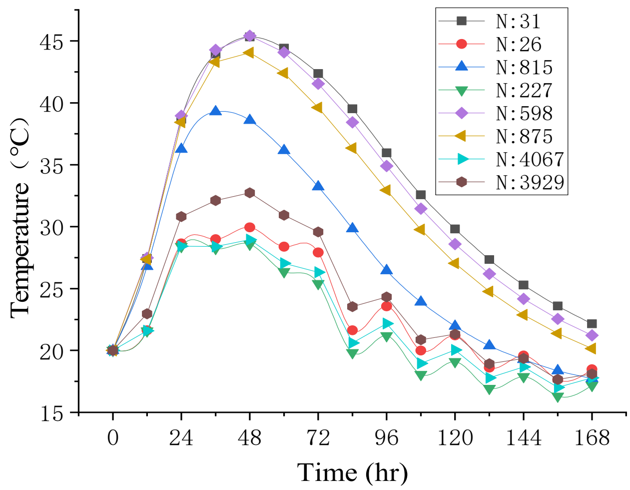

Figure 8. Time–temperature curves of the temperature at each key node of the box girder.

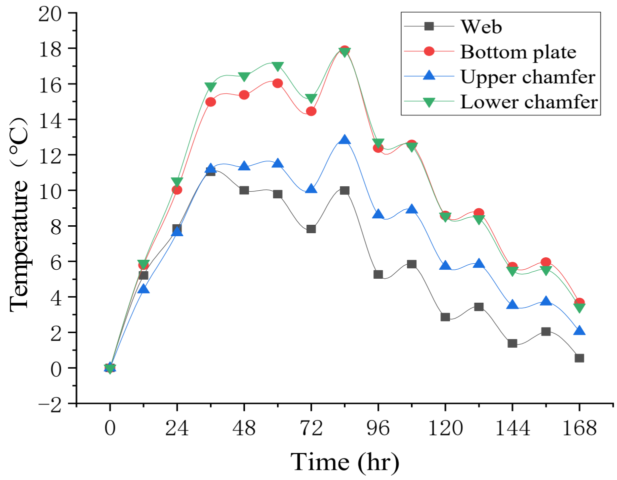

Figure 9. Time–history curves between the inside and outside of the box girder.

6. Combination B Method

Before the concrete is cast, a layer of permeable mold sticker is pasted on the outer surface formwork of the box girder, and the mold sticker is removed together with the formwork when the mold is demolished. The top surface of the bottom plate and the top surface of the top plate of the box girder are covered with 1 cm wet sacks, the concrete surface is kept moist by regular manual sprinkling, and the lower surface of the bottom plate and the outer surface of the web are maintained by sprinkling with an automatic water spray mist system. The convective exothermic coefficients and equivalent convective exothermic coefficients [9] are listed in Table 2.

Table 2. Exothermic coefficients of box girder surface unit: $\mathrm{kJ}/(\mathrm{m}^2 \cdot \mathrm{h} \cdot {}^\circ\mathrm{C})$.

Time	β_1	β_2	β_3	β_4
Before demolding	28.50	16.20	40.00	21.80
After demolding	28.50	23.90	40.00	23.90

Because the water temperature of automatic water spray curing can be adjusted, the exothermic coefficient of the concrete surface is taken as $\beta_s = 40\mathrm{kJ}/(\mathrm{m}^2{\cdot}\mathrm{h}{\cdot}{}^\circ\mathrm{C})$. The temperature field cloud diagram of the box girder using the Combination B method is shown in Figure 10.

The time–history curves of the temperature at each key node of the box girder using the Combination B method are shown in Figure 11, and the time–history curves of the temperature difference between the inside and outside at each position of the box girder using the Combination B method are shown in Figure 12. As can be seen from Figures 11 and 12, the temperature change pattern of each node is the same, reaching the peak temperature within about 3 d. The peak temperature of the bottom plate and the middle node of the upper chamfers is the biggest, and the peak temperature rises accordingly with the increase in the cross-sectional area sizes, and the time to reach the peak temperature is delayed accordingly. After demolding, the temperature curves do not show “sudden change” because of timely spraying water mist curing, and the temperature difference between the inside and outside of the lower chamfers and the bottom plate is the largest, 17.0 °C and 16.0 °C, respectively.

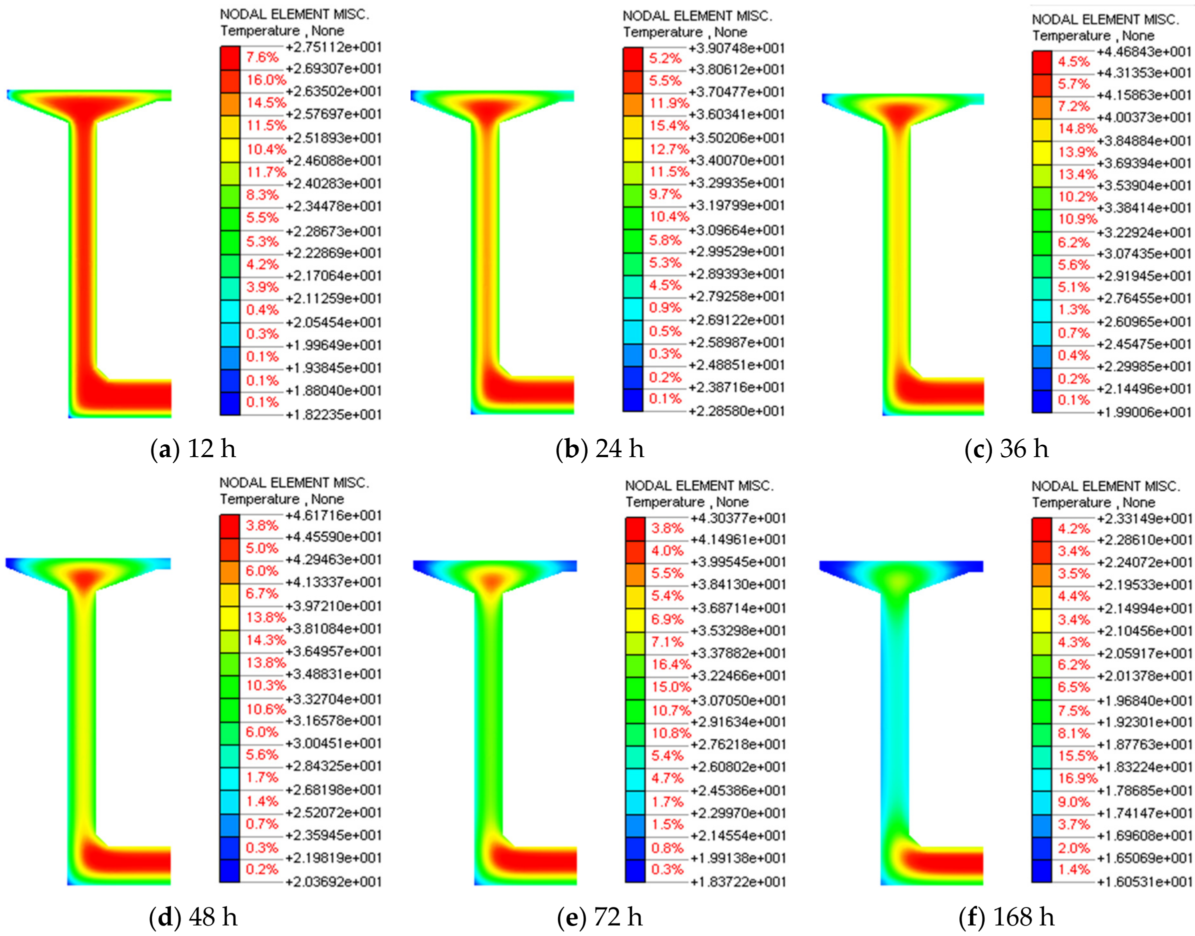

Figure 10. Temperature field distribution clouds of box girder section at each moment.

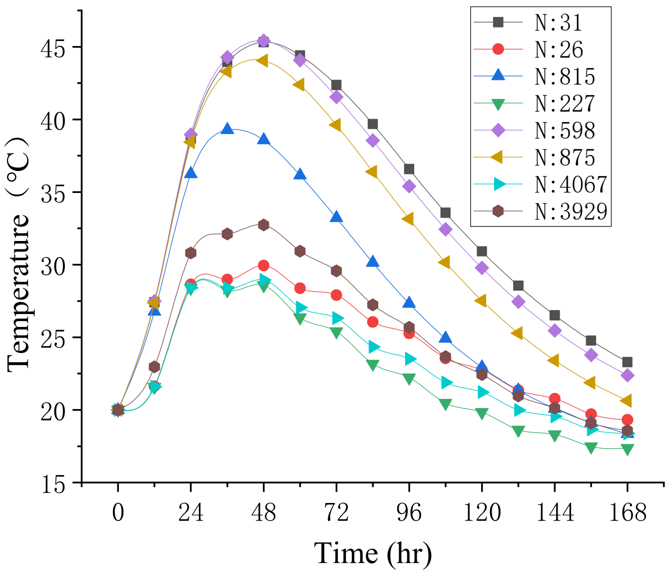

Figure 11. Time–temperature curves of each key node of the box girder.

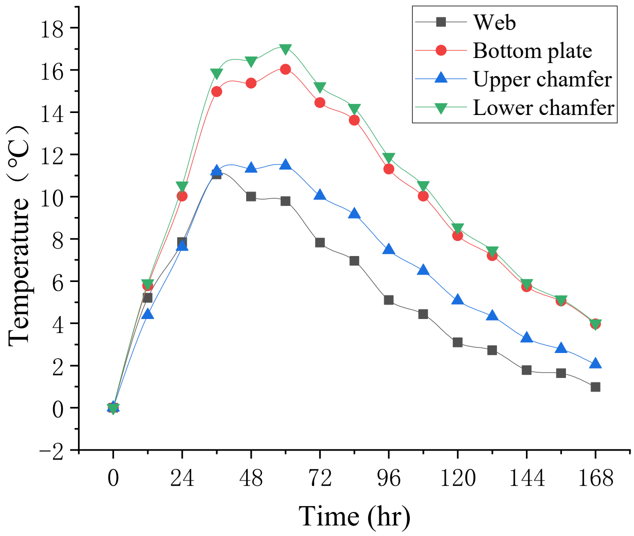

Figure 12. Time–temperature curves between the inside and outside of the box girder.

7. Comparative Analysis of Temperature Differences of Box Girders with Different Curing Methods

The three curing methods, namely natural curing, Combination A method, and Combination B method, are compared and analyzed for the internal and external temperature differences of the web and bottom plate of the box girder and the upper and lower chamfers. The comparison of the temperature differences between the inside and outside of each plate of the box girder with different curing methods is shown in Figure 13. The peak variations of the differences are shown in Tables 3 and 4.

Table 3. Peak temperature variation of box girder using different curing methods before demolding.

	Bottom Plate		Web		Upper Chamfer		Lower Chamfer	
Age	36 h/°C	Reduction Rate	36 h/°C	Reduction Rate	36 h/°C	Reduction Rate	36 h/°C	Reduction Rate
Natural conservation method	17.9	-	13.4	-	14.2	-	18.7	-
Combination A method	14.9	16.7%	11.0	17.9%	11.1	21.8%	15.9	14.9%
Combination B method	14.9	16.7%	11.0	17.9%	11.1	21.8%	15.9	14.9%

Table 4. Peak temperature variation of box girder using different curing methods after demolding.

	Bottom Plate		Web		Upper Chamfer		Lower Chamfer	
Age	84 h/°C	Reduction Rate	84 h/°C	Reduction Rate	84 h/°C	Reduction Rate	84 h/°C	Reduction Rate
Natural conservation method	15.7	-	8.2	-	11.7	-	15.7	-
Combination A	17.9	−14.0%	10.0	−21.9%	12.8	−9.4%	17.8	−13.3%
Combination B	13.6	13.3%	6.9	15.8%	9.2	21.3%	14.2	9.5%

The Combination A and B methods can significantly reduce the temperature difference between the inside and outside of the box girder section before demolding, and the peak temperature difference of the web was reduced from 13.4 °C to 11 °C, which was 17.9%. The peak temperature difference in the upper chamfers was also reduced by 21.8%. The sticky mold paste inside the box girder formwork can effectively reduce the temperature difference between the inside and outside of the concrete before demolding.

After demolding, the temperature difference value of the cross-section increased abruptly and inversely using the Combination A method and was even higher than the natural maintenance method. In contrast, the temperature difference value can still be effectively reduced in the Combination B method. The temperature difference values of the upper chamfers can be reduced from 11.7 °C to 9.2 °C, which is 21.3%. So, automatic water spray curing can well achieve the purpose of reducing the temperature difference between the inside and outside after demolding. Early curing can effectively reduce the temperature difference between the inside and outside of the box girder, and the Combination B method can be effectively applied to the early curing of the box girder in summer.

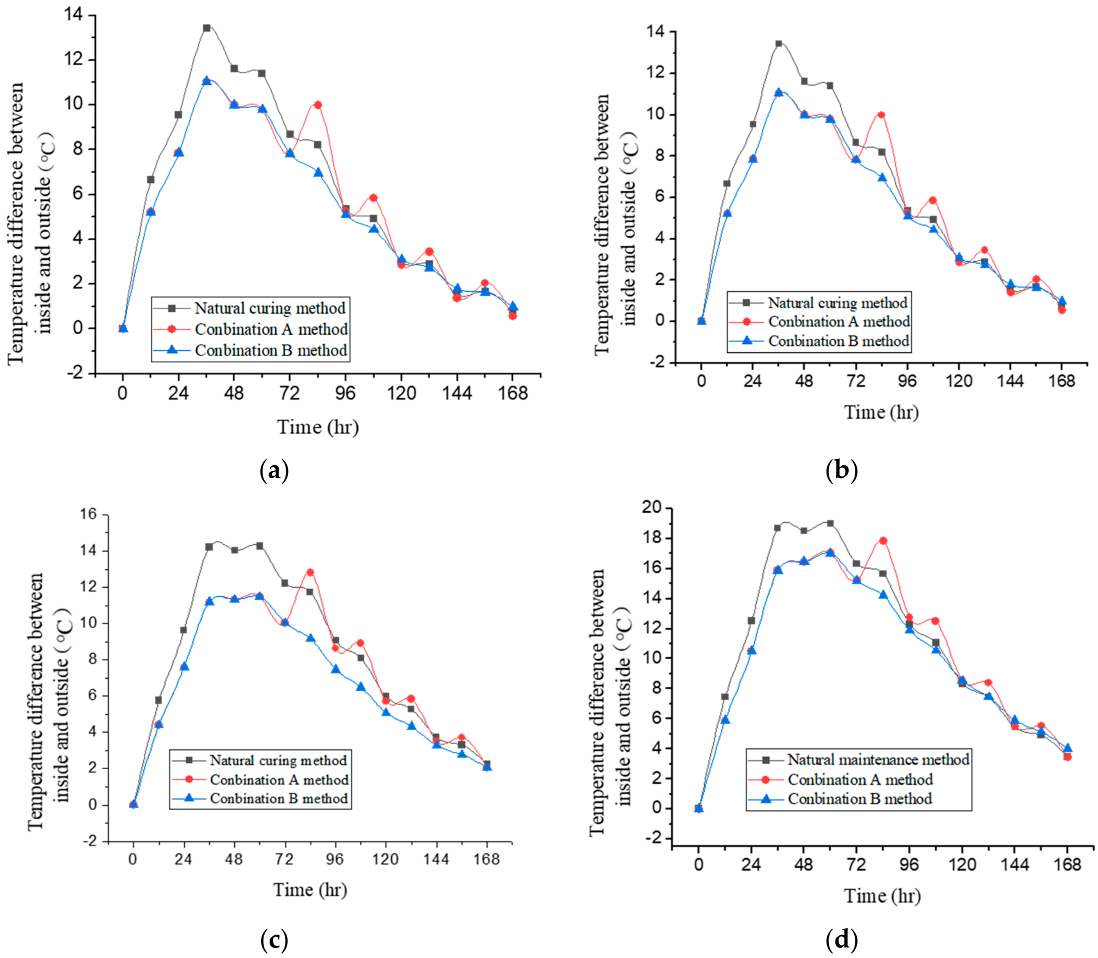

Figure 13. Comparison of the time-history curves of temperature differences of the key parts of the box girder. (**a**) Comparison of the time–history curves of the temperature difference between inside and outside of the web. (**b**) Comparison of time–history curves of the temperature difference between inside and outside of the bottom plate. (**c**) Comparison of time–history curves of the temperature difference between inside and outside of upper chamfers. (**d**) Comparison of time–history curves of the temperature difference between inside and outside of lower chamfers.

8. Conclusions

(1) By comparing and analyzing the common curing methods in summer, two innovative composite methods suitable for the current mass concrete construction are proposed: the Combination A method (mold paste method and natural curing method) and Combination B method (mold paste method and automatic water spray mist method).

(2) Before demolding, the Combination A method can effectively reduce the temperature difference between the inside and outside of the bottom plate. The temperature difference of the bottom plate was reduced by 16.7% from 17.9 °C to 14.9 °C, and the web and upper and lower chamfers were reduced by 17.9%, 21.8%, and 14.9% respectively.

(3) After demolding, the temperature difference between the inside and outside increased instead, and the curing effect was poor. The Combination B method achieved a good cooling effect before and after mold removal, and the effect was the same as that

of the Combination A method before mold removal. After demolding, the temperature difference of the bottom plate was reduced by 13.8%, and the web and upper and lower chamfers were reduced by 15.8%, 21.3%, and 9.5%, respectively.

(4) The Combination B method can effectively reduce the temperature difference between the inside and outside of the concrete box girder. For the early curing of box girders in summer, it is recommended to use the Combination B method, which is the mold paste method and automatic water spray mist method.

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