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Article

Thermo-Mechanical Response of Geocell-Reinforced Concrete Pavements: Scaled Model Tests and Finite Element Analyses

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Highlights

- Geocell reinforcement reduced central settlement by up to 17.4%.
- A damage-initiation threshold was identified at 1.1-1.3 kN.
- Thermal loading caused strongly non-uniform slab strain distributions.
- Optimum geocell height was about one-third of slab thickness.
- Scaled tests and FEM clarified load transfer and stress redistribution.

Abstract

This study investigates the thermo-mechanical response of geocell-reinforced concrete pavements through scaled model tests and three-dimensional coupled finite element analyses. Static, cyclic, thermal, and coupled loading tests were conducted to clarify deformation evolution, strain distribution, and damage characteristics of the reinforced structure. The results show that, under static loading, pavement settlement evolves through three stages, namely initial compaction, plastic development, and stabilization, indicating progressive mobilization of geocell confinement. Under thermal loading, slab strain exhibits pronounced spatial and temporal non-uniformity, and the slab centre is identified as the thermally sensitive zone. Under coupled high-temperature and static loading, both strain and settlement show a non-monotonic increase–decrease trend at approximately 1.1–1.3 kN, suggesting a potential threshold for damage initiation. Under cyclic loading, permanent deformation accumulates with load repetitions and is highly sensitive to load amplitude. Numerical results further show that geocell reinforcement reduces the central settlement by 17.4% relative to plain concrete pavement and by 7.6% relative to a doweled pavement, while producing a smoother deflection basin and a more uniform stress distribution. Parametric analyses indicate that the optimum geocell height is approximately one-third of the surface course thickness; beyond this range, the marginal reinforcement benefit decreases. The results demonstrate that geocell reinforcement can significantly improve load transfer, deformation compatibility, and thermo-mechanical stability of concrete pavements.

Keywords: geocell reinforcement; cement concrete pavement; thermal–mechanical coupling; scaled model test; finite element analysis; damage evolution; sustainable pavement design

1. Introduction

Recent climate warming and increasing traffic demand have intensified structural distress in conventional rural concrete pavements, leading to more frequent slab cracking, loss of support, faulting, pumping, and differential settlement. These problems substantially increase maintenance

costs and shorten pavement service life. For low-volume and rural roads, the challenge is particularly pronounced because the pavement system is expected to remain economical while sustaining increasingly heavy and complex vehicle loading. (Allen et al., 2025; Haekook et al., 2022; Mallick et al., 2018; Sushobhan et al., 2022; Yinghao et al., 2022)

Geocells are three-dimensional geosynthetic confinement systems that improve the load distribution capacity of infill materials by restricting lateral deformation and mobilizing passive confinement. In pavement engineering, geocell reinforcement has been widely shown to increase bearing capacity, improve structural stiffness, and reduce stress concentration in unbound base and subgrade layers (Karfa and Sarkar, 2024; M. et al., 2022). Through the formation of a confined composite layer, geocells can redistribute localized stresses and enhance deformation compatibility within the pavement system (HAN et al., 2013).

Recent studies have substantially advanced the understanding of geocell-reinforced pavement systems. (Thakur et al., 2012) demonstrated that geocell-reinforced RAP bases over weak subgrades exhibited lower permanent deformation and reduced interface stresses under cyclic plate loading. More recently, (Banerjee et al., 2024) reported that geocell geometry strongly affects rut depth and localized stress concentration under repeated loading, while (Banerjee et al., 2025) confirmed through field trials that geocell-reinforced pavements can improve bearing capacity and reduce subgrade vertical stress. In addition, analytical studies have refined the estimation of settlement, stress propagation, and modulus improvement in geocell-reinforced layers (Neto, 2019; R.S. and J.O., 2020). However, these studies have mainly focused on flexible pavements, unbound granular layers, or subgrade systems, whereas the thermo-mechanical response of geocell-reinforced rigid concrete pavements remains largely unexplored. (Burak et al., 2024) used large laboratory testing and finite element simulations to investigate the influence of geocell geometry on settlement trends in two-layer pavement structures, indicating that units with larger cell apertures produced better reinforcement performance under equivalent stress levels. (L.L.R. and J.O., 2022) further showed, through full-scale field testing, that geocell reinforcement can increase the back-calculated elastic modulus of granular pavement layers. Additionally, .K. (Ashrafuzzaman et al., 2023) further confirmed through in-situ non-destructive testing that geogrid-reinforced subgrades exhibited enhanced elastic modulus, reduced settlement and stress concentration under traffic loads, whilst mitigating the progression of rutting and cracking.

At the material level, systematic investigations have been conducted on the mechanical properties and temperature sensitivity of geocell materials. For instance, (Qiyu et al., 2022) experimentally analyzed the tensile behavior of geocell strips made from various polymers (e.g., HDPE, PP, PET) under low temperature conditions, revealing significant differences in stress-strain response and temperature sensitivity, which provide guidance for material selection in practical applications. Subsequent work by Lu and Zhao (Yang et al., 2024; Zhao et al., 2024; Zhao et al., 2025) developed novel geocell materials and examined creep behavior under different loading conditions. Their results show that nonlinear three-parameter models, modified for temperature effects, accurately capture accelerated creep due to increased temperature. (Bingbing et al., 2024) employed ABAQUS finite element software to model geocell-reinforced asphalt mixtures and explored optimal geocell configurations under various conditions.

Compared with flexible pavements, the behaviour of geocell-reinforced rigid concrete pavements remains insufficiently understood. In particular, the structural response of such systems under coupled traffic and temperature actions has not yet been clarified. Concrete pavements are highly sensitive to temperature gradients because thermal warping modifies the support condition, stress distribution, and load transfer mechanism of the slab. When repeated traffic loading is superimposed on temperature-induced deformation, the resulting thermo-mechanical response may differ substantially from that under isolated loading conditions.

The available literature on geocell-reinforced concrete pavements is still limited. Existing studies suggest that geocell inclusion can improve slab stiffness, reduce settlement, and delay cracking, but most work has been restricted to static loading or simplified laboratory configurations. Systematic

investigation of static, cyclic, thermal, and coupled loading conditions remains lacking, and the influence of geocell geometry on the response of rigid pavements has not been fully quantified.(Ni Fujian, 2004; Visser, 1999; Zhiyong, 2021)

To address these gaps, this study combines scaled model testing with three-dimensional thermo-mechanically coupled finite element analysis to investigate the structural response of geocell-reinforced concrete pavements under static, cyclic, thermal, and coupled loading conditions. The objectives are to: (1) characterize the settlement, strain, and stress evolution of the reinforced structure under different loading conditions; (2) identify critical response thresholds associated with damage initiation under thermo-mechanical coupling; (3) compare the performance of geocell reinforcement with that of plain and doweled concrete pavements; and (4) determine the influence of geocell height on the reinforcing efficiency of the pavement system.

2. Materials and Methods

2.1. Testing Apparatus

2.1.1. Loading Apparatus

Due to the difficulty of simultaneously applying environmental temperature and static/dynamic loads in large-scale models, the displacement loads in this study were applied using a multifunctional pavement material testing system (NL-UTM-150), as shown in Figure 1. This system employs pneumatic loading, providing a maximum axial force of 150 kN under static conditions, a maximum loading frequency of 10 Hz, and a maximum displacement range of 50 mm. Under dynamic conditions, the axial force ranges from 0.1 kN to 3 kN, with a maximum frequency of 10 Hz and a displacement range of 50 mm. The dynamic loading can be applied in sine, triangular, and rectangular waveforms, or customized waveforms according to experimental requirements.

Thermal loading was applied using a servo-hydraulic dynamic environmental chamber, as shown in Figure 2, with an adjustable temperature range of $\pm 80\text{ }^{\circ}\text{C}$. The model tank was placed on the test platform, with the platform center aligned with the loading system to facilitate uniform load application on the model.

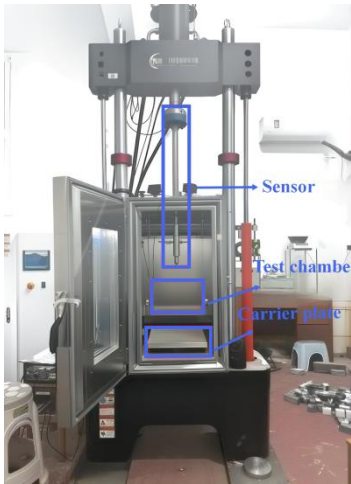


Figure 1. Dynamic Loading System and Test Rig.



Figure 2. Servo-Hydraulic Dynamic Test System with Environmental Chamber.

2.1.2. Model Tank

The internal clear dimensions of the model tank were 200 mm × 210 mm. The model tank was fabricated by welding 304 stainless steel plates with a wall thickness of 1.5 mm and a bottom thickness of 5 mm in order to ensure sufficient structural stiffness to withstand applied loads, as well as to facilitate heat transfer within the test apparatus. The model tank was mounted to the environmental test platform using four triangular prism-shaped fixtures located around its perimeter. In addition, displacement sensors provided with the multifunctional pavement material testing system were affixed to these triangular prism fixtures to enable accurate measurement of surface displacements of the pavement specimen during loading. This configuration ensured reliable constraint of the model tank and precise displacement monitoring throughout the experiments, as illustrated in Figure 3.

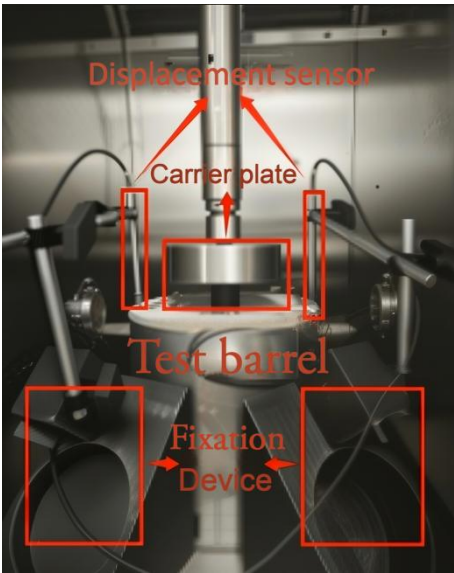


Figure 3. Triangular Prism Fixtures and Displacement Sensors.

2.2. Materials

2.2.1. Subgrade and Pavement Materials

The pavement specimen used in this experimental study consisted of four layers: a surface course, a base course, a subbase course, and a soil subgrade. The surface course was constructed with C30 grade cement concrete, The base course was composed of cement-stabilized crushed stone mixed with 5% cement by mass,. Such cement-treated base (CTB) materials are widely adopted in

pavement construction to improve load distribution and long-term performance. The subbase course was constructed using graded crushed stone, where the coarse aggregate was uniformly blended with fines to achieve a well-graded particle size distribution ranging from 0.075 mm to 4.75 mm. The gradation curves of the crushed stone and the mix proportions of the cement-stabilized materials are presented in Table 1 and Table 2, respectively.

Table 1. Aggregate Gradation Curve Chart.

Gradation type		Percentage by mass through the mesh below											
		26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
C-C-3	Upper limit	100	100	92	83	71	50	36	26	19	14	10	7
	Lower limit	100	90	79	67	52	30	19	12	8	5	3	2
	Median	100	95	85.5	75	61.5	40	27.5	19	13.5	9.5	6.5	4.5
Actual value		100	100	100	100	100	100	29.7	21.6	16.4	10.7	6.1	2.8

Table 2. Composition of Cement-Stabilised Crushed Stone Mixture.

Composition	Crushed stone:Sand	Cement quantity	Moisture content
Proportion	6:4	5%	6%

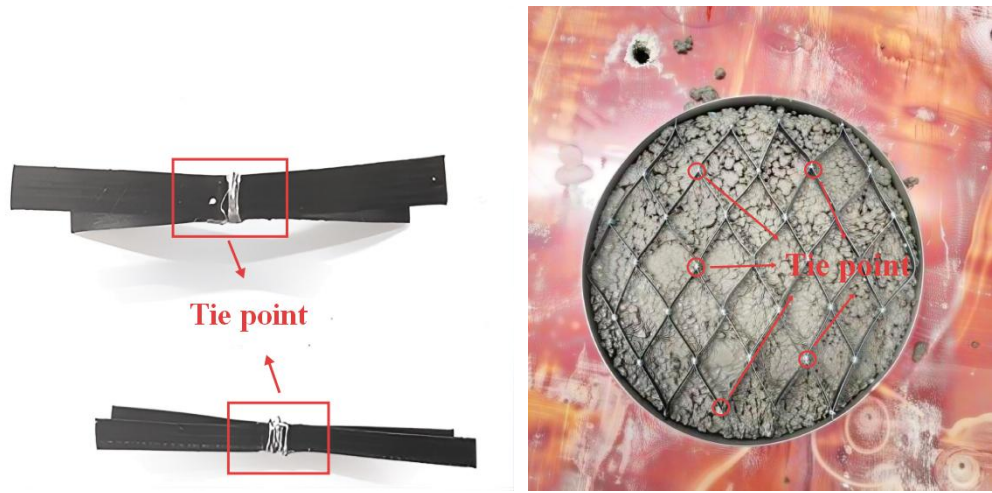
2.2.2. Geocells

In the present study, all geocell materials were supplied by the Yanshan Petrochemical Research Institute in Beijing. The geocells were manufactured from **polyethylene (PE)** polymer strips and joined by **ultrasonic welding** into a three-dimensional cellular confinement structure, consistent with the definition and product classification specified in the Chinese national standard GB/T 19274-2024: *Geosynthetics — Plastic Geocell* .

For the purposes of this experimental investigation and in accordance with geometric similarity principles, geocell panels were cut and configured with a cell height of 5 mm and a junction spacing of 32 mm. After cutting, the panels were bonded together using 502 adhesive to simulate the welding process. To replicate the effect of steel nail anchors in the field, specialized metal staples were used to interconnect the strips, and a single turn of 0.5 mm diameter iron wire was wrapped around each staple joint to reinforce the nodes mechanically. This simulated assembly procedure ensured structural integrity comparable to welded joints, thereby facilitating reproducible mechanical behavior in the model tests (Figure 4). Finally, the physical property parameters of the assembled geocell specimens were measured in accordance with the national standard GB/T 19274-2024 and are summarized in Table 3.

Table 3. Physical Performance Parameters of Geocells.

Tensile strength (KN/m)	Maximum breaking force (N)	B-1 node tensile strength (N/mm)	B-2 node tensile strength (N/mm)	C node tensile strength (N/mm)	D node peel strength (N/mm)
63.95	319.74	26.21	16.24	4.29	5.55



(a) Geocell Single-Piece Node Reinforcement (b) Geocell grid-connected reinforcement

Figure 4. Geocell Node Connections.

2.3. Test Model

The model simulates a proposed rural road section, with the prototype pavement structure designed in accordance with the Chinese national standard JTG/T 3311-2021:Design Specifications for Low Volume Rural Highway Engineering.The prototype consists of a 0.21 m concrete surface course, a 0.18 m cement-stabilized crushed stone base, a 0.12 m graded crushed stone subbase, and a 1.5 m subgrade, as shown in Figure 5.

Based on a geometric similarity ratio of 1:10, the thickness of each pavement layer and the dimensions of the geocell reinforcement were scaled down accordingly, resulting in model layers that are one-tenth the thickness of the prototype. However, due to experimental constraints and site limitations, the materials used in the model (concrete, crushed stone, and soil) could not strictly satisfy the similarity theory requirements for material properties. Therefore, some differences between the mechanical behavior of the model and the prototype are expected. Nevertheless, the focus of this study is on the relative trends and variations in reinforcement effectiveness under different loading conditions, and the experimental results are still considered valuable for reference in understanding the performance of geocell-reinforced pavements.

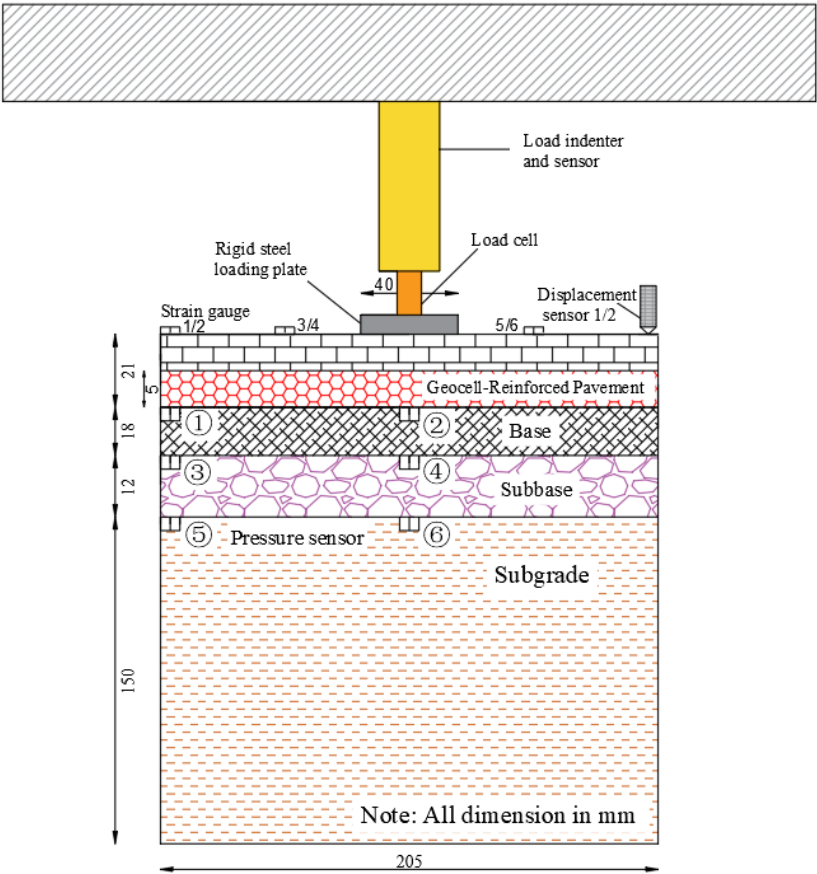


Figure 5. Model Structure and Dimensions (mm).

2.4. Test Conditions

To satisfy the requirements of the present experimental study, the applied loads were scaled proportionally in accordance with the established similitude ratios, enabling investigation of the response of the reinforced pavement under various environmental and loading conditions. A series of loading scenarios were defined and are summarized in Table 4

Table 4. Different load test conditions.

Operating Conditions	Load Type	Loading Method	Initial Value	Increment per Level	Frequency	Load Amplitude	Cycle Period
1	Static load	Progressive loading	0.3 kN	0.2	/	/	/
2	Thermal load	Progressive loading	30 °C	10	/	/	/
3	Coupled load	Progressive loading	0.3 kN	0.2	/	/	/
4	Dynamic load	Progressive loading	0.3 kN	0.2	1.6 Hz	0.9 kN	1000

3. Test Results and Analysis

3.1. Analysis of Static Load Test Results

To investigate the mechanical response and load transfer characteristics of the pavement structure under static loading, a graded loading protocol was adopted in the present experimental program. Vertical loads were applied incrementally using the test loading apparatus until either structural failure of the pavement specimen occurred or the pre-established termination criteria were reached, thereby simulating the cumulative effects of long-term static loading.

During graded loading, the **settlement of the pavement surface course** was recorded and is presented in Figure 6. Additionally, the measured **strain responses** at the mid-span (1/2 R) and at the slab edge (R) of the surface course are shown in Figure 7, illustrating the evolution of strain distributions in response to increasing static load levels

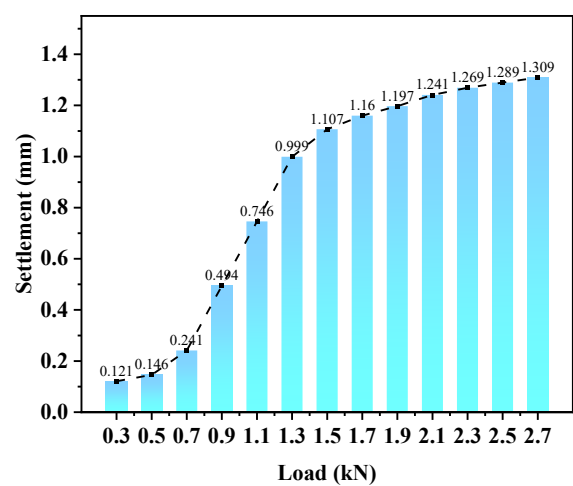


Figure 6. Settlement of Pavement Surface Layer under Graded Loading.

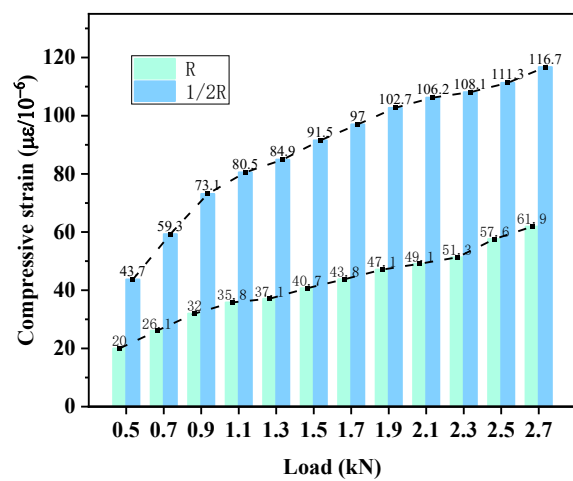


Figure 7. Strain Diagram of Pavement Slab under Graded Loading.

The strain monitoring results of the pavement slab clearly reflect the load transfer and distribution within the slab. As shown in Figure 7, with increasing applied load, the compressive strain measured within the slab exhibits an approximately linear increase, indicating that the geocell-reinforced concrete surface course remained within the linear elastic range throughout the applied load spectrum. Furthermore, the monitored strain values at the mid-span consistently exceeded those at the slab edge, directly demonstrating that the applied load is primarily transmitted

downward through the slab center and subsequently diffused laterally. This resulted in a strain gradient from the slab center toward the edge, which directly reflects the stress distribution pattern under static loading. Such observations further confirm that the geocell reinforcement layer facilitates effective lateral load spreading and optimizes the stress state of the surface course, consistent with reported mechanisms of enhanced load diffusion in geocell-reinforced pavement systems.

The settlement profile of the pavement also reveals the deformation characteristics at different stages of loading. Based on the variation in settlement rate, the deformation process can be divided into three distinct phases. During the initial compaction stage (0.3–0.7 kN), the settlement rate was relatively slow ($k_1 = 0.3$), primarily due to preliminary densification of the structural layers, with the system predominantly exhibiting elastic compression behavior. In the plastic development stage (0.7–1.5 kN), the settlement rate increased markedly ($k_2 = 1.26$), indicating the onset of plastic deformation within the subgrade soil, representing a critical period of deformation progression. In the subsequent stabilization and stiffening stage (1.5–2.7 kN), the settlement rate slowed again ($k_3 = 0.168$), a phenomenon closely associated with the reinforcing effect of the geocell layer. In this stage, the lateral confinement provided by the geocell became fully mobilized, resulting in a composite action between the geocell and the surrounding soil. This synergistic interaction significantly increased the overall stiffness of the structural system and restrained the continued rapid development of deformation.

3.2. Analysis of Dynamic Load Test Results

To investigate the service performance of the geocell-reinforced pavement under long-term dynamic loading, traffic loads were simulated using a triangular wave with a frequency of 1.6 Hz. The variation in pavement displacement with respect to the number of loading cycles (ranging from 25 to 1000 cycles) was monitored for different load amplitudes between 0.9 kN and 1.9 kN, and the experimental results are presented in Figure 8.

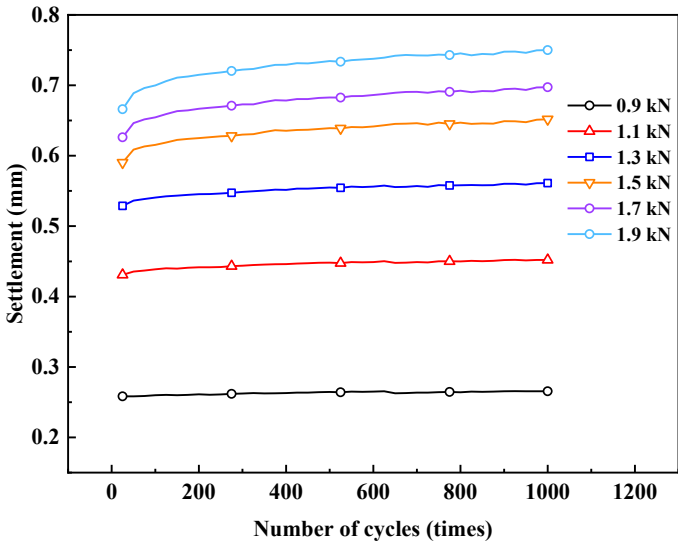


Figure 8. Settlement of road slabs under dynamic loads of varying amplitudes.

Under identical numbers of loading cycles, larger load amplitudes resulted in greater absolute settlement values. For a given load level, settlement accumulated progressively with increasing cycle count, but the rate of accumulation varied with load intensity. For instance, at a peak load of 1.9 kN, pavement displacement increased from -0.66604 mm after 25 cycles to -0.74997 mm after 1000 cycles, corresponding to an increase of approximately 12.6%, indicating a pronounced cumulative effect. In contrast, under a peak load of 0.9 kN, settlement only increased from -0.25835 mm to -0.26554 mm over the same cycle range, corresponding to an approximate 2.8% increase, whereas the 1.9 kN case exhibited a significantly larger accumulation. Similarly, at the 1000th cycle, the displacement at 0.9 kN was -0.26554 mm, while that at 1.9 kN increased to -0.74997 mm, representing an increase of

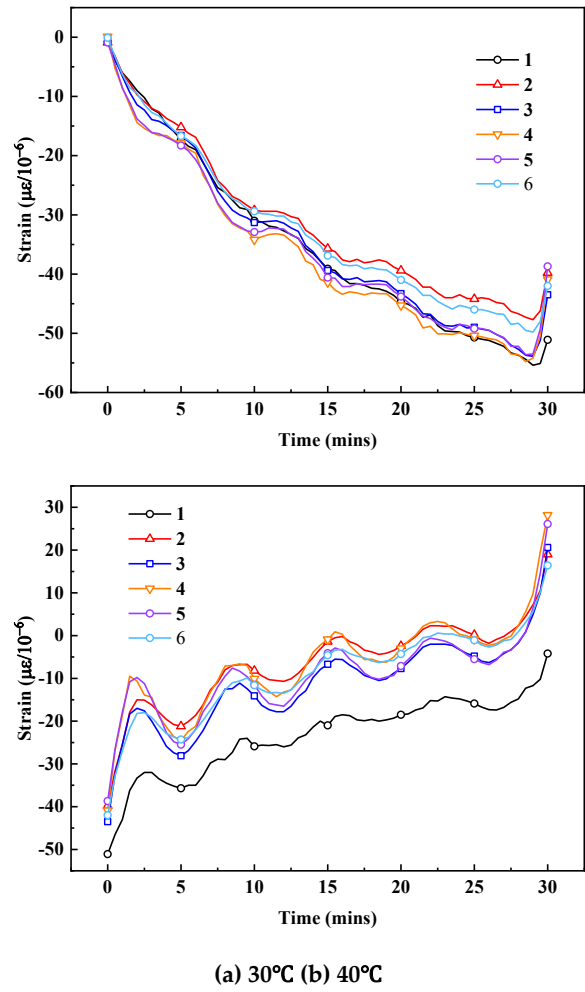
approximately 182%. These results demonstrate that the magnitude of dynamic loading is a critical factor controlling the deformation response of the pavement structure.

Moreover, the displacement–cycle relationship exhibited a similar evolutionary trend across all load levels: during the early loading phase (approximately the first 100 cycles), settlement accumulated rapidly; as the number of cycles continued to increase, the rate of settlement growth gradually decelerated and tended toward stabilization. This phenomenon reveals the adjustment and adaptation process of the pavement under dynamic loading: an initial stage dominated by structural compaction and plastic deformation, followed by a stage characterized by stable elastic response. Although displacement tended toward stabilization in the later stages, permanent (irrecoverable) displacement occurred at all load levels from the initial cycles through to the 1000th cycle, indicating plastic deformation accumulation. Furthermore, higher load levels resulted in larger amounts of accumulated permanent deformation. For example, from the 25th to the 1000th cycle, the displacement increment under 0.9 kN loading was only 0.007 mm, whereas at 1.9 kN, the increment reached 0.084 mm, which is approximately 12 times greater than that under 0.9 kN loading. These quantitative observations indicate that elevated dynamic load levels significantly exacerbate the accumulation of permanent structural damage in the pavement system.

3.3. Analysis of Temperature-Load Test Results

To investigate the response behavior of the geocell-reinforced cement concrete pavement under temperature variation, a series of environmental temperature loading tests were conducted. The test protocol simulated different ambient temperature conditions by incrementally increasing the temperature at a rate of 10 °C every 30 minutes, starting from an initial slab temperature of 35 °C. During the temperature loading process, strain at critical locations of the pavement slab was continuously monitored to analyze the evolution and spatial distribution characteristics of temperature-induced strain.

The average strain at different slab locations under varying temperature levels is summarized in Figure 9.



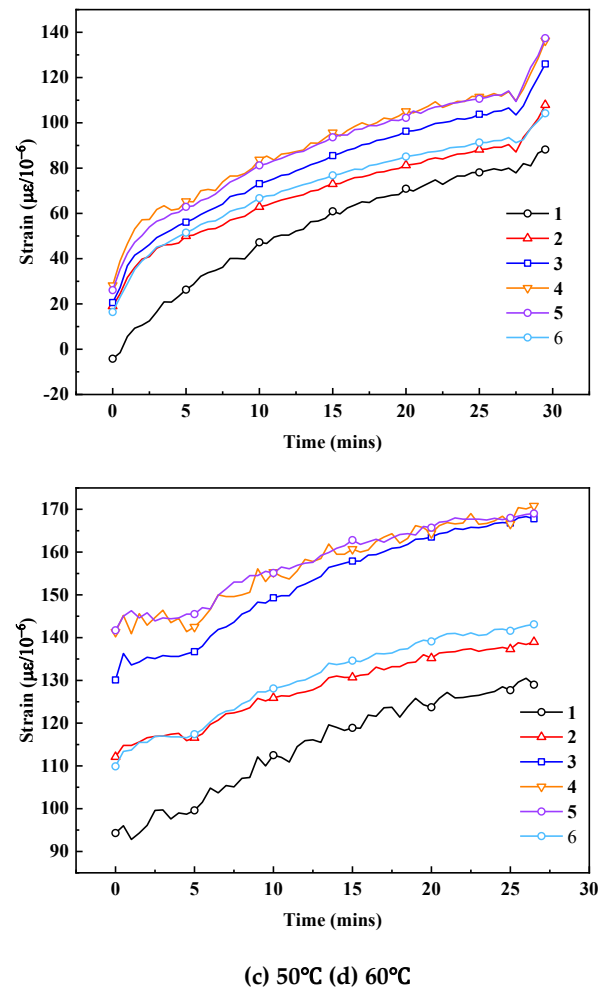


Figure 9. Strain in road panels over time at different temperatures.

As shown in Figure 9, the strain response of the pavement slab exhibits a strong correlation with the history of temperature variation, and the overall evolution can be divided into four characteristic stages based on thermodynamic behavior:

Stage I (0–30 min, 30 °C): Cooling-induced contraction stage. As the environmental temperature (30 °C) drops below the initial slab temperature (35 °C), the surface course undergoes cooling contraction. The concrete surface layer experiences compressive stresses due to thermal contraction, leading to a gradual development of compressive strain, with measured values increasing from 0 $\mu\epsilon$ to approximately $-50 \mu\epsilon$.

Stage II (30–60 min, 40 °C): Warming recovery stage. When the environmental temperature rises to 40 °C, exceeding the initial slab temperature, the slab begins to heat up. The concrete in the surface course transitions from contraction to expansion, and tensile stresses progressively replace compressive stresses. Consequently, the strain fluctuates and returns toward zero.

Stage III (60–90 min, 50 °C): Stable warming tensile stage. With the temperature continuing to increase to 50 °C, the slab remains in a steady warming state. Tensile strain in the surface course continues to increase smoothly from near zero to approximately 100 $\mu\epsilon$.

Stage IV (90–120 min, 60 °C): Sustained tensile stage. At an environmental temperature of 60 °C, the thermal expansion effect becomes more pronounced. Tensile strain continues to grow steadily, increasing from about 100 $\mu\epsilon$ to approximately 150 $\mu\epsilon$.

Furthermore, a pronounced **spatial gradient of temperature-induced strain** was observed across the pavement slab. Monitoring data indicate that the strain fluctuation amplitude at monitoring points located near the slab edges (Points 1 and 2) was significantly smaller than at points positioned near the slab center and mid-width (Points 3, 4, 5, and 6). This phenomenon suggests that

boundary constraints along the slab periphery strongly restrict free deformation. Such lateral constraints suppress upward deformation at the slab edges, preventing full release of temperature-induced stresses. In contrast, the slab center, being less constrained, is able to respond more freely to temperature changes and exhibits larger strain variations. This non-uniform strain distribution contributes significantly to thermal warping stresses and is recognized as a primary cause of temperature-induced distress in concrete pavements, which often initiates from central regions where deformation is less restrained.

Overall, the experimental results demonstrate that the geocell-reinforced cement concrete pavement exhibits pronounced thermal expansion and contraction behavior under temperature loading, with clear temporal and spatial heterogeneity in strain response. The central region of the slab, subjected to reduced boundary constraint, emerges as a sensitive zone and potential weakness for temperature-induced deformation.

3.4. Analysis of Thermal-Mechanical Test Results

To investigate the comprehensive mechanical performance of the geocell-reinforced pavement under the combined effects of elevated temperature and static loading, the present experimental program simulated a 60 °C environmental temperature field coupled with graded static loads. During these coupled loading tests, key structural responses—including soil pressure within the pavement layers, strain responses of the surface slab, and settlement behavior—were continuously monitored and analyzed. The resulting soil pressure, slab strain, and settlement data obtained under the combined temperature and static load conditions are presented in Figure 10、Figure 11、Figure12, respectively.

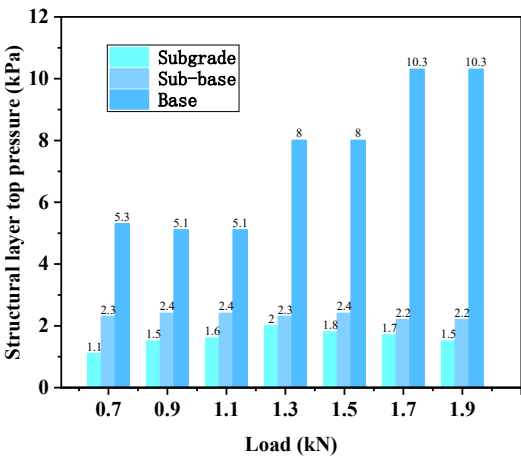


Figure 10. Top pressure at load centre of each structural layer.

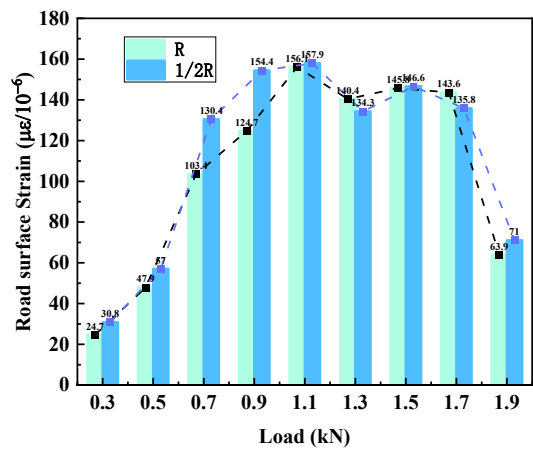


Figure 11. Pavement panel strain.

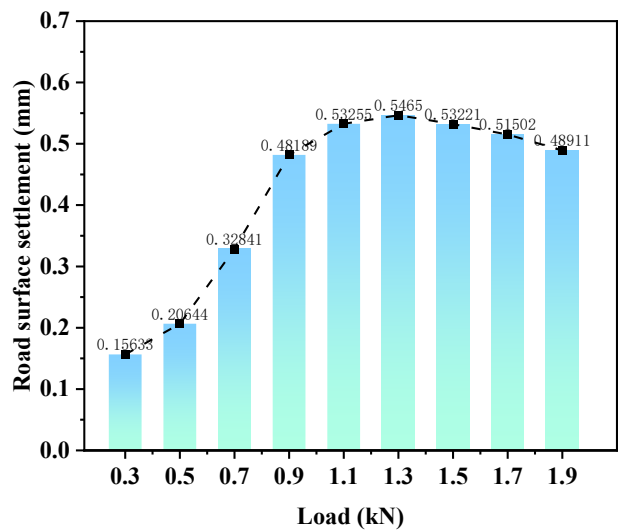


Figure 12. Road surface settlement.

Under the coupled effects of elevated temperature and static loading, the load transfer mechanism of the geocell-reinforced pavement structure exhibited characteristics significantly different from those observed under purely static loading conditions. As shown in the test results, the soil pressure at the top of the cement-treated crushed stone base exhibited a stepwise, nonlinear increase with increasing load: when the load was increased from 0.7 kN to 1.1 kN, the soil pressure remained essentially constant; at 1.3 kN, it abruptly increased to approximately 8 kPa and remained relatively stable up to 1.5 kN; a further increase to 1.7 kN caused soil pressure to rise again to approximately 10.3 kPa. This atypical trend can be attributed to the influence of high temperature, which caused overall thermal expansion of the slab and slight upward bulging near the center of the slab, thereby altering the contact conditions with the underlying base layer. Under this condition, the geocell-reinforced layer and the bulged slab worked in synergy, enhancing lateral load spreading and temporarily increasing the structural load-bearing capacity in this stage, which resulted in alternating plateaus and jumps in the measured soil pressure data. The enhancement of load diffusion due to geocell confinement has been identified in previous studies as one of the principal mechanisms through which geocells improve pavement performance by developing lateral stresses on the cell walls and increasing bearing capacity.

In contrast, soil pressure measured at the interface between the graded crushed stone subbase and the soil subgrade exhibited only minor variations throughout the entire loading process and remained nearly constant. This finding suggests that, under coupled loading, the geocell reinforcement effectively mobilized its three-dimensional confinement mechanism, dissipating the majority of additional stresses within the upper structural layers and significantly reducing stress transmission to the lower layers. As a result, the overall stability and load-bearing capacity of the foundation were markedly enhanced. Previous research has similarly demonstrated that geocell confinement produces composite action between infill and cell walls, thereby reducing stress concentrations and improving stiffness and bearing performance.

The strain response of the surface slab under coupled loading was also more complex than under static loading alone. Strain measured at both the center of the slab (R) and at half-width (1/2 R) exhibited a non-monotonic trend with increasing load. Within the loading range from 0.3 kN to 1.1 kN, strain increased continuously and reached a peak at 1.1 kN, indicating that the geocell's load diffusion effect became progressively more effective with increasing load. However, once the load exceeded 1.3 kN, the strains at both locations began to decrease. This anomalous drop in strain was not indicative of structural strengthening; rather, it suggests that the pavement structure may have entered an early stage of damage development, where the initiation and propagation of microcracks released a portion of the accumulated strain energy, leading to reduced measured strain values.

Settlement behavior also exhibited a unique response under coupled conditions: settlement peaked at a load of approximately 1.3 kN and subsequently decreased as the load increased from 1.3 kN to 1.9 kN. This "settlement rebound" phenomenon corroborates the observed decline in strain and strongly indicates that, under the combined effects of elevated temperature and loads exceeding a critical threshold (~1.3 kN), irreversible local damage occurred within the pavement structure. Possible damage mechanisms include concrete cracking, loss of bond between the slab and reinforcement, or delamination at layer interfaces, which would lead to reduced overall stiffness of the structural system and consequent stress redistribution.

4. Finite Element Model

Although model tests can effectively capture pavement settlement, strain, and soil pressure variations, comprehensively quantifying the internal structural mechanisms—such as stress distribution beneath concrete slabs, cell-concrete interactions, and the coupled response of temperature gradients with mechanical loading—remains challenging through experimental means alone. Numerical simulation techniques overcome this limitation while also providing complementary validation for model tests. Building upon systematic observations from the aforementioned laboratory tests concerning the macroscopic mechanical response of geocell-reinforced pavements under temperature-load coupling, this study established a thermo-mechanical coupled numerical model to further elucidate the underlying mechanical mechanisms and stress transfer patterns.

4.1. Model Establishment

Based on the parameters obtained from the laboratory model tests, a **three-dimensional finite element model** was developed using the commercial software **ABAQUS** to simulate the thermo-mechanical response of the geocell-reinforced pavement. The primary concrete surface slab in the model had dimensions of **5.0 m × 4.0 m**, while the overall computational domain was defined as **10.0 m × 8.0 m × 2.01 m** to minimize the influence of boundary effects and ensure accurate stress and deformation predictions across the structural layers.

In order to conduct comparative analyses, a conventional cement concrete pavement model **without geocell reinforcement** was also constructed as a control case. This control model incorporated equivalent **load transfer bars and tie rods** to provide a baseline structural configuration for evaluating the reinforcement effects.

Following the finite element modeling approach proposed by (Bingbing et al., 2024). for incompressible geocell representation, the three-dimensional geocell elements in this study were defined as incompressible materials . Each structural layer’s thickness and the corresponding mechanical properties of the materials used in the numerical model are summarized in Table 5

Table 5. Mechanical properties and layer thicknesses of materials used in the finite element model.

Structural Layer	Thickness(cm)	Modul	Poisso	Densi	Thermal	Coeffici	Specific	Element
		us of	n's	ty q	Conductivi	ent of	Heat	
		Elastici	n's	ty q	tyK	Thermal	Capacit	Type
		ty	Ratio	(kg·m	(J/(m·s·°C)	Expansi	yC	(ABAQ
		E	μ	-3)		on α	(J/(kg·°C	US)
		(MPa)				(10 ⁻⁵ /°C)	)	
Cement concrete surface course	21	31000	0.15	2500	1.5	1.1	900	C3D8R
Cement-stabilised crushed stone base course	18	2000	0.2	2300	1	1	900	C3D8R
Graded crushed stone sub-base course	12	500	0.35	2000	1	1	900	C3D8R
Subgrade	150	50	0.4	1800	1.2	30	1040	C3D8R
Geocell	/	2930	0.25	950	0.4	15	2000	M3D4R
Tension rod/load transfer rod	/	200000	0.3	7800	50	1.2	460	B31
Absolute zero temperature Tz(°C)					-273			
Stefan- Boltzman constant(J/(s· m²·k⁴)					5.67×10 ⁻⁸			

4.2. Constitutive Model and Boundary Conditions

Based on the aforementioned experimental observations, it was found that the reinforcing effect of the geocell became particularly pronounced when the concrete layer entered the plastic deformation regime. Therefore, in the finite element model, the cement concrete was assigned a plastic damage constitutive model to capture its inelastic behavior, whereas the remaining foundation materials (e.g., base, subbase, and subgrade) were characterized using the classical Mohr–Coulomb elastoplastic model.

The boundary conditions of the numerical model were defined such that the bottom of the soil subgrade was fully constrained to prevent displacement, while lateral displacement constraints were applied to the concrete surface course, base, subbase, and subgrade layers, allowing only vertical movement. To replicate the coupled thermo-mechanical behavior of the pavement structure under extreme conditions, a steady-state temperature field of 60 °C and a static load equivalent to a 7 MPa wheel load were applied to the longitudinal joint region of the first concrete slab (as indicated in

Figure 13). This setup enables the three-dimensional mechanical response of the pavement system under combined high-temperature and heavy-load conditions to be reproduced numerically. The finite element model configurations are illustrated in Figures 13 and 14.

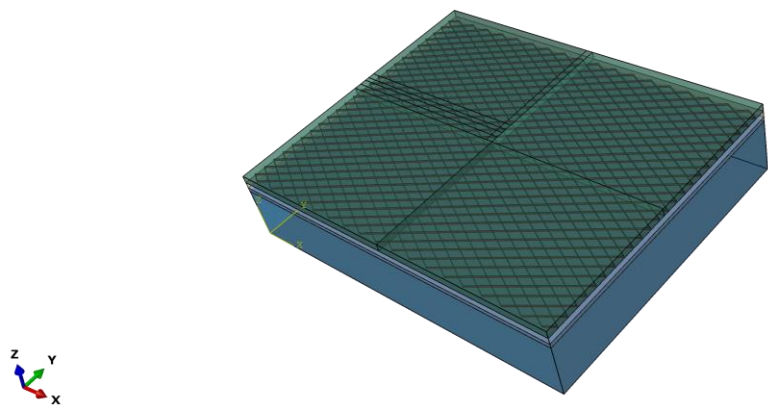


Figure 13. Three-Dimensional Cement Concrete Pavement Model.

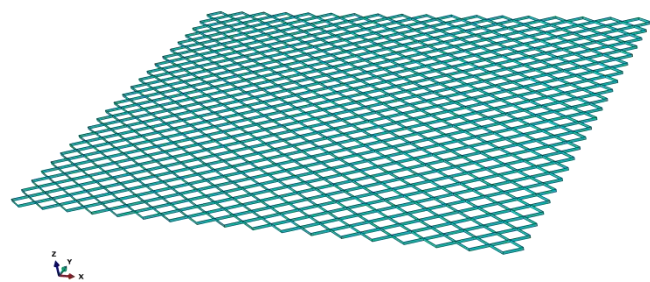


Figure 14. Three-Dimensional Geocell Model.

4.3. Model Validation

The **settlement and peak tensile stress responses** of the pavement slab under **Loading Condition 4** were analyzed using the finite element model. Figures 15 and 16 present the displacement and stress contour plots obtained from the numerical simulations, respectively, while Table 6 summarizes a comparison between the finite element results and the corresponding measurements from the physical model tests.

As shown in Table 6, the relative errors between the numerical and experimental results fall within acceptable engineering ranges, indicating satisfactory agreement between the finite element simulations and the laboratory observations. Moreover, both the **magnitude and trend** of the settlement and stress responses predicted by the numerical model are consistent with those recorded in the model tests. This consistency confirms the reliability of the finite element model in capturing the overall mechanical behavior of the reinforced pavement system under the specified loading conditions and supports its use for further analysis of internal structural responses.

Therefore, the validated numerical model can be reliably employed to investigate internal phenomena that are difficult to measure experimentally—such as stress distribution at the bottom of the concrete slab, interaction mechanisms between the geocell reinforcement and surrounding soil, and the **complex coupled field arising from temperature gradients and mechanical loads**. Such numerical analyses provide deeper insight into the internal load transfer mechanisms and structural responses beyond what can be directly observed from physical tests alone.

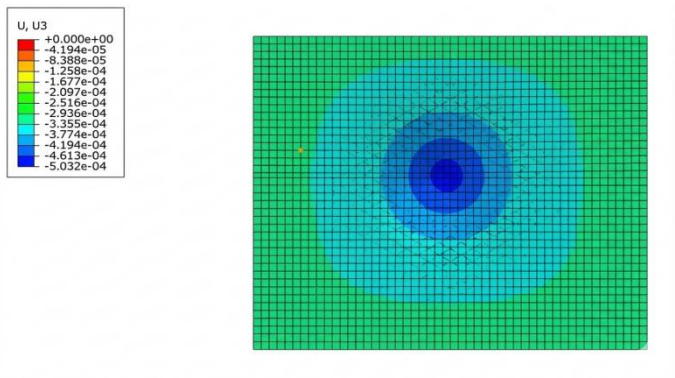


Figure 15. 3D Displacement Contour Map of Cement Concrete Pavement.

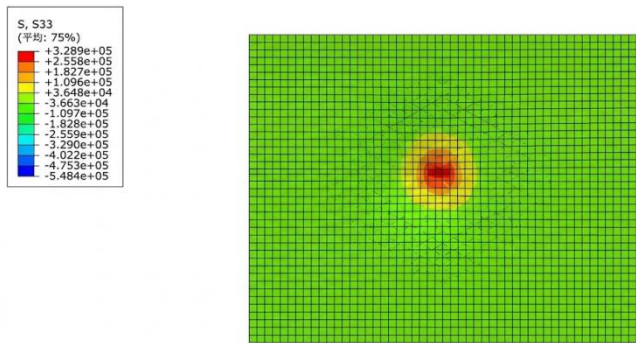


Figure 16. 3D Stress Contour Map of Cement Concrete Pavement.

Table 6. Comparison of finite element simulation results with physical model test measurements.

Operating Conditions	Item	Test Value	Simulation Value	Relative Error/%
Static load	Settlement	0.146 mm	0.132 mm	9.56
	Stress at point R	0.115 MPa	0.105 MPa	8.70
Thermal coupling	Settlement	0.206 mm	0.189 mm	8.25
	Stress at point R	0.271 MPa	0.257 MPa	5.17

4.4. Performance Analysis of Reinforced Structures with Different Cell Heights

To quantify the effect of geocell height and identify the optimal combination of reinforcement parameters, a parametric analysis was conducted on the geocell height (H) while keeping the cell spacing (L) constant at 32 cm. The selected geocell heights were H = 5 cm, 6 cm, 7 cm, 8 cm, 9 cm, 10 cm, and 15 cm. Key response metrics relevant to rigid pavement design—namely, the equivalent plastic strain (PEEQ) of the concrete slab, the maximum damage coefficient (DAMAGET), the maximum stress at the base of the base course, and the maximum stress within the geocell material—were used to comprehensively evaluate the performance of each configuration, as shown in Figures 17 and 18.

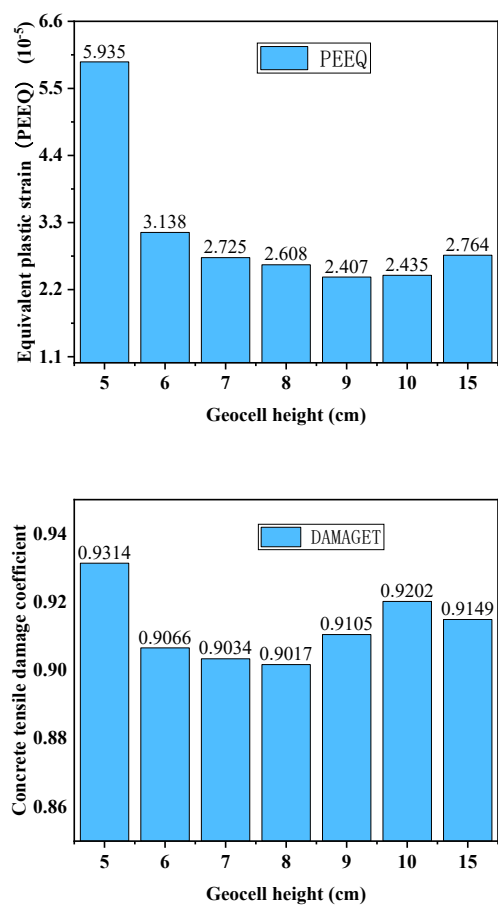
The results indicate that, for a fixed cell spacing (L = 32 cm), increasing the geocell height from 5 cm to 9 cm leads to a continuous reduction in PEEQ and a corresponding decrease in DAMAGET. Concurrently, the maximum stress at the base course also trends downward, suggesting that increasing geocell height effectively enhances the overall stiffness of the pavement structure and attenuates stresses transmitted to the underlying layers. However, when the geocell height exceeds 9 cm, both PEEQ and DAMAGET begin to increase again, with the effect particularly pronounced at H = 15 cm, indicating that excessive height may reduce reinforcement efficiency and diminish the

benefits of geocell confinement. Meanwhile, the maximum stress within the geocell layer generally decreases as H increases, reflecting a greater stress diffusion capability with taller cells; nevertheless, this advantage does not appear to translate into improved damage control in the concrete layer.

To elucidate the influence of geocell height on the stress mechanisms of the concrete pavement and to identify the optimal height range, stress contour plots in the load action zone were extracted for four representative heights— $H = 8\text{ cm}$, 9 cm , 10 cm , and 15 cm —as presented in Figure 19. The results demonstrate that, as H increases, the “**effective stress diffusion range**” along the cell height direction progressively narrows, while the low-stress (near zero) region expands. The principal load-bearing and stress-diffusion zones tend to concentrate toward the lower portion of the geocell and spatially correspond to the tensile region of the concrete surface course. This suggests that the primary reinforcement action of the geocell occurs in the slab’s tensile zone.

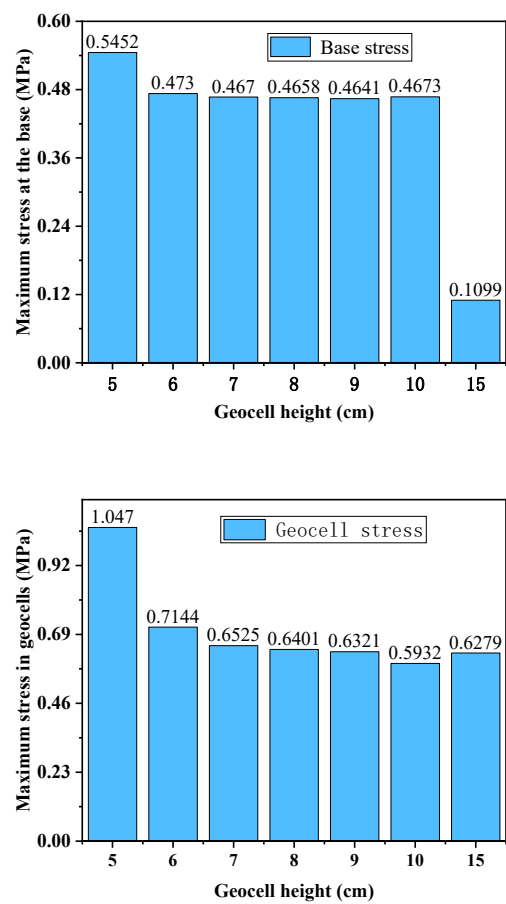
To further quantify the height threshold, the stress distribution along both the longitudinal (cell spacing) and vertical directions was extracted for all examined heights ($H = 5, 6, 7, 8, 9, 10, 15\text{ cm}$), as shown in Figure 20. Near the load center, geocell stress generally decreases with increasing height, indicating that taller geocells promote local reinforcement activation and stress diffusion. However, this trend does not hold consistently farther from the load center, and the reinforcement effect at $H = 15\text{ cm}$ is slightly degraded. Vertical sectional profiles further reveal that, at $H = 5\text{ cm}$, the upper portion of the geocell exhibits the most significant stresses, while increasing H shifts the prominent stress region downward. This observation suggests that beyond a certain height range, the upper portion of the geocell is less effectively mobilized, diminishing its contribution to stress diffusion and leading to **diminishing marginal returns** or even local performance reversal.

Taken together, the evaluation of the four response indicators indicates that, for a given surface course thickness, an optimal range of geocell height exists. The reinforcement effect increases with height up to approximately one-third of the concrete surface thickness, beyond which marginal benefits diminish and may even deteriorate. These findings underscore the importance of optimizing geocell height relative to pavement layer thickness for efficient reinforcement design.



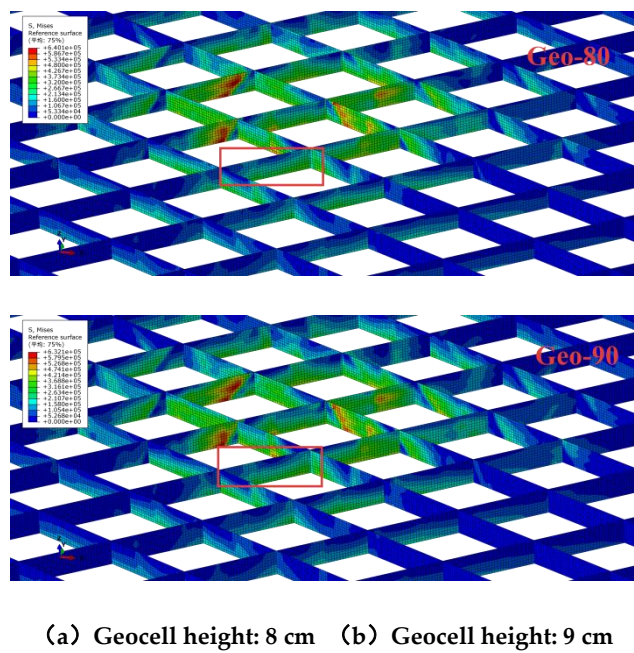
(a) Maximum equivalent plastic strain (b) Maximum tensile damage coefficient

Figure 17. Correlation Coefficient for Plastic Damage in Concrete Surface Layers at Different Cell Heights.



(a) Maximum stress at the base (b) Maximum stress at the bottom of the cellar

Figure 18. Maximum stress in geocell-reinforced pavement structural layers at different cell heights.



(a) Geocell height: 8 cm (b) Geocell height: 9 cm

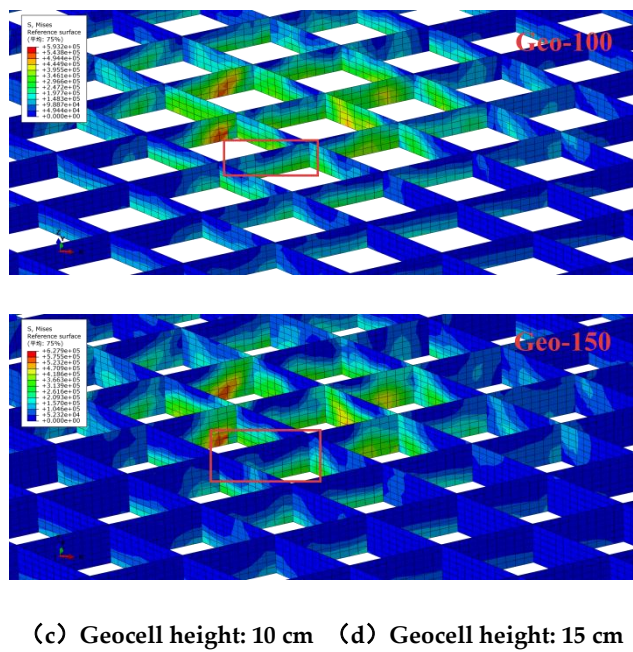


Figure 19. Stress distribution map at the load centre of geocell layers under varying cell heights.

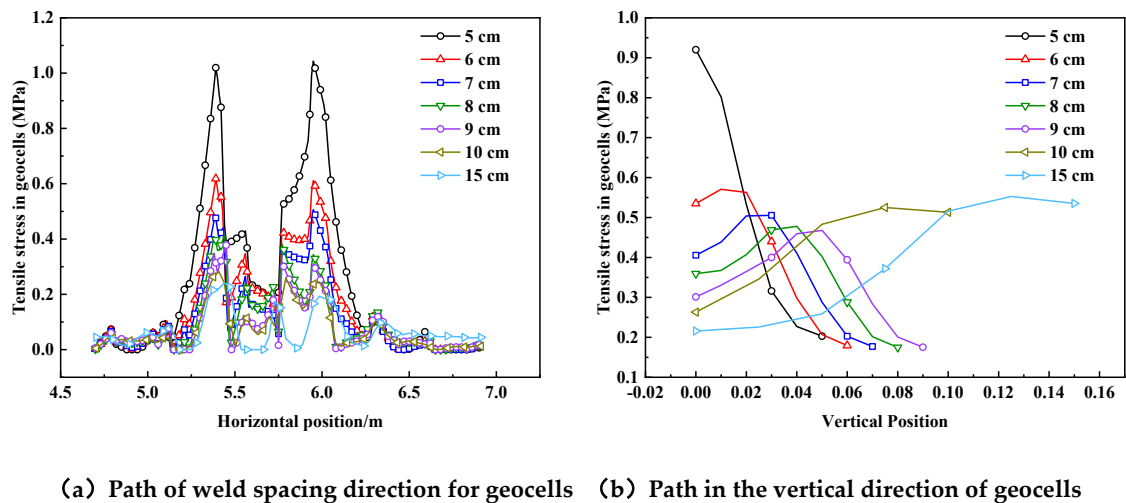


Figure 20. Diagram of Path Stress Variation in Different Directions at Different Geocell Heights.

4.5. Analysis of Reinforced Performance Under Thermo-Mechanical Loads at Different Temperatures

Under the high-temperature thermo-mechanical coupling condition (steady-state 60 °C temperature field combined with a 7 MPa static load), the settlement and stress distribution of differently reinforced pavements are illustrated in Figures 21 and 22. As shown in Figure 21, the maximum settlement consistently occurs near the loading point, indicating that deformation under thermo-mechanical coupling is still dominated by localized concentrated loading. Quantitative comparison reveals that the geocell-reinforced pavement exhibits the smallest central deflection, followed by the load-transfer-bar pavement, while the unreinforced concrete pavement shows the largest settlement. Relative to the unreinforced case, geocell reinforcement reduces peak settlement by approximately 17.4 %, and by about 7.6 % compared to the load-transfer-bar scheme.

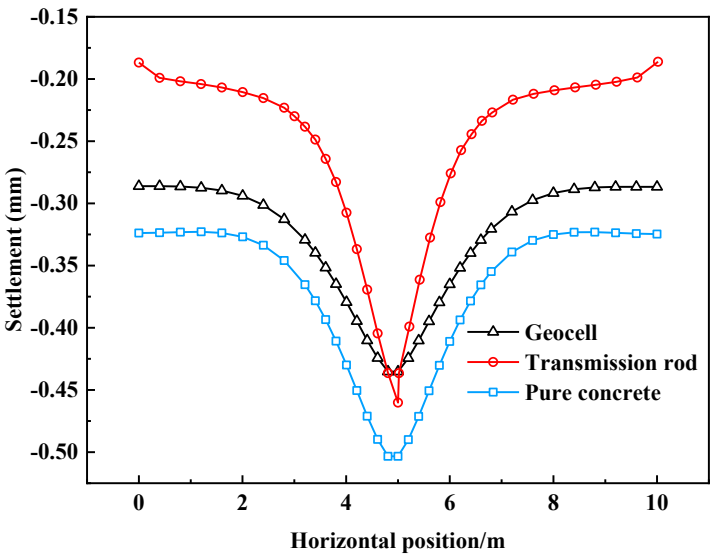


Figure 21. Settlement Variations of the Lower Layer Under Different Reinforcement Methods.

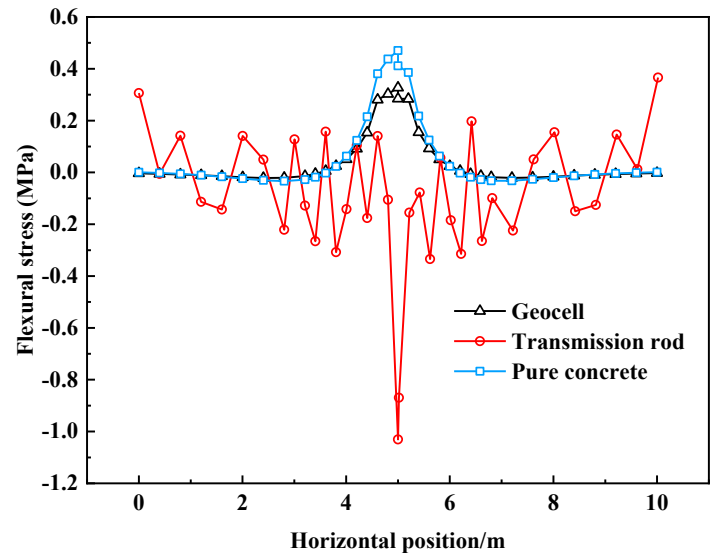


Figure 22. Stress Variations in the Lower Layer Under Different Reinforcement Methods.

More importantly, the displacement gradient on both sides of the load center is markedly gentler for the geocell-reinforced section, indicating that geocell reinforcement not only mitigates peak settlement but also significantly reduces curvature concentration in the vicinity of the load. This improvement in local bending response is attributed to enhanced lateral load spreading resulting from the three-dimensional confinement provided by the geocell reinforcement, which increases the equivalent stiffness of the reinforced layer and broadens the effective load diffusion zone.

The stress distributions in Figure 22 show pronounced local stress peaks near the load center across all reinforcement schemes, indicating that, under coupled conditions, stress response arises from the superposition of thermal warping stresses and load-induced stresses. Differences in reinforcement schemes are primarily reflected in the character of these stress peaks: the stress peaks in geocell-reinforced and unreinforced pavements exhibit relatively smooth spatial transitions, whereas the load-transfer-bar scheme produces more abrupt local fluctuations near the center. This suggests that, although load-transfer bars can improve shear transfer and continuity across joints, their relatively rigid local load path under thermo-mechanical coupling may promote stress

concentration and sharper peak responses. In contrast, geocell reinforcement provides a more flexible confinement mechanism that yields a more uniform and continuous stress distribution, thereby more effectively suppressing localized bending stress concentrations.

In summary, the geocell reinforcement achieves superior stress homogenization by interacting laterally with the slab and base layers: it reduces peak tensile stresses associated with cracking while avoiding excessive stiffness that can induce stress spikes in rigid load-transfer bar designs. Under the combined high-temperature and static loading condition, the geocell-reinforced pavement also demonstrates greater overall stiffness and enhanced resistance to vertical deformation. These advantages not only outperform unreinforced concrete pavements but also exceed the performance of load-transfer-bar reinforced pavements in terms of local bending resistance, indicating that the geocell reinforcement effectively increases the equivalent modulus of the composite slab system and improves its ability to resist deformation under coupled thermal and mechanical loads.

The settlement and stress responses of the geocell-reinforced concrete pavement under varying temperature and load conditions are shown in Figures 23–26. Specifically, Figures 25 and 26 illustrate the stress distribution at the bottom of the base course. It can be observed that the largest settlement consistently concentrates near the load center and gradually levels off toward the sides, indicating that deformation under coupled thermal and mechanical loading is still dominated by local load effects.

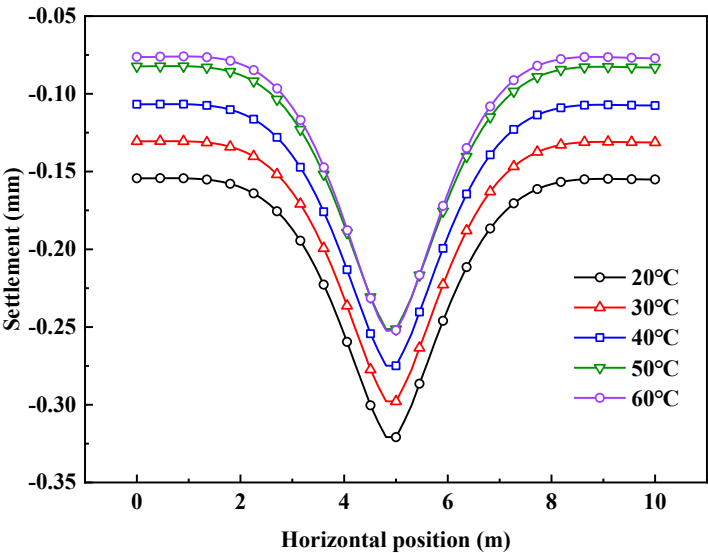


Figure 23. Settlement Changes of the the road surface at Different Temperatures.

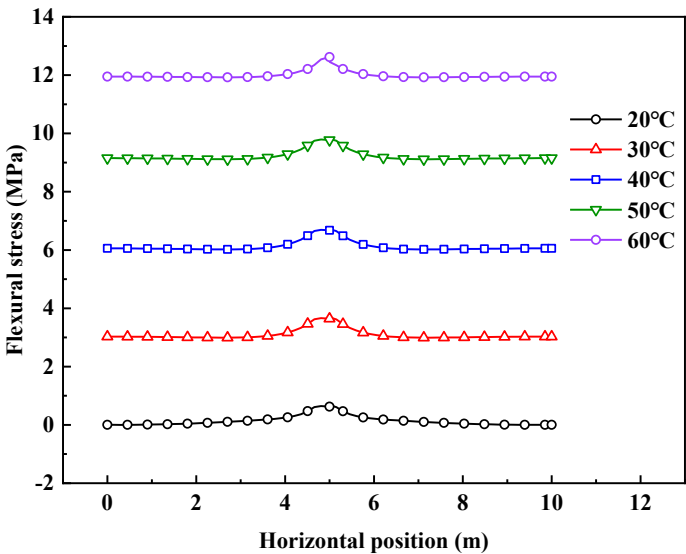


Figure 24. Stress Changes in the Substrate Layer at Different Temperatures.

As temperature increases from 20 °C to 60 °C, the maximum central settlement decreases from approximately **−0.33 mm to −0.24 mm**, representing a reduction of about **27 %**, and the incremental change diminishes at higher temperatures (especially between 50 °C and 60 °C). This trend suggests that under elevated temperatures, geocell reinforcement more effectively suppresses thermal warping and local bending deflection. Concurrently, baseline displacements far from the load zone rise from about **−0.19 mm to −0.11 mm**, indicating a shift in structural response from localized settlement toward coordinated global deformation.

In contrast to settlement, the top surface stress increases markedly with temperature. The far-field stress level rises from near **0 MPa at 20 °C to approximately 12 MPa at 60 °C**, with an additional localized peak stress of **0.5–1 MPa** at the load center. This behavior indicates that **temperature-induced constraint stresses** constitute a major component of the internal stress state, while wheel load effects contribute as superimposed local peaks.

From Figures 25 and 26, as temperature rises from 20 °C to 60 °C, the maximum stress at the base of the base course near the center decreases from approximately **0.055 MPa to 0.028 MPa** (a reduction of about **49 %**), indicating that high temperature significantly weakens stress concentration and promotes more diffuse load distribution. At the same time, the far-field baseline stress level increases with temperature, reaching about **0.023–0.025 MPa at 60 °C**, significantly higher than the **0.006–0.008 MPa** range at 20 °C. This rise reflects an increased contribution of **temperature-induced internal stresses** at the base course level.

Overall, elevated temperatures cause the base stress distribution to exhibit a **“lower peak, raised baseline”** pattern, indicating that while local peak stress risk decreases, the general stress level across the domain increases. Consequently, the dominant force mechanism transitions from **local stress concentration** toward **global temperature-driven internal stress accumulation** under coupled thermo-mechanical loading.

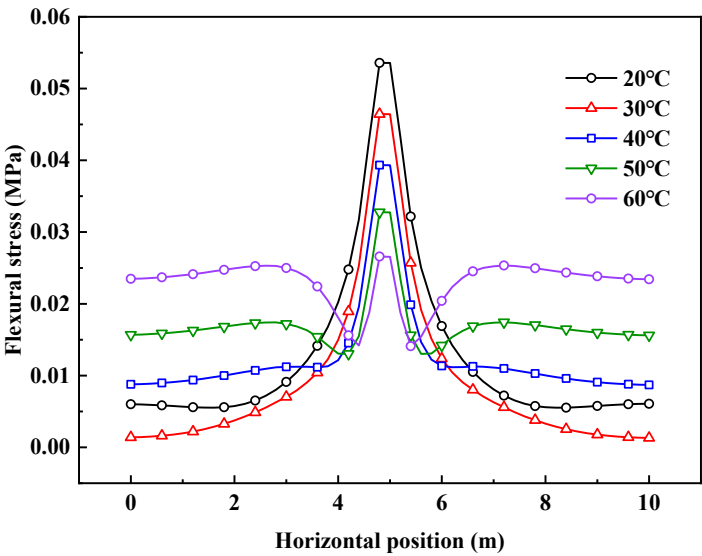


Figure 25. Stress Variations at the Bottom of Cement Concrete Pavement Bases at Different Temperatures.

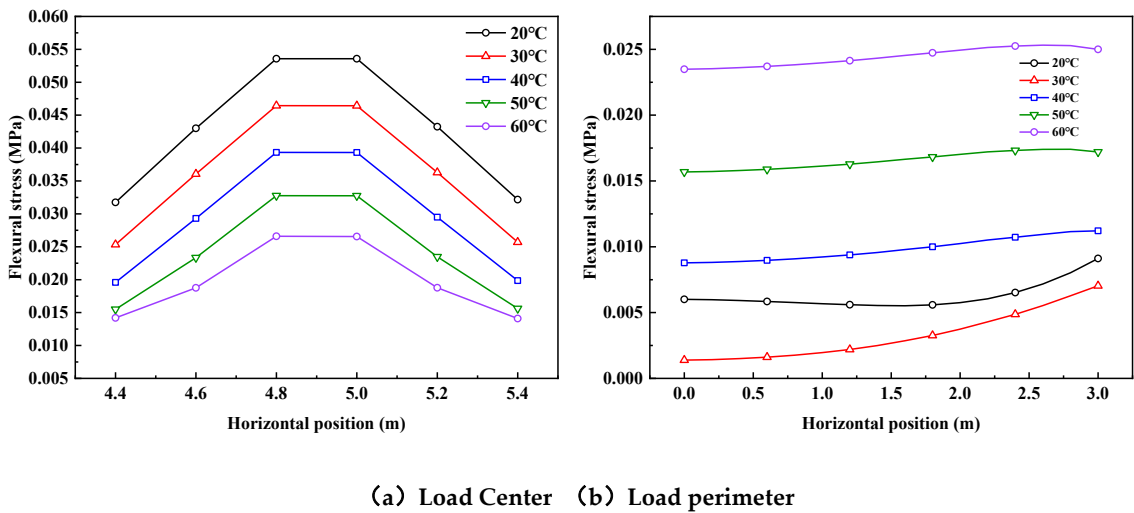


Figure 26. Local Stresses at the Bottom of Cement Concrete Pavement Bases at Different Temperatures.

5. Conclusions

Based on the comprehensive laboratory model tests and numerical simulations presented in this study, the following key conclusions can be drawn:

- 1. **Load Diffusion and Settlement Control:** Under static loading, the settlement of geocell-reinforced cement concrete (GRCC) pavements exhibits a three-stage evolution: initial compaction (0.3–0.7 kN, settlement rate ≈ 0.30 mm/kN), plastic development (0.7–1.3 kN, ≈ 1.26 mm/kN), and stabilization (1.3–2.7 kN, ≈ 0.168 mm/kN). The lateral confinement of the geocell is increasingly mobilized during the mid-to-late stages, significantly enhancing the overall structural stiffness.
- 2. **Thermal Response Characteristics:** Under thermal loading, slab strains show a clear sequential evolution (cooling contraction $\rightarrow$ heating recovery $\rightarrow$ stable tension $\rightarrow$ sustained tension) and pronounced spatial non-uniformity. Strains in the mid-slab region are approximately 1.8 times those at the slab edges, identifying this region as a thermally sensitive zone.
- 3. **Thermo-Mechanical Damage Threshold:** In high-temperature static load coupling tests, significant non-linear behavior is observed. Soil pressure in the cement-stabilized layer exhibits

a plateau–jump pattern, whereas pressures in the subbase and subgrade remain relatively constant. Slab strains and settlements display a non-monotonic “increase–decrease” trend around 1.1–1.3 kN, which may serve as an early warning threshold for damage initiation or abrupt changes in contact conditions under coupled loading.

4. **Dynamic Loading Accumulation:** Under cyclic loading, permanent deformation is highly sensitive to load amplitude. Within 1000 cycles, settlement under a peak load of 1.9 kN increased by 14.8%, much higher than the 2.8% increase observed under 0.9 kN, indicating that higher load amplitudes accelerate cumulative damage.
5. **Comparative Advantage of Reinforcement:** Under thermo-mechanical coupling, geocell-reinforced pavements reduce central settlement by 17.4% relative to unreinforced concrete and by 7.6% compared to load-transfer bar pavements. Deflection troughs are smoother, demonstrating superior stress diffusion and coordinated deformation performance.
6. **Thermo-Mechanical Coupled Numerical Simulation:** The validated numerical model reveals that **thermal warping stresses dominate** under coupled conditions. The far-field stress at the pavement surface increases from near 0 MPa at 20 °C to approximately 12 MPa at 60 °C, with an additional load-induced peak of around 0.5–1 MPa at the load center. At the base course, the central peak stress decreases from about 0.055 MPa to 0.028 MPa (~49 % reduction), while the background stress level away from the load increases significantly from approximately 0.006–0.008 MPa to 0.023–0.025 MPa as temperature rises. These results indicate a **reduction in local peak risk but an increase in widespread internal thermal stresses**.
7. **Geocell Height Threshold Effect:** With a fixed cell spacing ($L = 32$ cm), geocell heights between 5–9 cm reduce equivalent plastic strain (PEEQ) and maximum damage coefficient (DAMAGET). Within this range, reinforcement efficiency increases with height; however, exceeding this threshold results in diminishing marginal benefits and even performance reversal. Therefore, geocell height is recommended to be controlled at approximately one-third of the surface course thickness to optimize both mechanical performance and cost-effectiveness.

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Conflicts of Interest:

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