

Article

Prefabricated Integrated Anchorage Device and Continuous Tensioning Construction for Heterotrophic Prestressed Concrete Pavement

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Abstract

This study focuses on a critical issue in Heterotrophic Prestressed Concrete Pavement (HPCP), the closure pour, which is prone to weak interfacial bonding, stress concentration, and cracking under repeated aircraft loads. To overcome these shortcomings, a novel prefabricated integrated anchorage (PIA) device is designed, integrating the functions of both a tensioning end and an anchoring end. Based on the PIA, a continuous tensioning construction process is introduced, which eliminates the traditional closure pour by utilizing the casting space of the subsequent slab to tension the preceding one. Finite element analysis demonstrates that the PIA device exhibits complex stress alternation under prestressing, with the most critical cross sections located at depths of 100 to 150 mm. A parametric study further reveals a linear relationship between the tension angle and the maximum principal stress in the PIA. In the HPCP system, prestressing establishes a predominant compressive stress field in the slab, effectively enhancing crack resistance. However, localized stress concentration and tension–compression alternation occur not only around the PIAs but also notably at the slab corners. These results confirm that the PIA device and its associated continuous construction method not only overcome the drawbacks of closure pours but also provide an innovative, efficient, and sustainable technical pathway for improving the quality and performance of airfield pavement engineering.

Keywords: heterotrophic prestressed concrete pavement; prefabricated integrated anchorage device; continuous tensioning



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1. Introduction

Airport pavements, serving as the direct load-bearing structure for aircraft takeoff, landing, and taxiing, must withstand heavy aircraft wheel loads, high-frequency impacts, and harsh environmental conditions over the long term [1,2]. Traditional Portland cement concrete pavements (PCCPs), which rely on densely spaced joints (typically arranged in 5 m × 5 m slabs) to release thermal stress [3–5], are prone to various joint-related distresses—such as faulting, spalling, and pumping—under repeated aircraft loading [6]. These issues not only degrade the surface performance but may also lead to structural failures such as slab cracking, ultimately compromising aircraft operational safety. Therefore, airport pavements are subject to extremely high requirements for surface smoothness, durability, and structural integrity [7].

To address these challenges, Hossain et al. [8] outlined the fundamental design of diagonally arranged prestressed tendons in pavement, known as Cross-tensioned Concrete Pavement, also termed Heterotrophic Prestressed Concrete Pavement (hereinafter referred to as HPCP). This approach fully utilizes the high tensile strength of the tendons to effectively counteract the tensile stresses in the concrete panel, thereby significantly enhancing the bearing capacity, crack resistance, and durability of the pavement. Following this conceptual proposal, subsequent studies employing finite element analysis and field testing [9–18] have demonstrated the feasibility of the diagonal strand arrangement, particularly regarding the stress behavior near the anchorage zone and pavement edge.

Through further technical advancements, Hui Chen and Jianming Ling et al. [19–24] successfully implemented this system in airport pavement projects and achieved a breakthrough by expanding the dimensions of a single HPCP slab to 80 m × 7 m, as shown in Figure 1. This accomplishment has reduced the number of joints by approximately 95%, effectively mitigating common joint-related distresses and enhancing the pavement performance.

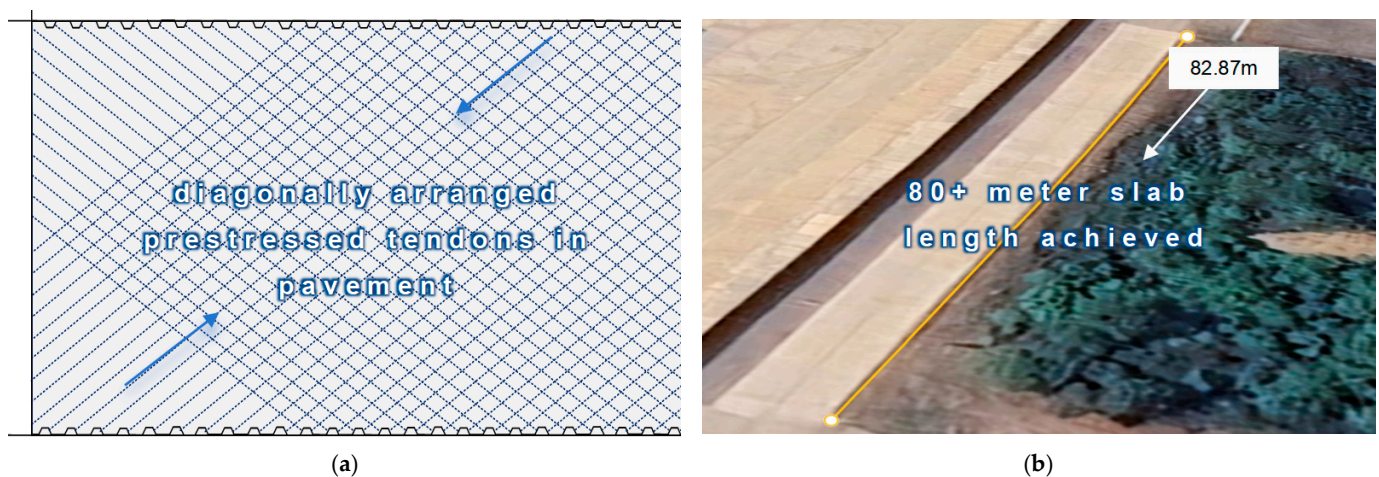


Figure 1. Heterotrophic Prestressed Concrete Pavement (HPCP) implemented in airport: (a) the concept of HPCP; (b) construction of an 80 m Long Joint-Free Slab (Satellite Image).

However, the practical application of HPCP technology still faces a critical problem. In current construction practice, HPCP commonly employs closure pours to connect adjacent slabs, as illustrated in Figure 2. Due to sequential casting, this closure pour area inherently suffers from weak bonding at the interface between newly placed and already hardened concrete, resulting in microstructural discontinuity and insufficient bond strength development [25–28]. Under long-term repeated aircraft loading, this vulnerable interface is highly prone to becoming a critical stress concentration zone and a pathway for moisture infiltration [29–33]. Together, these issues severely compromise the mechanical continuity of the pavement structure and impair effective load transfer in both longitudinal and transverse directions [34,35], thereby undermining the durability and load-bearing safety of the overall pavement system.

Furthermore, the shrinkage deformation of the closure pour concrete is significantly influenced by the ambient temperature and humidity [36–40]. Its shrinkage process and rate often differ from those of the main slab, which has already undergone most of its shrinkage. This differential shrinkage induces constrained stresses at the interface, leading to microcracks or even macroscopic separation along the joint [25]. Such damage impairs the collaborative load-bearing behavior between adjacent slabs and poses a considerable threat to the long-term service performance of the pavement [41–43]. It is noteworthy that the Federal Aviation Administration (FAA) [44] design specifications impose stringent

requirements on the detailing of tensioning and anchoring ends in prestressed concrete pavements. This emphasis in design specifications confirms that such connection zones are critically important to the overall performance and reliability of prestressed pavements [45].

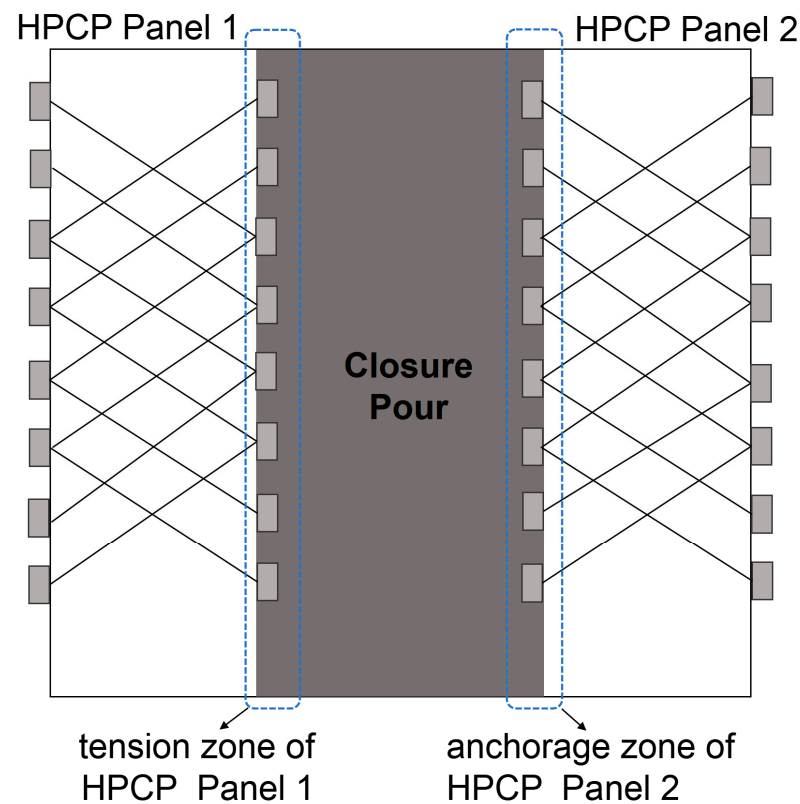


Figure 2. Closure pour between adjacent HPCP panels.

To enhance the connection zones in prestressed concrete structures, researchers have approached the issue from different perspectives. Several studies [46–54] have focused on improving the joint material performance by investigating connection methods using high-performance grout. Their work aimed to optimize the fluidity, strength, and shrinkage characteristics of the grout, thereby increasing the compactness and mechanical strength of the joint area, which in turn improves the load transfer and durability. Other researchers [55–57], on the other hand, have addressed construction techniques by exploring optimized methods for closure pours. This included refined pouring processes and coupled temperature–humidity curing control, with the goal of enhancing the quality and interface performance of the closure pour concrete, reducing shrinkage cracks and interfacial defects, and improving the overall reliability of the joint.

To improve the connection zones in HPCP structures, Li [58] proposed a traditional prefabricated anchorage device capable of both anchoring and tensioning prestressed tendons, as illustrated in Figure 3. Although this device allows for factory prefabrication of components, it is functionally limited: each unit can only serve as either a tensioning end or an anchoring end and cannot integrate both functions within the same structure. In practical applications, when connecting adjacent prestressed concrete pavement panels, the device still relies on closure pours to complete the final connection and prestressing force transfer through cast-in-place concrete. This process involves multiple steps and long cycles, making it difficult to achieve truly continuous and prefabricated construction, thereby constraining the construction efficiency and the stability of the overall performance.

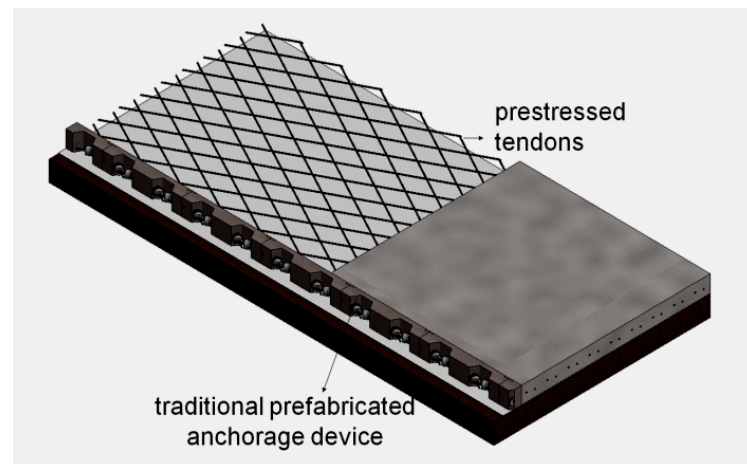


Figure 3. Traditional prefabricated anchorage device.

In summary, while the aforementioned studies have improved joint performance to some extent, they have not fundamentally moved beyond the traditional closure pour approach. They have failed to resolve core issues such as construction interruption, quality variability, and long-term reliability deficiencies caused by cast-in-place concreting, interface bonding between new and old concrete, and segmented construction. Therefore, developing a new anchorage system that can completely eliminate closure pours and achieve continuous tensioning and prefabricated connection remains a key direction for advancing this technology.

Based on the aforementioned research background and technical limitations, this study aims to systematically overcome the constraints of conventional one-way anchorage systems by proposing and designing an innovative prefabricated integrated anchorage (PIA) device. Structurally, the PIA integrates the functions of both a tensioning end and an anchoring end. Through modular design and prefabricated construction, the same component can serve dual load-bearing roles at different construction stages, thereby effectively addressing the issues of functional singularity and reliance on several operations associated with traditional anchorage devices. Building on the PIA, a corresponding continuous tensioning construction method is further introduced. This method optimizes construction sequencing and spatial utilization, enabling prestress transfer and structural connection between multiple pavement slabs without the need for closure pours, significantly enhancing the construction continuity and efficiency. The mechanical performance of the PIA device and the structural response of the HPCP system are evaluated through finite element analysis, confirming the feasibility and reliability of the proposed system under prestressing conditions. It is anticipated that this integrated approach will address the interfacial, constructional, and quality-control issues associated with traditional closure pours, offering a sustainable and efficient technical solution for the development of high-performance airport pavements.

2. Prefabricated Integrated Anchorage Device and Principle of Continuous Tensioning Construction

This section systematically explains the functional principles and workflow of the proposed prefabricated integrated anchorage (PIA) device. First, to address the limited functionality of traditional prefabricated anchorage systems, the core design concept of the PIA device is introduced, featuring a bidirectional working mode that integrates both tensioning and anchoring functions. Subsequently, a continuous construction process based on the PIA is described in detail, integrating casting, tensioning, and connection into a

seamless procedure. The explanation highlights how this method fundamentally eliminates the need for closure pours and enables efficient, sequential, and streamlined construction of HPCP, thereby representing a significant innovation in HPCP construction methodology.

2.1. Prefabricated Integrated Anchorage Device and Its Functional Innovation

The detailed design of the Prefabricated Integrated Anchorage (PIA) device is illustrated in Figure 4. The device adopts a fully prefabricated and assembled structure, primarily comprising two sets of symmetrically arranged bidirectional anchoring units. Each anchoring unit is equipped with 16 standardized reserved holes, which serve to accommodate the prestressed tendons embedded in the pavement slab and to provide permanent anchorage after tensioning. In addition, each unit integrates a prefabricated connection structure designed with precise detailing to enable rapid and accurate on-site splicing and assembly of multiple PIA devices. In order to achieve fast and accurate on-site splicing, a trapezoidal mortise is integrated at both ends of each unit (one end is a tenon and one end is a mortise), and a connecting groove with fastening bolts is arranged on the side of the joint.

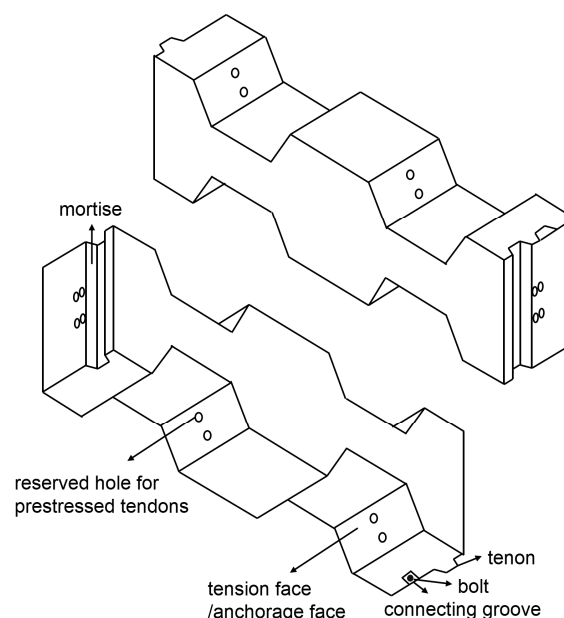


Figure 4. Prefabricated integrated anchorage (PIA) device.

From the perspective of connection mechanism, the PIA forms a well-defined and structurally stable connection node between two adjacent pavement slabs through the interlocking of multiple sets of holed anchoring surfaces and matching grooved joints. This node not only ensures the continuous transfer of prestressing forces but also undertakes shear and moment transfer between the slabs, thereby completely replacing the traditional reliance on closure pours for slab connection. This design effectively avoids the common interfacial weaknesses associated with closure pours while significantly enhancing the degree of prefabrication and overall structural reliability in construction.

During the assembly process, the installation baseline is first established, with its ends extended outward and fixed in position; alignment strings are then used to precisely locate each PIA unit. The assembly proceeds by sequentially pushing the tenon of one unit into the mortise of the adjacent unit to achieve preliminary alignment and connection. Subsequently, the fastening bolts on the side of each joint are tightened, integrating the modules into a solid unit. Throughout the assembly, close contact between adjacent units must be ensured, gaps minimized, and joint surfaces kept flush. Assembly operations can

be carried out simultaneously on both sides of the pavement to improve efficiency. After splicing, position verification is required, with a permitted installation tolerance of ± 3 mm. Through the above splicing of multiple PIA units, integrated PIAs can be quickly assembled, as shown in Figure 5.

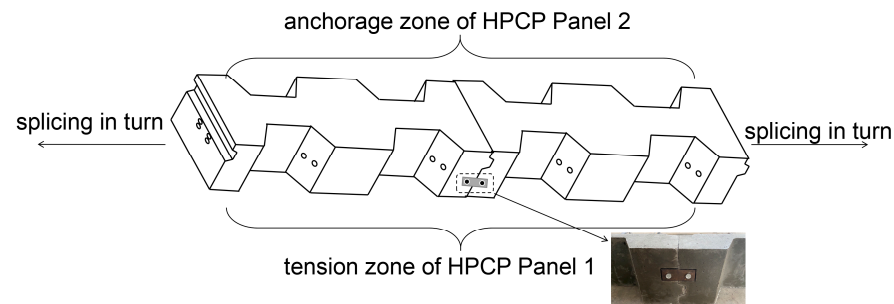


Figure 5. Splicing the PIA by connection structure (PIAs).

These PIAs reliably connect two adjacent heterotrophic prestressed concrete pavement slabs. Taking adjacent HPCP Panel 1 and Panel 2 as an example, one side of the PIAs is specifically designed as the tensioning end for the prestressed tendons of Panel 1. It not only provides sufficient workspace for tensioning operations but also forms an effective temporary anchorage during the tensioning process, ensuring stable prestress establishment. The opposite side serves as the fixed end for the prestressed tendons of Panel 2, enabling pre-positioning and pre-anchoring of the tendons before Panel 2 is cast, thereby preparing for subsequent tensioning.

The bidirectional design of the PIAs combines tensioning and anchoring to ensure continuous force transfer between the prestressing systems of adjacent slabs. Consequently, Panels 1 and 2 can be directly connected via the PIAs, achieving both structural continuity and prestress transfer without the need for a traditional closure pour. This not only simplifies the structural detailing but also avoids the common quality defects associated with closure pours. The overall configuration and connection of the PIAs are illustrated in Figure 5.

2.2. Principle of the Continuous Tensioning Construction Process

The continuous tensioning construction process based on Prefabricated Integrated Anchorages (PIAs) is illustrated in Figure 6. This method innovatively uses the future casting area of the next slab as a workspace to tension the previous slab's tendons, allowing for seamless continuous construction without joints. The key steps are as follows:

- (1) Position and install the PIAs: Precisely install the PIAs nodal units at their designated locations, ensuring alignment with the prestressing tendon ducts of adjacent slabs and temporary support fixation, thus establishing a reliable connection foundation for the subsequent prestressing system.
- (2) Place the prestressing tendons: Thread the prestressing tendons through the PIAs nodes and the designed slab positions, ensuring that the tendons are straight, accurately positioned, and preliminarily fixed at one end.
- (3) Cast the first HPCP slab: Cast the concrete for the first slab (e.g., Panel 1). At this stage, the prestressing tendons of this slab are not yet tensioned; the side of the PIAs' node corresponding to Panel 2 serves only as an embedded fixed end for the tendons.
- (4) Utilize the subsequent space for tensioning: After the concrete of Panel 1 reaches the specified strength, tension the prestressing tendons of Panel 1 within the reserved casting space of Panel 2. This step fully exploits the area intended for Panel 2 as the tensioning workspace.

- (5) Anchor and complete the slab: Anchor the tensioned prestressing tendons through the side of the PIAs node corresponding to Panel 1, thereby establishing effective prestress in Panel 1 and completing the construction of that slab.
- (6) Repeat the process sequentially: Repeat steps 2 to 5 for Panel 2, Panel 3, and subsequent slabs in turn. This creates a streamlined cycle of “casting—tensioning—connecting” until the entire pavement construction is finished.

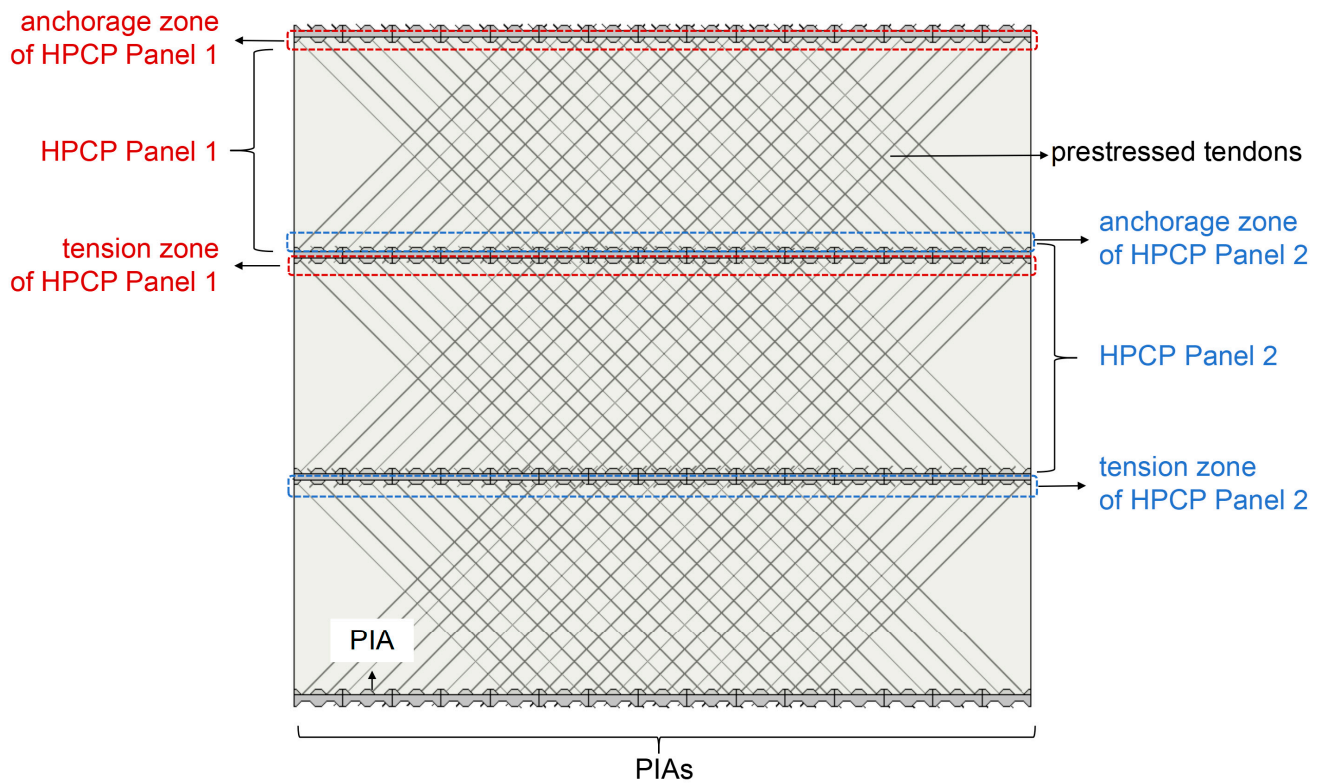


Figure 6. Principle of the continuous tensioning process (based on PIA).

Following the systematic elaboration of the continuous tensioning construction process based on the Prefabricated Integrated Anchorage (PIA), as shown in Figure 7, the innovative significance and engineering value of this method can be summarized as follows:



Figure 7. PIA device used in test site: (a) after placing prestressing tendons; (b) after the assembly process.

Traditional prefabricated anchorage systems require concrete to undergo an independent curing period, typically lasting at least 14 days. This results in idle work areas and

interrupted construction. The PIA-based continuous construction process introduced in this study overcomes these limitations. It enables truly continuous operation by dynamically reusing space and seamlessly integrating construction stages. This method completely eliminates the need for closure pours, thereby avoiding common problems such as poor interfacial bonding, shrinkage, and cracking. Furthermore, its standardized and prefabricated approach significantly improves construction efficiency, enhances quality control, and increases schedule reliability.

Therefore, the PIA-based continuous tensioning process represents not only a breakthrough in construction methodology but also embodies a modern engineering philosophy oriented toward green, efficient, and high-quality development. It provides an innovative solution with distinct technical advantages and practical feasibility for pavement projects such as airfields, which demand high durability, tight schedules, and reliable performance.

3. Finite Element Analysis

To investigate the mechanical performance of the PIA device and the structural response of the HPCP system, a three-dimensional finite element model is developed in this section using ABAQUS software version 6.14. The study is designed to address the following objectives:

- (1) Analyze the stress distribution of the PIA device under heterotropic prestressing, and identify regions of stress concentration and potential weak zones of the device.
- (2) Investigate the influence of key design parameters, especially the tendon angle, on the mechanical behavior of the PIA device through parametric studies. The analysis systematically examines how variations in the tension angle affect stress levels and deformation characteristics, thereby providing a theoretical basis for subsequent design optimization.
- (3) Study the mechanical response of the HPCP system with the PIA device installed, including the stress distribution in the pavement slab under prestress, and identify potential weak areas in the slab that may affect the long-term durability and structural reliability.

3.1. Finite Element Model Development

3.1.1. Global Model for HPCP

A three-dimensional finite element (FE) model of global HPCP was developed. The model considers the foundation as a Winkler-type elastic base, following the approach referenced in Kim et al. [59]. The pavement structure was simplified into a two-layer system: the upper layer consists of two adjacent HPCP slabs connected by the PIA device, each with dimensions of 21 m (length) $\times$ 6.5 m (width) $\times$ 0.25 m (thickness). The lower base layer has dimensions of 23 m $\times$ 8 m $\times$ 0.2 m. The prestressed tendons are arranged diagonally at a 45° tension angle with the longitudinal direction, and a spacing of 750 mm between each other.

The transverse joints at both ends of the HPCP slab were fixed, while the other boundaries remained free. A frictional contact (coefficient = 0.66) was defined at the interface between the slab and the base to simulate the sliding layer [23]. The model was discretized using eight-node linear brick elements (C3D8R) with a global mesh size of 100 mm for the slab and 200 mm for the base, as shown in Figure 8.

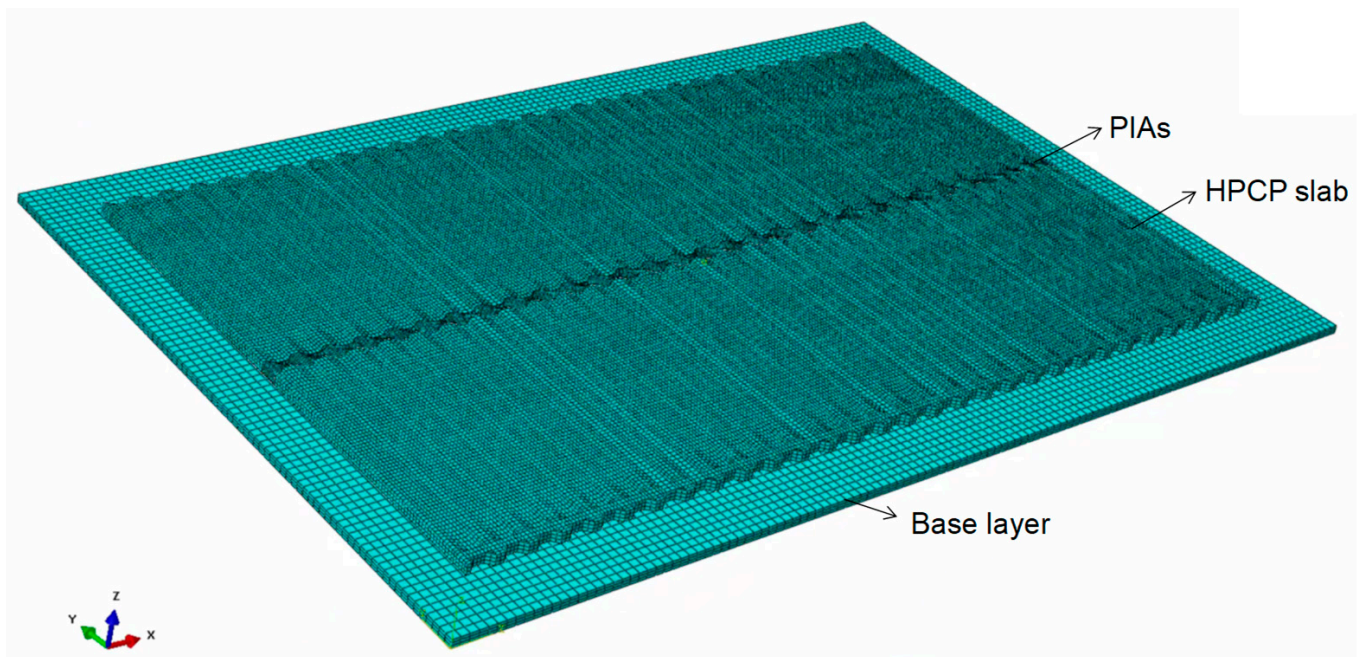


Figure 8. Global model for HPCP.

As for applying prestressing, the model has been refined to implement a prestressing scheme that closely follows the actual construction process (as illustrated in Figure 6): (1) Edge zones of the slab are prestressed in one direction only (longitudinal or transverse). (2) Central regions are prestressed in both directions, simulating the completed biaxial prestress state after the panels are joined via the PIA system.

3.1.2. Local Model for PIA

To accurately analyze the stress of the PIA device and minimize the influence of boundary conditions, a refined local model of the anchorage zone was developed, as shown in Figure 9. The detailed dimensions of the PIA device are presented in Figure 9a. Figure 9b shows the local model comprises a 500 mm long PIA segment and a 500 mm long adjoining concrete slab segment. As displacements at the cross section 1000 mm from the loaded end were negligible, the far-end face of the 1000 mm combined segment was fixed in both the x- and y-directions to represent the restraint provided by the larger structure, improving both realism and numerical convergence. The bottom surface of the model was in frictional contact with the base layer (coefficient = 0.66), with the sides free. It should be noted that the interface between adjacent PIA units in the model is initially traction-free. In reality, post-assembly bolt tightening creates partial contact and compression, meaning the actual condition lies between a free and a fully bonded interface. Surface-to-surface contact was defined between the PIA and the HPCP panel, with a reasonable friction coefficient assigned to simulate the interfacial mechanical behavior during prestress transfer [60].

A mesh size of 20 mm was adopted for the PIA region to capture the stress gradients accurately. The PIA device is fabricated from Ultra-High Ductile Cementitious Composites (UHDC). Its material parameters (elastic modulus, Poisson's ratio, and density) were adopted from reference [61] and are listed in Table 1. The material properties for the concrete slab and base were consistent with those in the global model, taken from references [24,62].

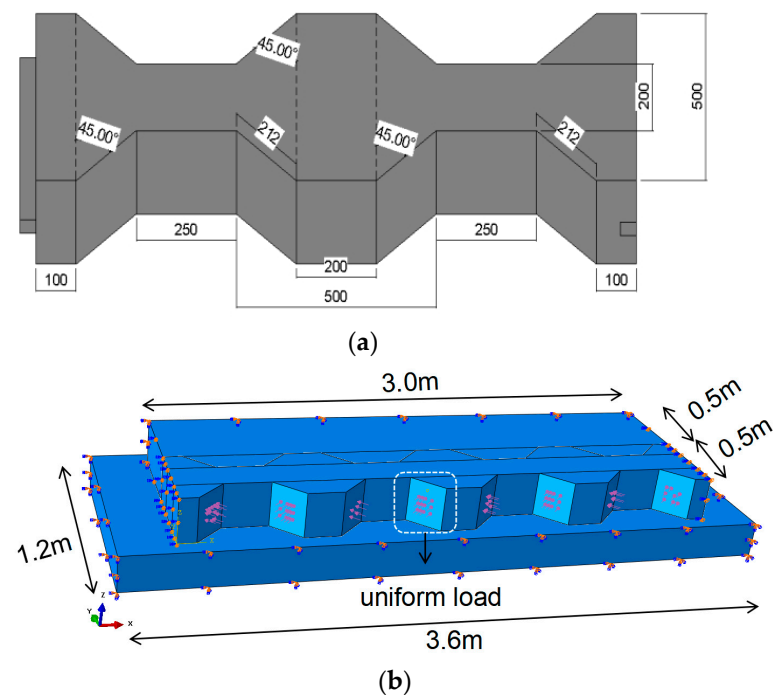


Figure 9. Local model for PIA: (a) the detailed dimensions of PIA (mm), (b) the development of model for PIA.

Table 1. Parameters of HPCP model.

Parameter	Description	Value
E_c	Modulus of concrete slab	37 GPa
μ_c	Poisson's ratio of concrete slab	0.15
ρ_c	Density of concrete slab	2400 kg/m ³
E_b	Modulus of base	4 GPa
μ_b	Poisson's ratio of base	0.2
ρ_b	Density of base	2100 kg/m ³
E_i	Modulus of PIA	20 GPa
μ_i	Poisson's ratio of PIA	0.24
ρ_i	Density of PIA	1800 kg/m ³
k	Winkler foundation's stiffness	65 MN/m ³
f	COF	0.66

The simulation of prestressing force is crucial in the FE analysis of HPCP systems. Unlike bonded post-tensioning, unbonded prestressing—commonly used in HPCP—allows the tendons to move longitudinally relative to the concrete. This is typically achieved by encasing each strand in a plastic sheath filled with corrosion-inhibiting grease. Two common simulation methods were considered: the uniform load (UL) method and the initial temperature (IT) method. In the UL method, the prestress is simulated as a uniform pressure over the anchorage bearing area. In the IT method, the tendon is modeled explicitly with truss elements, and an initial temperature drop is applied to induce the equivalent tensile force [23]. In this study, the UL method was selected for the primary analysis due to its computational efficiency and stability, and because the anchorage surfaces in the PIA are perpendicular to the tendon direction, ensuring the applied pressure aligns with the tendon axis, as shown in Figure 9b. Therefore, the prestress can be equivalently simulated as a uniform load applied over the anchorage zone. The loaded area refers to the bearing

area of the anchor plate, and the magnitude of the uniform pressure is calculated using (1), resulting in approximately 25 MPa:

$$\sigma_T = \frac{F_T}{S_a} \quad (1)$$

where F_T is the tensioned control stress, typically taken as 195.3 kN; σ_T is the uniform load (MPa); S_a is the cross-sectional area of the anchor plate, approximately 78.5 cm².

3.2. Mechanical Response of the PIA Device

The variation in the maximum principal stress along the longitudinal direction (x-direction) at different cross-sectional depths ($z = 20, 50, 100, 150, 200, 250$ mm) was analyzed as shown in Figure 10. The findings are summarized as follows:

- (1) The stress curves at various depths show clear alternation between tension and compression along the x-direction, which is closely related to the sectional geometry and symmetrical loading. The stress amplitudes at depths of $z = 100$ mm and $z = 150$ mm are significantly larger than those at other depths, while the curves at $z = 20$ mm and 50 mm are the flattest, with the smallest stress variations. Specifically, tensile stress dominates in the central region, while compressive stress prevails near the corner regions, forming a distinct alternating pattern.
- (2) The maximum tensile stress occurs in the central region ($x = 400\sim 600$ mm) and reaches its peak values at depths of $z = 100$ mm and $z = 150$ mm, approaching 1.23 MPa. The tensile stress peaks at other depths are notably lower.
- (3) The maximum compressive stress appears near the two corner locations ($x = 300$ mm and 750 mm), also attaining its highest values at $z = 100$ mm and $z = 150$ mm. The compressive peak is approximately -6.68 MPa at $z = 150$ mm and about -1.5 MPa at $z = 100$ mm, with significantly lower magnitudes at other depths.
- (4) The cross sections at depths of $z = 0.10\sim 0.15$ m are identified as the most critical. This is primarily because the core layer within this depth range experiences the most significant stress transfer and redistribution under symmetrical compression. Stress concentration induced by geometric discontinuities at the corners is also most marked in this layer. In contrast, stress amplitudes are reduced near the top/bottom surfaces ($z = 20, 50$ mm) and in regions farther from the core ($z = 200, 250$ mm) due to boundary constraints and stress dispersion. Therefore, these cross sections represent the key areas for crack-resistance design and strength verification.

To optimize the design of the PIA, the influence of the tension angle (θ) within a range of $20^\circ\sim 45^\circ$ on the maximum principal stress in the PIA device was investigated. The results are shown in Figure 11. The following findings can be drawn:

- (1) As the θ increases from 20° to 45° , the maximum stress of the PIA device shows a linear upward trend. The fitting equation $y = 0.0285x + 2.486$ indicates that for every 1° increase in the angle, the maximum principal stress increases by approximately 0.0285 MPa on average.
- (2) The coefficient of determination $R^2 = 0.94$ demonstrates that the linear relationship between the angle and the maximum principal stress is significant and well-fitted.
- (3) In optimization design, if the aim is to reduce the maximum stress of the PIA device to enhance safety or decrease material stress, a smaller θ angle should be selected whenever possible. Conversely, if a higher stress state is intended to be utilized, the angle may be appropriately increased.

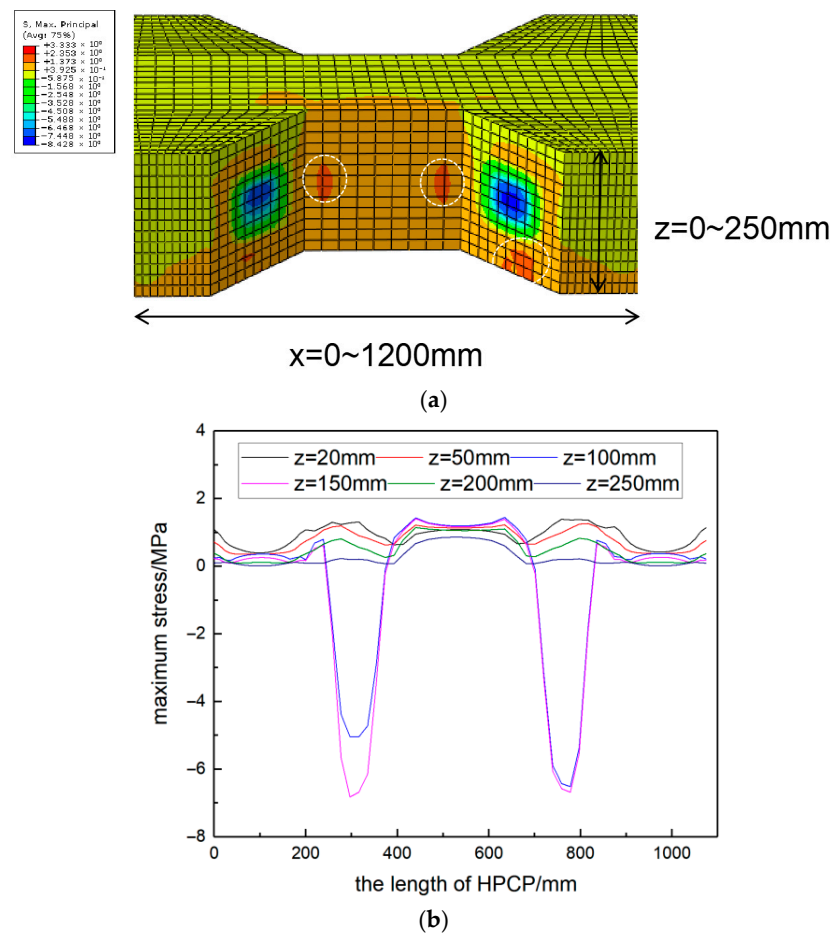


Figure 10. Mechanical response of the PIA device: (a) maximum stress contour of the PIA device under prestressing (MPa), (b) the stress distribution along the longitudinal of HPCP under different thickness.

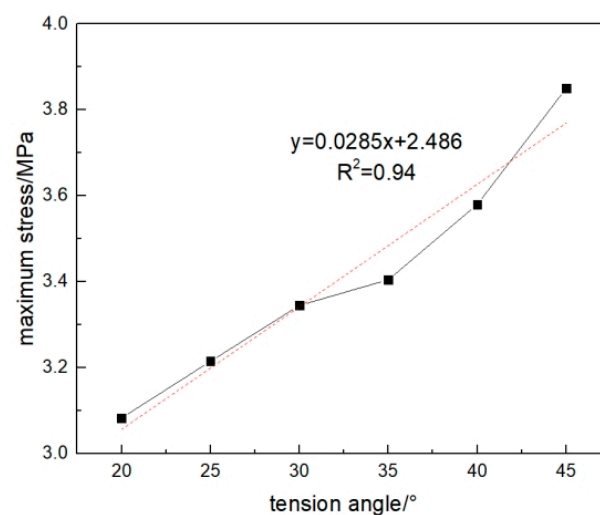


Figure 11. Maximum principal stress in the PIA device under different tension angles.

3.3. Mechanical Response of HPCP

The maximum principal stress contour of the HPCP slab after prestressing is shown in Figure 12. The following findings can be observed:

- (1) The slab is predominantly under compression: Most regions in the contour plot show compressive stress, indicating that biaxial prestressing generates a uniform and

effective pre-compressive stress field throughout the slab. This outcome aligns with the design intent of prestressing, which effectively counteracts the tensile stresses induced by subsequent operational loads and significantly enhances the cracking resistance of the pavement slab.

- (2) In addition to the PIA regions, significant stress concentration and tension–compression alternation occur at the slab corners: Apart from the stress concentration and alternating tension–compression still existing around the PIAs in the slab center and longitudinal joints, the four corners of the slab also exhibit marked tensile stress concentration. Furthermore, the characteristic of tension–compression alternation extends from the PIA zones to the corner regions, reflecting the complexity of corner restraint and stress redistribution under the applied prestressing.
- (3) The characteristics of tensile stress at the corners differ from those at the PIAs and exhibit higher magnitudes: The tensile stress at the slab corners is characterized by a relatively concentrated distribution and significantly higher values, with a peak tensile stress reaching approximately 4.426 MPa, while the tensile stress around the PIAs still shows the feature of a large extent but smaller magnitude. This indicates that the stress concentration effect at the slab corners is more obvious, making the corners a more critical control location for crack resistance than the PIA zones.

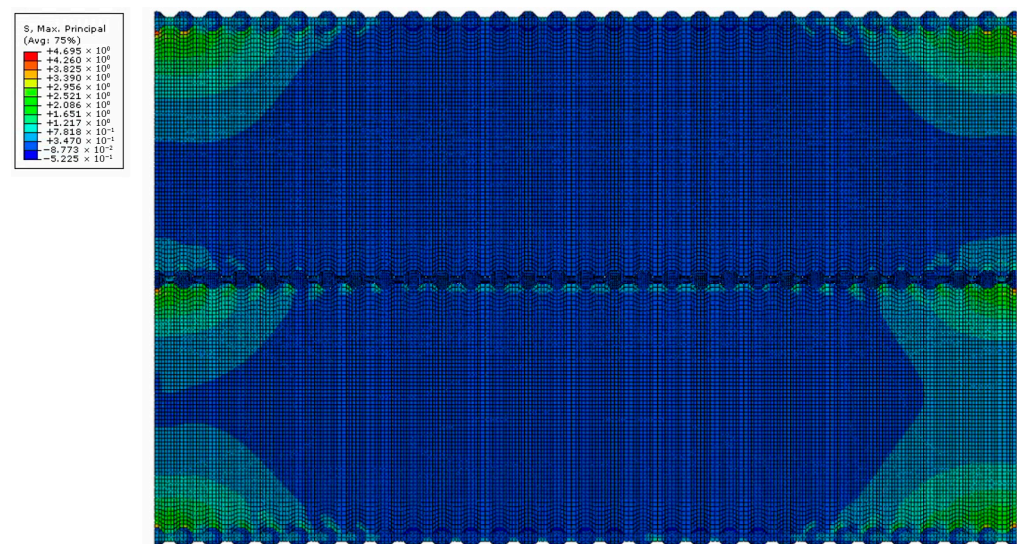


Figure 12. Maximum stress contour of HPCP under prestressing (MPa).

Figure 13a illustrates the longitudinal stress (S_{11}) characteristics in the longitudinal joints and in the slab center (PIA zones). The following observations can be made:

- (1) The S_{11} at the longitudinal joints exhibits periodic tension–compression alternation, whereas the S_{11} in the slab center (PIA zones) shows a smooth transition from the edge zones to the central region, characterized by tensile stress in the edge zones and compressive stress in the central region. This reflects the overall stress gradient of the pavement slab under the applied prestressing. This pattern is directly related to the periodic arrangement of the PIA devices, reflecting the cyclic transfer of prestress within the slab.
- (2) The stress amplitude at the longitudinal joints remains significant, with tensile and compressive peaks fluctuating around ± 1 MPa. In contrast, the stress variation in the slab center is more gradual: the tensile stress peak in the edge zones is about 0.5 MPa, and the compressive stress in the central region is approximately -0.5 MPa.
- (3) The maximum tensile stress still occurs at the PIAs in the longitudinal joints, but its magnitude is reduced to about 1 MPa. Meanwhile, a certain level of tensile stress

also appears in the edge zones of the slab center, indicating that under the longer-slab condition, the stress response in the edge zones requires special attention.

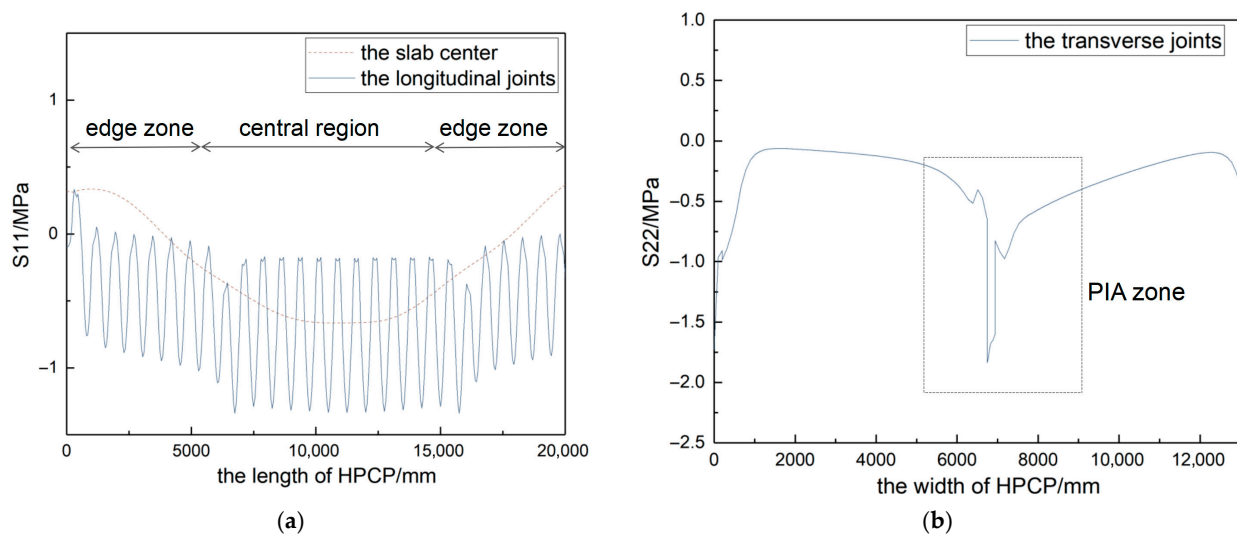


Figure 13. Stress distribution in HPCP: (a) S11 in the slab center and the longitudinal joints; (b) S22 in the transverse joints.

This confirms the earlier findings from the contour plot: tensile stresses at the PIAs in the longitudinal joints show sharper and higher peaks, whereas tensile stresses at the PIAs in the slab center are distributed over a wider area but with smaller magnitudes.

Figure 13b illustrates the transverse stress (S22) in the transverse joints, and the following observations can be made:

- (1) All S22 stresses in the transverse joints are negative, indicating that the region is entirely under compression under prestressing. No tensile stress is generated, implying a low risk of cracking.
- (2) In the PIA zones along the transverse joint, the compressive stress shows a distinct change, forming a localized stress concentration. In other areas, the compressive stress remains stable between -1.75 MPa and -0.5 MPa, reflecting the local stress redistribution induced by the constraint effect of the PIA devices at the transverse joints and reflecting local stress concentration due to the constraint imposed by the transverse joint detailing.

In summary, although the PIA system enables continuous tensioning structural connection, stress concentration and uneven stress distribution remain evident not only around the PIA zones and near the joints but also in the slab edge regions. Specifically, the PIAs in the longitudinal joints still exhibit periodic tension–compression alternation, while the central slab region shows a smooth stress gradient from the edge zones (under tension) to the central region (under compression). In the transverse joints, distinct local spikes in compressive stress occur within the PIA zones; although the overall region remains in compression, the local stress-concentration effect becomes more significant. These phenomena indicate that the layout of the PIAs and the restraint conditions at the joints detailing significantly influence on the stress distribution of the pavement slab, with the slab edge zones and the PIA zones emerging as new critical control regions. Therefore, in future design and construction, emphasis should be placed on optimizing the transition between the PIA and the pavement slab, reasonably adjusting the angle and spacing of prestressing tendons, and enhancing local reinforcement or detailing in the joint regions. These measures will help improve stress transfer paths, reduce stress concentration, and further enhance the overall durability and load-bearing reliability of the pavement slab.

4. Conclusions

This study developed an innovative prefabricated integrated anchorage (PIA) device and a corresponding continuous tensioning construction method to overcome the inherent limitations of closure pours in heterotrophic prestressed concrete pavement (HPCP). Through numerical simulation, the mechanical behavior of the PIA device and the structural response of the HPCP assembled with PIA were thoroughly investigated. The main conclusions are summarized as follows:

- (1) The PIA device successfully integrates the functions of a tensioning end and an anchoring end within a single prefabricated unit, enabling direct connection between adjacent HPCP panels. This design fundamentally eliminates closure pours, thereby avoiding associated issues such as weak interfacial bonding, differential shrinkage, and construction interruptions.
- (2) The proposed continuous tensioning construction method makes innovative use of the casting space of the subsequent slab as a tensioning zone for the preceding slab, achieving a seamless “cast–tension–connect” workflow. This approach removes the need for long curing periods, significantly improves construction continuity and efficiency, and is well-suited for fast-track airport pavement projects.
- (3) Finite element analysis of the PIA device under prestressing reveals complex stress distribution patterns. Stress alternates between tension and compression along the longitudinal direction, with the most critical cross sections located at depths between 100 mm and 150 mm. The maximum tensile stress (approximately 1.23 MPa) occurs in the central region, while significant compressive stress concentration (up to -6.68 MPa) is observed near the corners of PIA.
- (4) Parametric studies show a clear linear relationship between the tendon angle (θ) and the maximum principal stress in the PIA device. For angles ranging from 20° to 45° , the stress increases by approximately 0.0285 MPa per degree. This finding offers a direct basis for optimizing the tendon layout to control device stress in design.
- (5) In the HPCP system, prestressing establishes an overall compressive stress field that effectively enhances crack resistance. However, significant stress concentration and tension–compression alternation occur not only around the PIA zones and longitudinal joints but also at the slab corners. The tensile stress at the corners shows a concentrated distribution with a higher peak (up to 4.426 MPa) compared to the more distributed lower-magnitude tensile stress around the PIAs.

This study is primarily derived from finite element numerical simulation. A limitation of this research is the lack of experimental validation for the mechanical response of the PIA device, as well as for its long-term durability, corrosion protection efficacy, and fatigue performance under realistic loading conditions. Consequently, the experimental verification of these aspects remains to be addressed in future work.

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