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Research on Early-Age Cracking Mechanisms and Control Factors in Continuously Reinforced Concrete Pavements

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Abstract. Continuously Reinforced Concrete Pavement (CRCP) has been widely adopted internationally due to its superior crack resistance and lower maintenance costs. However, research into the early-age cracking mechanisms and control factors of CRCP still presents numerous challenges, such as insufficient studies on crack formation and development patterns, the bond-slip relationship between steel bars and concrete, and the characteristics of interlayer friction.This paper systematically analyzes the influence of reinforcement ratio, reinforcement arrangement, concrete age, and interlayer bonding conditions on early-age cracking of CRCP through axial tensile tests and interlayer friction push-out tests. Furthermore, it establishes a mechanical model based on the Winkler foundation assumption to investigate the crack formation mechanism and load stress distribution patterns. The research indicates that different reinforcement ratios and arrangements significantly affect crack width and stress distribution, while interlayer friction is collaboratively composed of bonding force, bearing capacity, and shear force, which determines the overall mechanical performance of the pavement slab. The relevant research provides theoretical basis and practical guidance for optimizing CRCP design and construction.

Keywords: CRCP; early-age cracking; reinforcement ratio; interlayer friction; load stress

1. Introduction

Continuously Reinforced Concrete Pavement (CRCP), as a high-quality pavement structure, has been widely researched and applied internationally due to its excellent crack resistance, durability, and lower maintenance costs. Since the construction of the world's first CRCP experimental road in the United States in 1921, significant progress has been made in CRCP design, construction, and performance research[1]. Through the construction of numerous experimental roads and actual engineering projects, countries such as the United States, Belgium, and Japan have progressively refined the theoretical foundation and engineering technology of CRCP, forming a systematic research framework ranging from crack control to load response analysis. Particularly in the United States, through the development of design procedures from CRCP-1 to CRCP-10, extensive investigations have been conducted on the stress, strain, and crack development patterns of CRCP under vehicle and environmental loads using the finite element method[2]. However, compared to foreign countries, CRCP research in China started relatively late. Since the completion of the first experimental road in Yancheng, Jiangsu, in 1989, although relevant applications and research scale have gradually expanded, the overall development remains in an exploratory stage, with its promotion and application on high-grade highways just beginning.

Despite numerous achievements in CRCP design methods, crack control, and load response analysis both domestically and internationally, existing research still faces several pressing issues. On one hand, foreign research is mostly based on large-scale experimental roads and long-term performance investigation data, with relatively comprehensive statistical regression analysis. However, there is still insufficient collection and analysis of key data such as crack initiation time and location[3]. Furthermore, research on the relationship between crack development patterns and punch-out failure is relatively weak. On the other hand, domestic research is limited by the scale of experimental roads and data volume, leading to dispersed conclusions that lack uniformity and representativeness. In addition, both domestically and internationally, while considerable research

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has been conducted on the factors influencing CRCP crack spacing and width, precise observation of critical factors such as the bond-slip relationship between steel bars and concrete and interlayer friction remains inadequate[4]. Existing computational models also have certain limitations in practical engineering applications.

Based on these considerations, this paper systematically investigates the crack formation mechanism, load stress distribution patterns, crack control methods, and design optimization of CRCP, building upon existing research on early-age cracking of CRCP both domestically and internationally, focusing on two key issues: crack control and load response analysis. Through laboratory tests and theoretical modeling, the study explores the main influencing factors of crack spacing and width and their sensitivity. Combined with experimental road research, it validates the applicability and reliability of the theoretical models. The innovation of this paper lies in comprehensively considering the coupled effects of environmental and vehicle loads, establishing a mathematical model-based method for CRCP cracking mechanism analysis. Simultaneously, through sensor monitoring and grating ruler measurement techniques, it profoundly reveals the early-age crack development patterns, providing a scientific basis for CRCP design and construction.

2. Methodology

2.1 Axial Direct Tensile Test of Reinforced Concrete

This test used an MTS servo testing machine to perform axial direct tensile tests on reinforced concrete specimens. We applied the load in displacement control mode at a rate of 0.5 mm/min. The specimens were designed in a dumbbell shape to prevent stress concentration at the ends, and the test force was directly applied to the concrete via clamps[5]. Before the test, we checked the strain gauges' resistance with a multimeter to ensure the strain acquisition system was working correctly. During loading, the MTS machine recorded tensile force and displacement, while an NI dynamic strain tester recorded real-time strain values from strain gauges on both the steel reinforcement and the concrete surface. This data helped us analyze changes in the axial tensile force of the steel and concrete[6]. We used a digital camera to record the entire process and image recognition software to measure changes in crack width. At the beginning of the test, we performed a pre-load to eliminate any gaps in the force transmission components and to check for eccentric loading. We adjusted the specimen's position based on the loading curve to ensure the loading effect met our requirements[7]. After fracture, we used the average strain within the gauge length to characterize the deformation in the test area and analyze the experimental data.



Figure 1 Physical Diagram of Specimen Mold

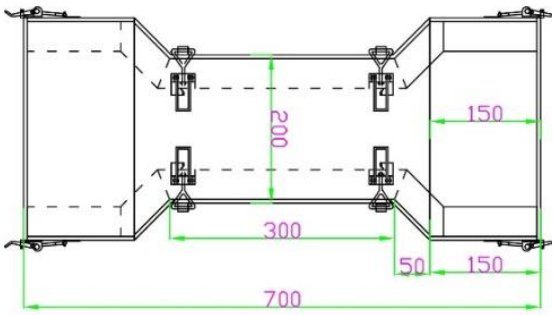


Figure 2 Schematic Diagram of Specimen Mold Dimensions

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Figure 3 Schematic Diagram of Concrete Strain Gauge Placement



Figure 4 Experimental Equipment Layout

2.2 Interlayer Friction Push-Out Test

As a crucial indicator of friction between the surface layer and the base layer, the interlayer friction coefficient is widely used in concrete pavement design methods across various countries. Its classic physical calculation formula is[8]:

$$\mu = \frac{F}{W}$$

Where: μ—Interlayer friction coefficient;

F—Horizontal pushing force in push-out test (kN);

W—Weight of pavement slab (kN)

This study conducted push-out tests on seven different interlayer conditions: plastic film, geotextile, emulsified asphalt, and asphalt functional layers of varying thicknesses, as well as direct concrete pouring onto the base layer. To minimize the influence of size effects on the push-out test results, pavement slabs measuring 80cm × 80cm × 26cm and semi-rigid bases measuring 100cm × 100cm × 16cm were cast. Different contact states between the surface layer and the base layer were achieved by laying various media. A jack was used to firmly fix the base layer horizontally, preventing any displacement throughout the test. An MTS machine applied horizontal loads to the pavement slab using different loading methods and rates, recording the pushing force corresponding to various displacement values. Counterweights were used to simulate pavement slabs of different thicknesses, allowing us to investigate the effects of different interlayer bonding conditions, loading rates, loading methods (monotonic loading, cyclic loading), and pavement slab thickness on the interlayer friction of the pavement[9]. The experimental equipment layout is shown in Figure 5.

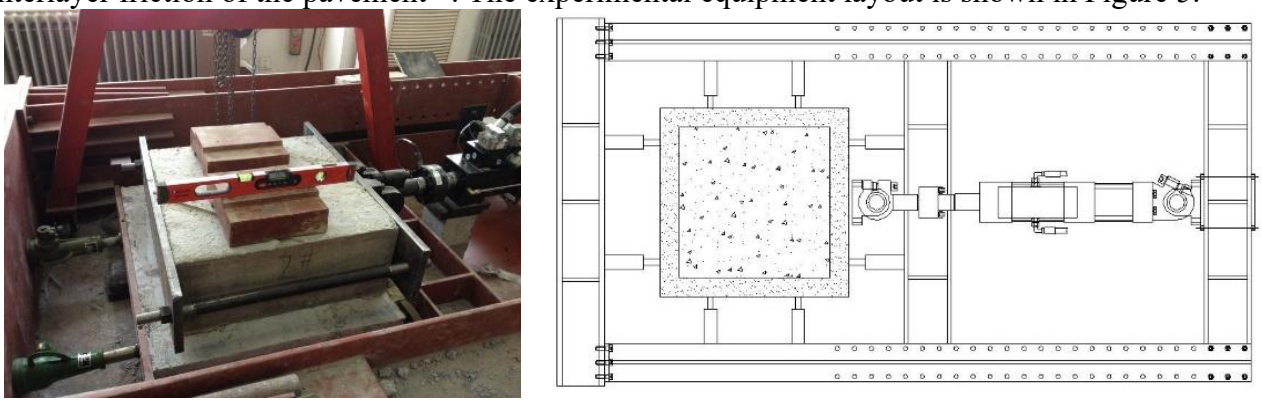


Figure 5 Push-Out Test Equipment Layout

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3. Results and Discussion

3.1 CRCP Load Stress Analysis

3.1.1 Load Position Analysis

The critical load position is where the pavement experiences maximum tensile stress or is most prone to damage. Due to transverse cracks dividing CRCP into multiple slab sections, it possesses good load transfer capabilities[10]. To analyze its critical load position and stress distribution, a pavement slab model with dimensions of 1.5m × 4m × 24cm was used for calculation based on the Winkler foundation assumption. The vehicle load was a standard single axle dual wheel set with an axle load of 100kN and tire pressure of 0.7MPa. The concrete elastic modulus was 3×10^4Mpa,Poisson's ratio was 0.15, the subgrade reaction modulus was 180MN/m³ , and the crack width was 1 mm. The load was moved along the longitudinal and transverse joints, with a step size of 0.1 m, from the slab corner towards the slab center.

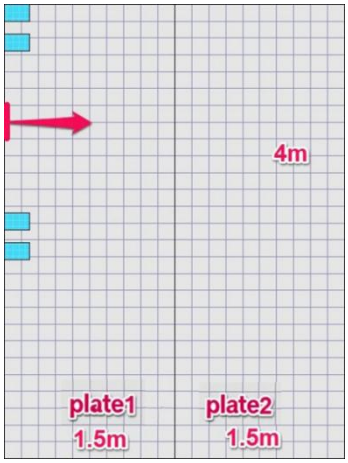


Figure 6 CRCP Longitudinal Joint Movement Start Position

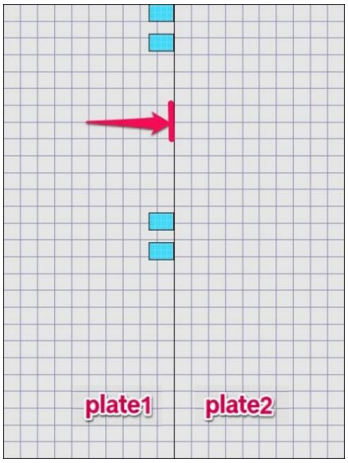


Figure 7 CRCP Longitudinal Joint Movement End Position

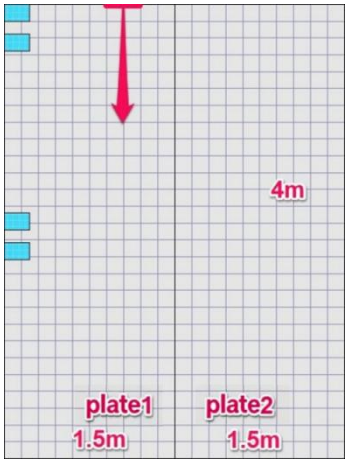


Figure 8 CRCP Transverse Joint Movement Start Position

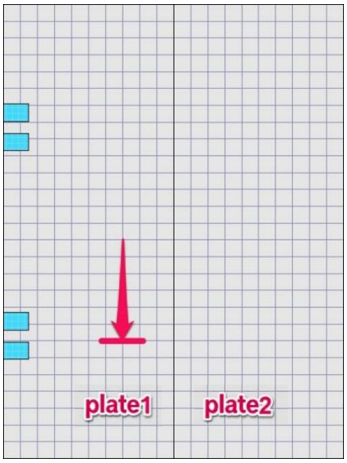


Figure 9 CRCP Transverse Joint Movement End Position

Calculation results indicate that when moving along the longitudinal joint, the maximum bending tensile stress at the slab bottom appears near the middle of the longitudinal joint edge, approximately 0.8 m from the starting point. At this point, the X-direction stress (σ_x) is significantly greater than the Y-direction stress (σ_y), making it the primary direction of concern. When moving along the transverse joint, the change in bending tensile stress at the slab bottom is not significant, with the maximum value approximately equal to the stress in the middle of the slab, and σ_x also being the controlling direction.

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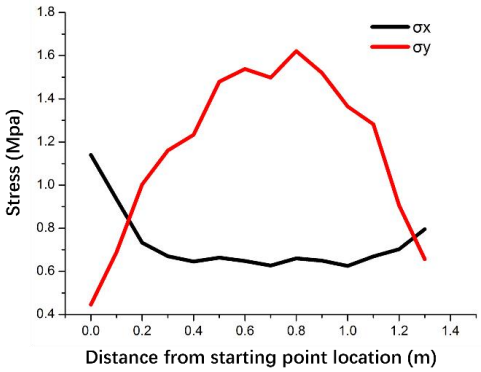


Figure 10 X and Y Direction Stresses when Load Moves Along Longitudinal Joint

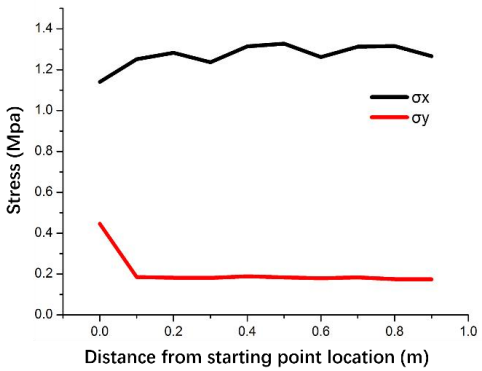


Figure 11 X and Y Direction Stresses when Load Moves Along Transverse Joint

3.1.2 Slab Bottom Stress Analysis

CRCP and JPCP (Jointed Plain Concrete Pavement) differ in their slab size design and failure modes, leading to differences in slab bottom stress distribution and critical load positions[12]. CRCP uses punch-out failure as its design criterion, while JPCP uses fatigue failure due to slab bottom load stress as its criterion[13]. To analyze the changes in slab bottom stress under vehicle loads for both types, comparisons were made for loads moving along longitudinal and transverse joints.

When the load moves from the slab corner towards the slab center, the maximum tensile stress at the bottom of both CRCP and JPCP slabs gradually increases, reaching its maximum when the load moves near the middle of the longitudinal joint edge. At this point, the Y-direction (traffic direction) stress (σ_y) is the controlling stress. For CRCP, the load moved from the starting point (0 m) to 1.5 m with a step size of 0.1 m. For JPCP, the load moved from the starting point (0 m) to 5 m with a step size of 0.5 m. Results show that when the load is near the middle of the longitudinal joint edge, the tensile stress at the slab bottom is significantly higher than at the slab corner.

When the load moves from the slab corner towards the slab center to the middle of the transverse joint edge, the trend of slab bottom tensile stress change for both CRCP and JPCP is essentially consistent, gradually increasing and reaching its maximum at the middle of the transverse joint edge. At this point, the X-direction (perpendicular to the traffic direction) stress (σ_x) is the controlling stress. For both CRCP and JPCP, the load moved from the starting point (0 m) to 0.9 m with a step size of 0.1 m. Results show that the slab bottom tensile stress peaks at the middle of the transverse joint edge, with the σ_x stress perpendicular to the traffic direction being the controlling stress.

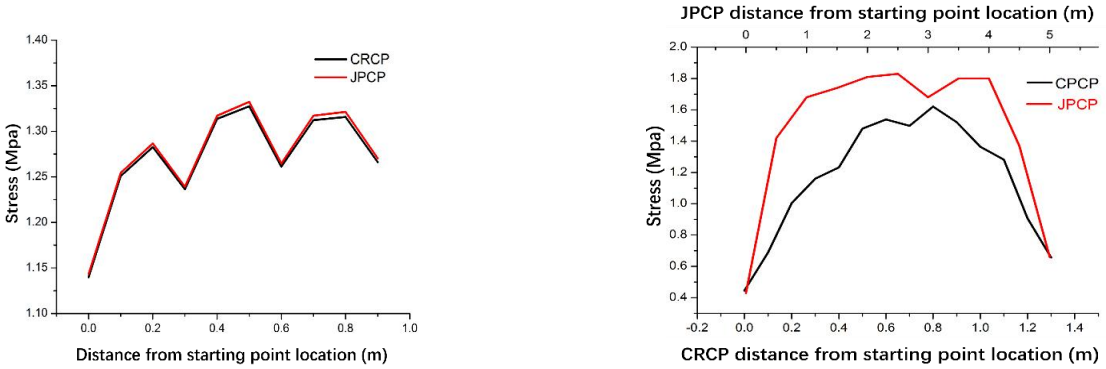


Figure 12 Maximum Tensile Stress at Slab Bottom of JPCP and CRCP Under Load Movement in X and Y Directions

In summary, the maximum stress for both CRCP and JPCP occurs when the load is positioned in the middle of the longitudinal or transverse joint edge, and the overall tensile stress at the bottom of CRCP slabs is slightly higher than that of JPCP. The analysis results provide a reference for slab thickness design and failure control.

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3.2 CRCP Cracking Mechanism Analysis

3.2.1 Analysis of Cracking Influencing Factors

In the formation process of early-age cracks in Continuously Reinforced Concrete Pavement (CRCP), the definition of the concrete's "early-age" stage is particularly crucial. Based on the cement hydration process, concrete development can be divided into the plastic stage, early-pre-hardening stage, early-hardening stage, and mature stage[14]. Among these, CRCP early-age cracking primarily occurs in the early-pre-hardening stage (12-72 hours after final setting) and the early-hardening stage (72 hours to 90 days). During these two stages, concrete experiences drying shrinkage and thermal shrinkage deformation due to factors such as cement hydration reactions and changes in temperature and humidity, leading to a gradual accumulation of internal tensile stress[15]. When the tensile stress exceeds the concrete's ultimate tensile strength, transverse cracks first appear at the weakest cross-section.

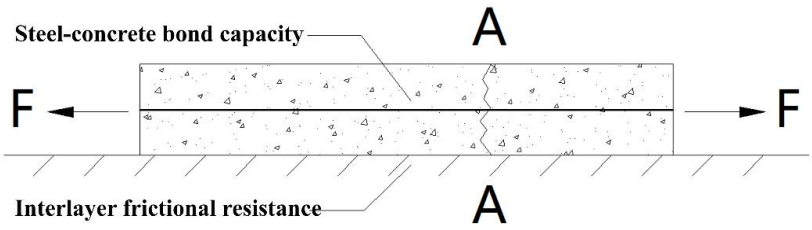


Figure 13 CRCP Cracking Mechanism Analysis Diagram

CRCP early-age cracking can be divided into two phases: The first phase extends from paving to the end of curing, before traffic is opened. During this period, approximately 70% of cracks are caused by drying shrinkage and thermal shrinkage deformation. Drying shrinkage occurs due to moisture loss during concrete hardening, while thermal shrinkage results from temperature differences caused by heat exchange with the air. Simultaneously, the restraint imposed by longitudinal reinforcement and the base layer further increases the internal tensile stress in the concrete. The second phase is after traffic is opened, where crack widths gradually expand under traffic loads, accompanied by the appearance of a small number of new cracks, but primarily characterized by width expansion.

The main factors influencing CRCP early-age cracking include concrete material properties, steel reinforcement material properties, environmental conditions, the bond between steel reinforcement and concrete, and the friction between the surface layer and the base layer[16]. The bond between steel reinforcement and concrete is fundamental to their combined load-bearing capacity, primarily composed of chemical bonding, friction, and mechanical interlock. When a crack appears, the concrete ceases to bear the load, and the tensile force previously borne by the concrete is transferred to the steel reinforcement, leading to increased steel stress and further crack propagation.

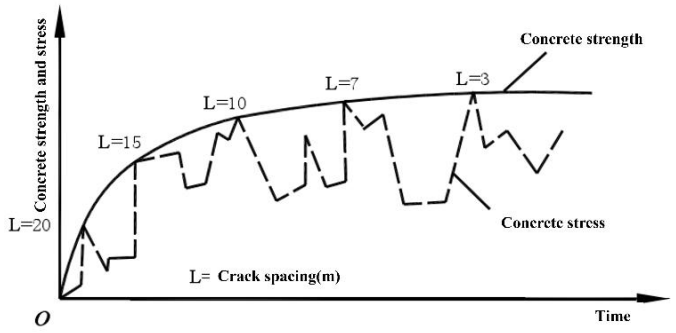


Figure 14 Schematic Diagram of CRCP Cracking Modes

Furthermore, the friction between the surface layer and the base layer also significantly impacts CRCP early-age cracking. Concrete pavement slabs undergo horizontal shrinkage and tensile

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deformation with changes in temperature and humidity. The interlayer friction is composed of bonding force, bearing capacity, and shear force. Interface roughness, temperature and humidity gradients, and construction conditions all alter the magnitude of friction, thereby affecting crack distribution and width[17].

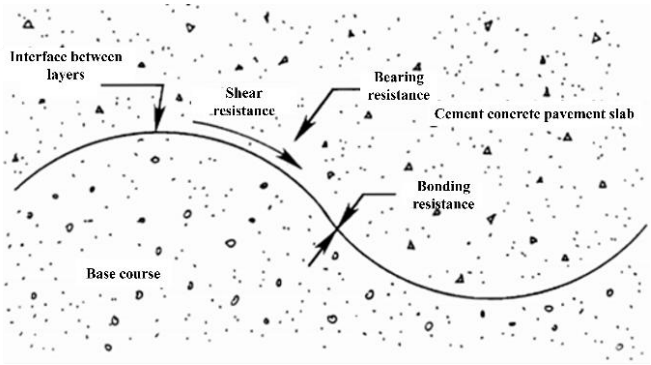


Figure 15 Components of Interlayer Friction in Cement Concrete Pavement

In summary, the formation of early-age transverse cracks in CRCP is the result of the coupled action of multiple factors. Its main influencing factors include the material properties of concrete and steel reinforcement, environmental loads, the bond between steel reinforcement and concrete, and interlayer friction characteristics. These studies provide an important theoretical basis for optimizing CRCP design and construction.

3.2.2 Axial Tensile Test

The axial tensile test investigated the influence of reinforcement ratio, reinforcement arrangement, and concrete age on the early-age cracking performance of CRCP (Continuously Reinforced Concrete Pavement)[18]. In the test, the cracking behavior of reinforced concrete specimens with different reinforcement ratios, ages, and reinforcement arrangements was analyzed by testing their force-displacement curves and strain-displacement curves under axial tensile load. The results show that for both 3-day and 7-day ages, as the axial displacement increased, the concrete specimens exhibited initial linear stress-strain characteristics[19]. After the tensile force reached the ultimate tensile strength, the concrete specimens suddenly cracked. The tensile force in plain concrete specimens dropped directly to zero, while specimens with embedded steel reinforcement showed higher residual bearing capacity due to the steel bearing the tensile force[20].

Changes in the reinforcement ratio did not significantly affect the tensile force required for the first crack, but a higher reinforcement ratio could effectively reduce crack width. Figures 15-18 visually demonstrate the crack width changes for specimens with different reinforcement ratios.

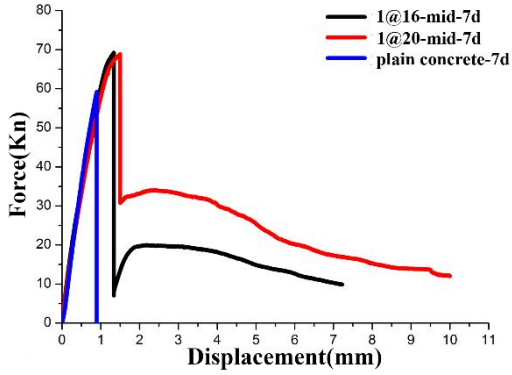


Figure 16 Force-Displacement Curves of Specimens with Different Reinforcement Ratios at 7-Day Age

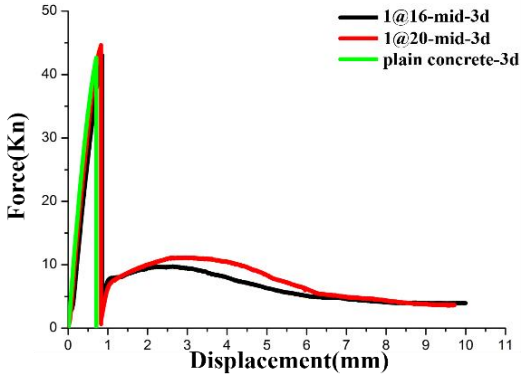


Figure 17 Force-Displacement Curves of Specimens with Different Reinforcement Ratios at 3-Day Age

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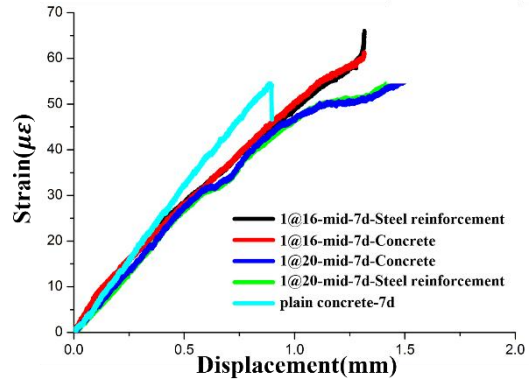


Figure 18 Strain-Displacement Curves of Specimens with Different Reinforcement Ratios at 7-Day Age

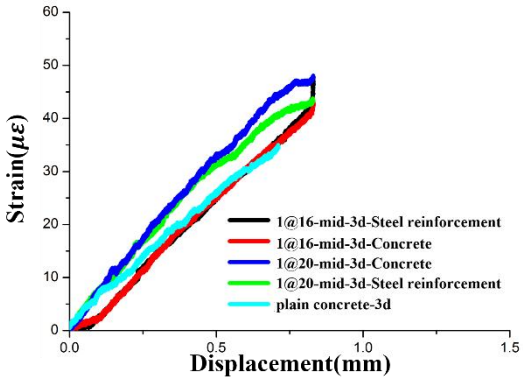


Figure 19 Strain-Displacement Curves of Specimens with Different Reinforcement Ratios at 3-Day Age

Furthermore, the test also found that the reinforcement arrangement plays an important role in crack control. Placing the steel reinforcement at one-third of the specimen's depth from the top surface restricted crack width better than placing it in the middle. Additionally, adopting a "fine and dense" reinforcement layout was more effective in reducing initial crack width than a "coarse and sparse" layout.

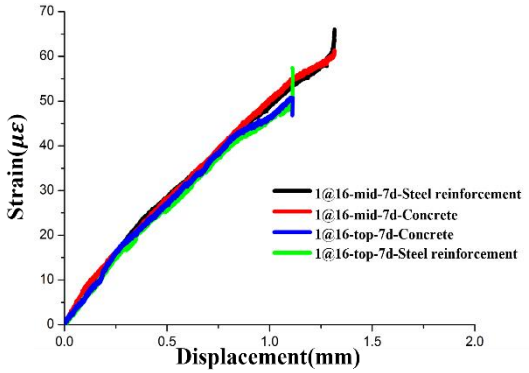


Figure 20 Strain-Displacement Curves for Different Reinforcement Positions with the Same Reinforcement Ratio

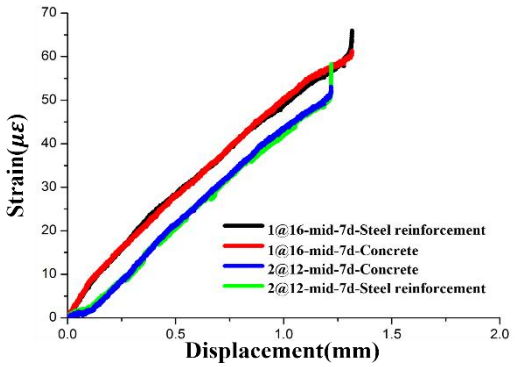


Figure 21 Strain-Displacement Curves for Different Reinforcement Quantities with the Same Reinforcement Ratio

Changes in age also significantly affected the tensile properties of concrete. The tensile strength of 7-day old concrete increased by approximately 43% compared to 3-day old concrete, and the ultimate tensile strain increased by about 38%. Figures 21 and 22 show the force-displacement curves and strain-displacement curves for specimens of different ages. Damage and spalling at the crack edges were more pronounced in older specimens, directly leading to a further increase in crack width.

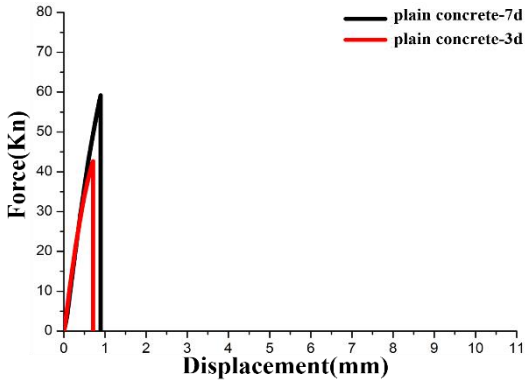


Figure 22 Force-Displacement Curve of Plain Concrete with Same Reinforcement Arrangement and Different Ages

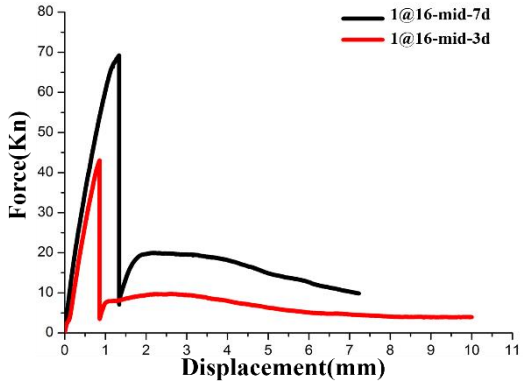


Figure 23 Force-Displacement Curve of Reinforced Concrete with Same Reinforcement Arrangement and Different Ages

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3.2.3 Analysis of Cracking Influencing Factors

The push-out friction test aimed to study the composition of interlayer friction between the CRCP surface layer and base layer and its influencing factors, providing a theoretical basis for pavement design[21]-[23]. The test measured the change in interlayer friction with relative displacement by loading push-out specimens. Results show that interlayer friction is composed of bonding force, bearing capacity, and shear force. The entire loading process is divided into three stages: in the initial displacement stage, friction increases parabolically with displacement, then rapidly decreases after reaching a peak; upon entering a complete sliding state, friction tends to stabilize. Figure 23 shows a typical friction-displacement curve.

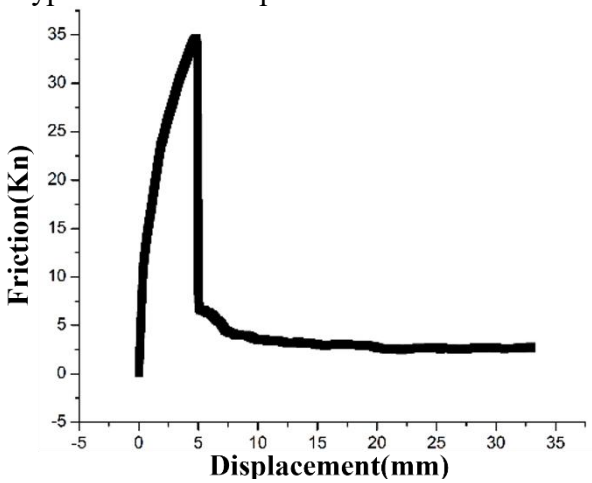


Figure 24 Typical Friction-Displacement Diagram from Push-Out Test

The test further analyzed the effect of different interlayer bonding treatments on friction. Using plastic film as an isolation layer significantly reduced friction, while the bonding action of emulsified asphalt maximized friction. Additionally, after cyclic loading, partial loss of interlayer bond occurred, friction rapidly decreased and stabilized, indicating that bonding force is the main source of interlayer friction. Loading rate and pavement slab thickness had a minor impact on friction. The test showed that when the loading rate varied from 0.01 mm/min to 10 mm/min, the friction coefficient consistently remained around 0.7. When the pavement slab thickness increased from 26 cm to 32 cm, the friction coefficient decreased from 0.66 to 0.58, indicating that increasing slab thickness reduces interlayer friction.

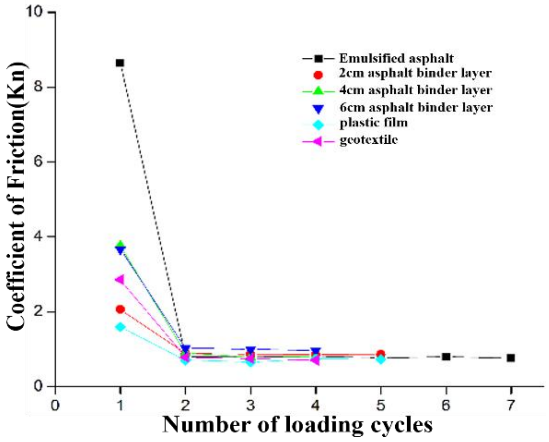


Figure 25 Effect of Loading Cycles on Interlayer Friction

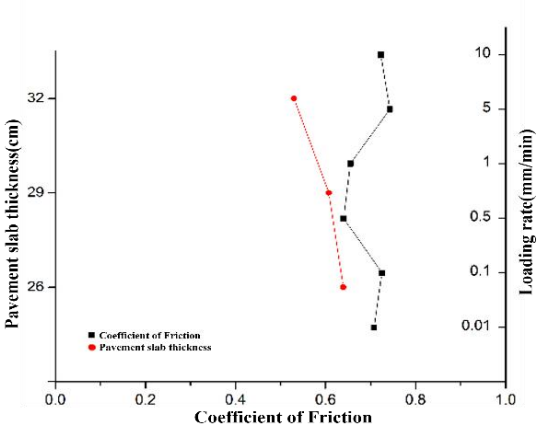


Figure 26 Effect of Loading Rate and Pavement Slab Thickness on Interlayer Friction

Through the axial tensile test and push-out friction test, it can be seen that optimizing reinforcement design and properly treating the interlayer bonding condition are key to improving

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CRCP's crack resistance. The experimental data and curves presented provide a reliable basis for further improving pavement design.

4. Conclusion

(1) Early-age cracking in continuously reinforced concrete pavements primarily occurs in the early-pre-hardening stage (12-72 hours) and the early-hardening stage (72 hours to 90 days). Crack formation results from the combined effects of concrete drying shrinkage, thermal shrinkage, and the restraint from steel reinforcement and the base layer. Approximately 70% of early-age cracks occur during the curing phase after concrete hardening, and crack widths gradually expand after traffic is opened.

(2) The axial tensile test revealed that reinforcement ratio and reinforcement arrangement significantly influence crack width control and stress distribution. While a higher reinforcement ratio had little effect on the tensile force required for the first crack, it notably reduced crack width and enhanced residual bearing capacity at the cracks. Placing steel reinforcement at one-third of the slab thickness from the top surface and adopting a "fine and dense" reinforcement pattern were more effective in controlling crack width development. Increasing concrete age significantly improved the specimens' tensile strength and ultimate tensile strain, but older specimens showed more prominent damage at crack edges, leading to increased crack width.

(3) Push-out friction test results indicated that interlayer friction is composed of bonding force, bearing capacity, and shear force, and its magnitude is affected by the interlayer bonding condition, loading method, and pavement slab thickness. Using plastic film significantly reduced friction, while emulsified asphalt enhanced the bond, maximizing friction. Loading rate had little effect on friction, but the friction coefficient slightly decreased with increasing pavement slab thickness.

(4) CRCP load stress analysis showed that the critical load position is when the load is located in the middle of the longitudinal or transverse joint edge, where the maximum tensile stress at the slab bottom is significantly higher than at the slab corner. By optimizing reinforcement design and appropriately treating the interlayer bonding condition, CRCP's crack resistance can be significantly improved, extending pavement service life.

In conclusion, this paper, through experimental and theoretical research, revealed the early-age cracking mechanisms of CRCP and its controlling factors. It provides a scientific basis for optimizing design and construction and is of great significance for enhancing the application performance of CRCP on high-grade highways.

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