Original Research Article

Research on key processes of UHPC for the exhibition building facade of the northern branch of the Palace Museum

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Abstract: As a significant cultural landmark dedicated to the preservation, exhibition, and research of cultural relics, the Northern Branch of the Palace Museum requires its exhibition building facade to not only meet stringent architectural aesthetic demands but also to possess excellent durability, impermeability, and structural stability, thereby accommodating the special environmental requirements for relic conservation. Ultra-High Performance Concrete (UHPC), owing to its ultra-high strength, high toughness, and excellent formability, has emerged as an ideal material for this facade project. Focusing on the production of UHPC components for the facade, this paper centers on the entire process of 1:1 steel mold fabrication, with an emphasis on the technical optimization of two critical aspects: The casting process and the selection of the back mold. To address issues such as the settlement of steel fibers to the bottom caused by traditional vibration techniques, leading to insufficient component compactness, and the formation of blowholes on the back surface due to the use of an unpainted wood board back mold, comparative process tests were conducted. An improved casting method, termed "rolling while casting," and an optimized back mold strategy, "replacing unpainted wood boards with ordinary wood boards," are proposed. The results validate the significant effectiveness of the optimized processes in enhancing the compactness of UHPC components, reducing blowhole defects, and ensuring surface quality, thereby providing a technical reference for the production of UHPC components for similar cultural building facades.
Keywords: northern branch of the Palace Museum; UHPC; key processes; casting optimization; back mold improvement

1. Introduction

The Northern Branch of the Palace Museum, located in Haidian District, Beijing, is a major project aimed at expanding the Palace Museum's cultural exhibition space and enhancing its capacity for cultural relic preservation and research. The exhibition building, as the core functional area, requires a facade that not only embodies architectural aesthetics harmonizing with the traditional style of the Palace Museum but also meets the stringent demands for high durability, low permeability, and temperature stability of the building envelope, which are essential for the preservation environment of cultural relics. As traditional building materials struggle to simultaneously satisfy the requirements for form flexibility, mechanical performance, and long-term durability, Ultra-High Performance Concrete (UHPC) has been introduced into the facade of this project due to its unique material advantages.

UHPC is a novel cement-based composite material composed primarily of cement, ultra-fine reactive powders, aggregates, high-performance water-reducing admixtures, and steel fibers, optimized through a carefully designed mix proportion. It exhibits high compressive strength, high tensile strength, good toughness, excellent impermeability and freeze-thaw resistance, as well as outstanding formability. These properties enable the precise realization of complex architectural geometries while providing long-term, reliable envelope protection for the exhibition building. However, the performance and surface quality of UHPC components are highly dependent on the rationality of the production process. Particularly under the 1:1 steel mold production mode, the control of air bubbles during casting, the uniformity of steel fiber distribution, and the air-release and water-absorption characteristics of the back mold directly influence the final quality of the components.

The main research content of this paper focuses on the 1:1 steel mold production process of UHPC components for the facade of the exhibition building at the Northern Branch of the Palace Museum, emphasizing two key process aspects: (1) optimization of the casting process to resolve the issues of steel fiber settlement and front-face blowholes caused by traditional vibration techniques; and (2) improvement of the back mold process to address the back-face blowhole defects induced by the use of an unpainted wood board back mold. The technical roadmap is as follows: First, define the raw material system and basic process flow for component production; second, analyze the problems associated with traditional casting and back mold processes and design comparative test schemes; third, verify the effectiveness of the optimized processes through tests, including compactness evaluation, blowhole defect statistics, and surface quality assessment; finally, summarize the key technical points of the optimized processes to establish a critical process system for UHPC component production suitable for this project.

2. Raw material system for UHPC component production

The raw material system for UHPC components of the facade of the exhibition building at the Northern Branch of the Palace Museum must balance mechanical performance, durability, and aesthetic appearance. After multiple rounds of mix proportion trials, the formulation was determined using Subote powder as the core cementitious material, combined with color powder, high-performance water-reducing admixture, and steel fibers. The specific material selection and performance requirements are as follows:

3. Analysis and optimization of key process issues in UHPC component production

3.1. Analysis and optimization of the casting process

The casting process is the core step in forming UHPC components, directly affecting component compactness, uniformity of steel fiber distribution, and surface blowhole defects. In the early stage of this project, traditional vibration techniques were adopted, which led to significant technical problems. Quality improvement was subsequently achieved through process optimization.

3.1.1. Problem analysis of the traditional vibration technique

Initially, to reduce air bubbles in the mixture, an internal vibrator was used to vibrate the UHPC mixture after casting, with a vibration frequency of 50 Hz and a vibration duration of 30–60 seconds per cast layer. However, actual production revealed two major drawbacks of this technique:

(1) Severe settlement of steel fibers: Because the density of steel fibers in the UHPC mixture is much higher than that of the cementitious paste, the vibration action accelerated the downward settlement of steel fibers under gravity. This resulted in an excessively high steel fiber content at the bottom of the component (measured >10%) and an excessively low content at the top (<5%), leading to severe non-uniform distribution. Such uneven distribution causes a mechanical performance imbalance between the top and bottom of the component: the tensile strength of the upper part is less than 70% of the design value, making it prone to cracking. Meanwhile, the agglomeration of steel fibers at the bottom increases internal porosity and reduces impermeability.

(2) Ineffective control of front-face blowholes: Although vibration can expel some air bubbles, the insertion of the vibrator creates voids in the mixture. If the mixture has insufficient fluidity after vibration, these voids cannot close on their own and instead form new blowholes on the front face. Moreover, controlling the vibration duration is difficult: too short a duration results in inadequate bubble removal, while too long a duration induces mixture segregation, further exacerbating steel fiber settlement. Consequently, the blowhole ratio on the front face remained as high as 3%–5%, failing to meet the surface quality requirements for the facade.

3.1.2. Optimized process: Rolling while casting

To address the drawbacks of the traditional vibration technique and leveraging the self-leveling property of the UHPC mixture, an improved casting process named "rolling while casting" was proposed. The specific technical points are as follows:

(1) Selection of rolling equipment: A defoaming roller with a diameter of 80–120 mm was chosen to ensure effective bubble removal without disrupting the self-leveling state of the mixture.

(2) Control of rolling process parameters: The casting adopts a "layer-by-layer casting, layer-by-layer rolling" approach. The thickness of each cast layer is controlled at 100–150 mm. When the mixture reaches

80% of the target layer thickness, rolling begins slowly along the length of the mold using the defoaming roller, at a rolling speed of 2–3.0 m/min, with 2–3 passes. The overlap width between adjacent rolling paths is ≥50 mm. After rolling is completed for one layer, the next layer is cast, and the procedure is repeated until the entire component is cast.

3.2. Analysis and optimization of the back mold process

The back mold is a critical component for shaping the back surface of UHPC components. Its air-release and water-absorption characteristics directly affect blowhole defects and surface quality on the back side. In the early stage of this project, an unpainted wood board back mold was used, which led to excessive blowholes on the back surface. Process optimization was achieved by replacing the back mold material.

3.2.1. Problem analysis of the traditional unpainted wood board back mold

Initially, to ensure a smooth back mold surface and reduce subsequent finishing work, a 15-mm-thick unpainted wood board was selected as the back mold material. The surface of the unpainted wood board is covered with a PVC decorative film, which is smooth and easy to clean. However, actual production revealed serious air-release problems with this back mold:

(1) Blockage of air-release channels: The PVC film on the surface of the unpainted wood board is a dense, non-breathable material, and the joints between boards are sealed with sealant. This creates a closed space at the interface between the back mold and the UHPC mixture. During casting, air in the mixture cannot escape through the back mold and instead accumulates on the back surface of the component, forming blowholes. These blowholes are typically 1–3 mm in diameter, with some exceeding 5 mm, and the blowhole ratio reaches as high as 8%–10%, severely compromising the surface quality and impermeability of the back surface.

(2) Lack of water absorption: During the hydration process of the UHPC mixture, excess water is generated. The PVC film on the unpainted wood board prevents the dissipation and absorption of this moisture. Consequently, the excess water on the back surface layer cannot be removed, resulting in a "bleaching" phenomenon that affects color uniformity. Meanwhile, the retained excess water forms pores inside the component, reducing its compactness.

3.2.2. Optimized process: Ordinary breathable wood board back mold

To address the air-release and water-absorption problems of the unpainted wood board back mold, an optimized back mold process using ordinary wood boards instead of unpainted wood boards was proposed. The specific technical points are as follows:

(1) Selection of ordinary breathable wood board: A 15-mm-thick Chinese fir board was selected. Chinese fir wood offers good breathability and water absorption, is lightweight, and is easy to machine. The boards must be dried to prevent deformation caused by excessive moisture content, which would affect the dimensional accuracy of the components.

(2) Installation process of the back mold: The boards are joined using a tongue-and-groove connection without sealant, leaving a 0.5–1 mm gap as an air-release channel. The back mold is fixed to the steel mold using fasteners to ensure a tight fit, preventing mixture leakage through the gaps. Before casting, a water-based release agent is brushed onto the wood surface, which facilitates demolding without compromising the breathability or water absorption of the wood.

4. Engineering application effects of the optimized processes

4.1. Comparison of casting process optimization effects

Validation of process advantages: Comparative tests were conducted to evaluate the performance of UHPC components produced using the traditional vibration technique versus the "rolling while casting" technique. The results are as follows:

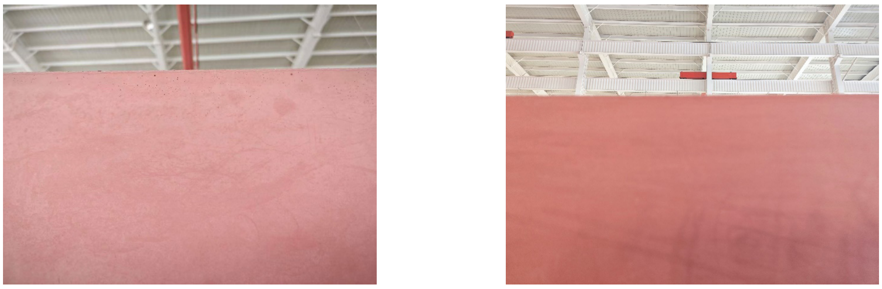
Uniformity of steel fiber distribution: For components produced with the "rolling while casting" technique, the difference in steel fiber content between the top and bottom was controlled within 1% (7.8%–8.2% at the top, 8.0%–8.3% at the bottom), which is far superior to that of the traditional vibration technique (difference exceeding 8%). The uniformity of steel fiber distribution was significantly improved, ensuring consistent mechanical performance throughout the component.

Compactness and blowhole ratio: Ultrasonic testing showed that the average compactness of components produced with the "rolling while casting" technique was 2.45 g/cm³, representing a 5.6%

increase over the traditional vibration technique (2.32 g/cm³). The blowhole ratio on the front face was reduced to 0.03%–0.06%, meeting the design requirements. All blowholes were ≤0.5 mm in diameter, with no visible blowholes, and the surface quality was significantly improved.

Mechanical properties: The average compressive strength of components produced with the optimized process was 140 MPa, and the average tensile strength was 12.5 MPa, representing increases of 10.2% and 18.6%, respectively, over the traditional vibration technique. The mechanical properties met the design specifications.

A comparison of the component quality before and after process optimization is shown in the figure below.



(a)before (b)after

Figure 1. Effects for treatment.

4.2. Comparison of back mold improvement effects

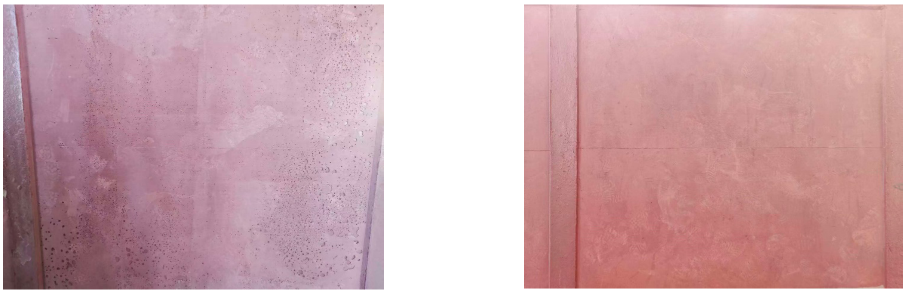
Validation of process advantages: Comparative tests were conducted to evaluate the back-surface quality of UHPC components produced using the unpainted wood board back mold versus the ordinary breathable wood board back mold. The results are as follows:

Control of blowhole defects: For components produced with the ordinary breathable wood board back mold, the blowhole ratio on the back surface was reduced to 1%–2%, with most blowholes ≤1 mm in diameter and no visible blowholes. Microscopic observation revealed a dense surface layer on the back side with no apparent pores, and the impermeability was significantly improved.

Water absorption and surface quality: The water absorption of the ordinary wood board effectively removed excess moisture from the back surface layer, avoiding the "bleaching" phenomenon. The surface color uniformity was consistent with that of the front face. Moreover, the absorption of moisture promoted the hydration reaction of UHPC, increasing the compressive strength of the back surface layer to 140 MPa, which is 5.3% higher than that of components produced with the unpainted wood board back mold (133 MPa).

Demolding performance: After applying a water-based release agent to the surface of the ordinary wood board, demolding resistance was low, and no adhesion occurred on the back surface of the component. After demolding, the boards could be cleaned, dried, and reused (with a service life of 5–8 cycles), reducing the material cost of the back mold.

A comparison of the component quality before and after process optimization is shown in the figure below.



(a)before (b)after

Figure 2. Effects for treatment.

5. Conclusion

Focusing on the production practice of UHPC components for the facade of the exhibition building at the Northern Branch of the Palace Museum, this study systematically analyzed process issues and conducted optimization experiments to address two major technical challenges encountered during 1:1 steel mold production: uneven distribution of steel fibers and blowhole defects in the components. The following main conclusions are drawn:

(1) The optimized casting process of "rolling while casting" effectively improved the overall performance of the components. By adopting a layer-by-layer casting approach combined with simultaneous rolling using a defoaming roller, this process successfully resolved the steel fiber settlement problem caused by traditional vibration techniques. The difference in steel fiber content between the top and bottom of the components was controlled within 1%, ensuring uniformity and consistency of mechanical properties. This process also significantly enhanced component compactness and reduced the blowhole ratio on the front face, enabling both mechanical performance and surface quality to meet the design requirements of this high-standard cultural project.

(2) Using ordinary breathable wood board instead of unpainted wood board as the back mold material is key to controlling blowhole defects on the back surface. The good breathability and water absorption of ordinary wood board provide effective channels for the release of air trapped in the mixture during casting and the migration of excess hydration water. This fundamentally solves the problems of blowhole accumulation (reducing the blowhole ratio from 8%–10% to 1%–2%) and the "bleaching" phenomenon on the back surface caused by the airtightness of the unpainted wood board back mold, while also improving the impermeability and surface strength of the back side.

(3) The electric blanket curing process significantly enhances production efficiency while ensuring quality. Compared with natural curing and greenhouse curing, electric blanket curing provides a stable and uniform thermal environment. It not only substantially shortens the demolding cycle from several days to 20–24 hours, improving mold turnover rate and production line capacity, but also effectively eliminates surface cracking of the components and microcracks around inserts caused by temperature non-uniformity. Under the optimized temperature control regime, UHPC hydration is more complete, with both early-age and later-age mechanical properties improved by approximately 3%–5% compared with greenhouse curing, while also offering better comprehensive energy efficiency and economic benefits.

(4) The key process system developed in this study, centered on "rolling while casting" and "ordinary breathable wood board back mold," offers significant technical and economic advantages. This system not only ensures the production quality of UHPC components for the facade of the Northern Branch of the Palace Museum but also provides a reliable and replicable technical reference for other large-scale cultural buildings and landmark structures requiring complex geometries and high-performance UHPC facades. It holds positive practical significance for promoting the standardized application of UHPC materials in high-end building envelope systems.

About the author

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