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COMPREHENSIVE ANALYSIS OF THE OPERATIONAL AND ECONOMIC ADVANTAGES AND TECHNOLOGICAL LIMITATIONS OF CEMENT CONCRETE PAVEMENTS IN MODERN ROAD CONSTRUCTION

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Highlights

Rigid pavements provide superior load distribution and rutting resistance under heavy freight traffic.

Life-cycle cost analysis shows that cement concrete pavements can cut 30-year total costs by almost half.

Thermal stability, high albedo, and long service life make concrete pavements suitable for continental climates.

Joint deterioration, high initial cost, and slow strength gain remain the key technological limitations.

CRCP, fiber-reinforced concrete, and UHPC are effective pathways for improving rigid pavement performance.

Abstract

In recent decades, the sharp increase in axle loads on highways and the growing impact of extreme climatic conditions have renewed interest in rigid pavement systems. This paper presents a comprehensive technical and economic analysis of cement concrete pavements in comparison with asphalt pavements, with special emphasis on regions exposed to hot summers, cold winters, and rising freight intensity. The study combines comparative engineering analysis, mechanistic interpretation of pavement behavior, simplified mathematical modeling using the Westergaard and Bradbury equations, finite element assessment of critical stress zones, and a 30-year life-cycle cost evaluation. The results show that cement concrete pavements possess a substantially higher elastic modulus, better load-spreading capacity, greater resistance to rutting and temperature-related softening, and lower long-term maintenance demand. Although their initial construction cost remains 1.3–1.5 times higher than that of asphalt pavements, the total cost over 30 years is considerably lower, especially for continuously reinforced concrete pavement systems. The main constraints are high initial investment, strict technological requirements during construction, curing time, and vulnerability of poorly designed joints. The paper also discusses modern engineering solutions, including CRCP, fiber-reinforced concrete, ultra-high-performance concrete, and accelerated curing technologies, as practical instruments for mitigating those limitations. The findings confirm that cement concrete pavements are a strategically rational option for high-category roads, logistics corridors, and freight-intensive highways.

Keywords: cement concrete pavement; rigid pavement; Westergaard equation; life-cycle cost; joint deterioration; temperature stress; CRCP; FEA; albedo

1. Introduction

Transport infrastructure is one of the most capital-intensive and strategically important sectors of the national economy. The reliability of roads directly affects freight turnover, travel time, safety, logistics cost, and regional accessibility. Under modern traffic conditions, highways are increasingly exposed to repeated heavy axle loads, aggressive temperature fluctuations, and moisture-related deterioration. These factors are especially critical for countries with sharply continental climates, where the surface temperature of dark pavements may exceed 60°C in summer while winter temperatures can fall far below freezing.

Traditional asphalt pavements remain widely used because of their technological flexibility and comparatively low initial cost. However, under heavy truck traffic and high summer temperatures they frequently suffer from rutting, fatigue cracking, and repeated maintenance needs. In contrast, cement concrete pavements are characterized by high stiffness, stable mechanical performance over a broad temperature range, and a long structural life [1–3]. For this reason, many countries use rigid pavements on freight corridors, airport facilities, industrial roads, and high-category motorways.

The present study aims to provide an integrated engineering assessment of cement concrete pavements by examining their mechanical behavior, operational advantages, economic efficiency over the full life cycle, and the technological disadvantages that still constrain their broader adoption. In addition, the paper outlines current innovation pathways that reduce the negative effect of joint-related distress, long curing periods, and high capital cost.

2. Literature review and international practice

The theoretical and practical basis for rigid pavement design has been shaped by several decades of international research. The AASHO Road Test remains a foundational source for understanding the interaction between axle loads, slab thickness, subgrade support, and serviceability [2]. Huang systematized the mechanics of both flexible and rigid pavements and demonstrated the importance of slab stiffness, edge loading, and environmental effects in concrete pavement design [1]. Classical analytical solutions proposed by Westergaard and Bradbury are still relevant for evaluating load-induced and temperature-induced stresses in concrete slabs [4,5].

International experience confirms the strategic role of rigid pavements in high-demand transport systems. In the United States and Germany, concrete pavements are widely used on interstate, industrial, and heavy-duty road sections. In Japan and China, the share of cement concrete pavements is especially high on freight corridors, logistics hubs, and selected high-performance road segments. Their popularity is explained not only by structural durability but also by reduced maintenance frequency and better resistance to permanent deformation.

Recent research has focused on improved materials and long-life design concepts. Continuously reinforced concrete pavement (CRCP) reduces dependence on transverse joints and controls crack spacing through distributed reinforcement [6]. Fiber-reinforced concrete improves post-cracking behavior and fatigue resistance, while ultra-high-performance concrete (UHPC) offers exceptional mechanical strength and durability for specialized pavement solutions [7]. These developments indicate that the technological limitations of traditional concrete pavements are increasingly manageable within modern road engineering practice.

3. Methodology

This research is based on a combined analytical and comparative methodology. First, the main physical, mechanical, and operational parameters of asphalt and cement concrete pavements were compared using published engineering ranges and representative design values. Second, simplified stress analysis was performed using classical rigid pavement equations. The Westergaard formulation was used to estimate maximum flexural stress caused by wheel loading, while the Bradbury equation was used to assess thermal stress caused by temperature gradients through the slab depth. Third, a conceptual finite element interpretation was introduced to identify the most critical zones of stress concentration under center, edge, and joint loading scenarios.

A life-cycle cost (LCC) comparison was then performed for three pavement alternatives: asphalt pavement, jointed plain concrete pavement, and continuously reinforced concrete pavement. The calculations were normalized per 1 km of road and covered a 30-year analysis horizon. The cost structure included initial construction, major rehabilitation, and routine annual maintenance. Finally, the technological limitations of rigid pavements were analyzed together with modern mitigation measures, allowing the study to bridge analytical theory and practical engineering decisions.

4. Operational advantages of cement concrete pavements

The first major operational benefit of cement concrete pavements is their superior stiffness and load-distribution capacity. A concrete slab acts as a rigid plate that redistributes concentrated wheel load over a much larger area before it reaches the subbase and subgrade. This reduces vertical stress on weaker foundation layers and lowers the risk of permanent deformation. In freight-intensive conditions, this property is especially important because it minimizes rut formation and helps preserve riding quality over long periods.

The second advantage is structural durability. Properly designed concrete pavements commonly provide a service life of 30–50 years, and in many cases even longer performance is achieved with timely joint maintenance and localized slab repair. Unlike bituminous binders, hardened cement paste does not soften dramatically under high summer temperatures. Therefore, concrete pavements maintain their bearing capacity and geometry more effectively under hot-climate conditions. Their frost resistance can also be improved through optimized water–cement ratio, adequate curing, air entrainment, and high-quality aggregate selection.

The third advantage is functional and environmental. Cement concrete has a higher albedo than asphalt, reflecting a greater portion of solar radiation. This can reduce pavement surface temperature, improve nighttime visibility, and lower road-lighting energy demand. On urban and peri-urban roads, the higher reflectivity of concrete surfaces may also reduce the local heat-island effect. From the perspective of network management, lower maintenance frequency translates into fewer work-zone disruptions, less traffic delay, and more predictable asset-performance planning.

5. Comparative life-cycle cost analysis

A critical question in pavement selection is whether a higher initial cost can be justified by lower expenditures during the service period. To answer this question, a simplified 30-year life-cycle cost model was developed for the three pavement alternatives. The analysis shows that although the initial cost of cement concrete pavement is substantially higher than that of asphalt pavement, concrete alternatives require fewer major interventions and much lower routine maintenance. As a result, their total 30-year cost becomes significantly lower.

The economic effect is amplified on roads with high freight intensity, where asphalt pavements tend to require repeated overlays, rut correction, and more frequent surface treatments. In addition to direct agency cost, concrete pavements also reduce indirect user cost associated with lane closures and traffic delays. Consequently, a rational economic assessment should not be limited to the first construction budget alone; it should cover the entire life cycle, from commissioning to rehabilitation. Under such an integrated view, concrete pavements demonstrate clear strategic advantages for long-haul and heavy-duty corridors.

6. Mathematical modeling of stresses in rigid pavements

The stress–strain behavior of a rigid pavement depends on slab geometry, elastic properties, support conditions, load position, and thermal gradient. For a wheel load applied to a slab, the classical Westergaard equation can be used to estimate maximum flexural stress at the slab center:

$$\sigma c = (3P / (2\pi h^2)) \cdot [\ln(l / b) + 0.6159], \tag{1}$$

where σc is the flexural stress, P is the design wheel load, h is slab thickness, l is the radius of relative stiffness, and b is the equivalent radius of load contact. The radius of relative stiffness is defined as:

$$l = [Eh^3 / (12k(1-\mu^2))]\hat{}(1/4), \tag{2}$$

where E is the elastic modulus of concrete, k is the modulus of subgrade reaction, and μ is Poisson's ratio.

Temperature-induced stress can be evaluated using a simplified Bradbury expression:

$$\sigma t = (C \cdot E \cdot \alpha \cdot \Delta t) / 2, \tag{3}$$

where σt is thermal stress, C is the Bradbury coefficient, α is the coefficient of thermal expansion, and Δt is the temperature difference between the upper and lower slab fibers. The equations show that slab thickness, subgrade support, and thermal gradient are among the governing factors of structural safety. In practical design, the highest tensile stress often occurs near slab edges or joints, especially when environmental curling acts simultaneously with wheel loading.

7. Technological limitations and engineering problems

Despite their long-term advantages, cement concrete pavements have several well-known technological limitations. The most obvious drawback is the higher initial cost, which results from increased material demand, stricter quality control, and the need for specialized paving equipment. Slipform pavers, dowel-basket installation systems, and precision finishing operations raise both capital and organizational requirements.

A second limitation concerns joints. In traditional jointed concrete pavements, contraction and expansion joints are necessary to control restrained shrinkage and thermal movement. If joints are poorly designed, badly saw-cut, or inadequately sealed, water can infiltrate into the base layers, initiating pumping, spalling, and loss of support. Joint distress may become the governing maintenance problem even when the slab body itself remains structurally sound.

The third limitation is construction time. Concrete gains strength progressively and requires curing to achieve its design performance. This delays traffic opening compared with asphalt pavement, which can often be reopened within a very short time after placement. Furthermore, construction defects such as poor curing, segregation, inadequate dowel alignment, or insufficient subbase preparation may create long-term performance deficiencies that are difficult to correct later. Therefore, rigid pavement technology is highly dependent on process discipline and construction quality management.

8. Modern solutions and innovation pathways

Current engineering practice offers several solutions for overcoming the traditional disadvantages of concrete pavements. The most important is continuously reinforced concrete pavement (CRCP), in which transverse joints are largely eliminated and distributed reinforcement controls crack width and spacing. This technology reduces maintenance needs related to joint sealing and improves ride continuity under heavy traffic.

Another promising direction is fiber-reinforced concrete. The inclusion of steel, basalt, glass, or polymer fibers improves crack control, impact resistance, and residual flexural performance. Fiber addition is especially valuable in reducing shrinkage cracking and improving fatigue life. Ultra-high-performance concrete provides even greater compressive and tensile capacity, very low permeability, and outstanding durability, making it attractive for demanding applications such as industrial platforms, bridge-deck overlays, and premium heavy-duty pavements.

Accelerated curing systems and optimized mix design also address the problem of slow traffic opening. The use of rapid-hardening cements, chemical admixtures, thermal curing control, and prefabricated pavement panels can significantly reduce downtime. Finally, digital quality control, laser-guided paving, embedded sensing systems, and data-driven asset monitoring are making rigid pavement construction more precise and more predictable. These innovations collectively shift the discussion from whether concrete pavements have disadvantages to how effectively those disadvantages can be engineered away.

9. Discussion

The results of the present analysis indicate that pavement-type selection should be based on a systems perspective rather than on initial budget alone. Asphalt pavements retain important advantages in rapid construction, stage-by-stage rehabilitation, and operational flexibility. However, when heavy freight, thermal severity, and long design life are the dominant criteria, cement concrete pavements become increasingly attractive.

For countries seeking to modernize strategic road corridors, rigid pavements should be prioritized for sections where cumulative axle loading is high, long maintenance intervals are desirable, and route closure has large economic consequences. At the same time, successful implementation requires institutional readiness: reliable cement supply, advanced paving equipment, experienced contractors, and robust quality-control protocols. Thus, the question is not merely technical but also organizational and economic. The best policy is selective and data-driven deployment of rigid pavement technology on those corridors where its superior life-cycle performance produces the greatest infrastructure value.

10. Conclusions

Cement concrete pavements provide a combination of structural reliability, rutting resistance, thermal stability, long service life, and lower long-term maintenance demand that makes them highly suitable for modern freight-intensive transport infrastructure. Their principal engineering advantages stem from high slab stiffness, efficient load spreading, resistance to high-temperature softening, and functional benefits such as higher albedo and better nighttime visibility.

The main barriers to wider adoption are high initial cost, slower commissioning, and vulnerability of poorly executed joints. Nevertheless, current technological solutions such as CRCP, fiber-reinforced concrete, UHPC, accelerated curing systems, and digital construction control significantly reduce these disadvantages. The overall assessment confirms that for high-category highways, logistics corridors, and other heavy-duty road sections, cement concrete pavements are not merely an alternative to asphalt but a strategically advantageous long-life solution.

Figures and graphs

The following high-resolution figures summarize the core engineering relationships discussed in the manuscript.

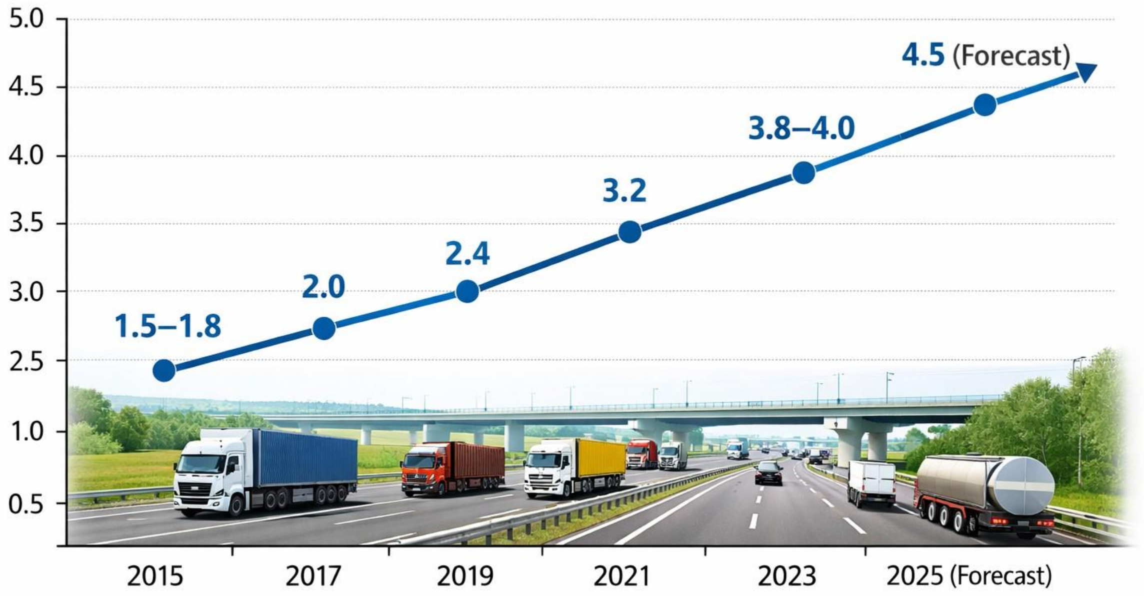


Figure 1. Growth dynamics of freight traffic intensity on main highways (2015–2025)
(illustrative reconstruction based on the manuscript data).

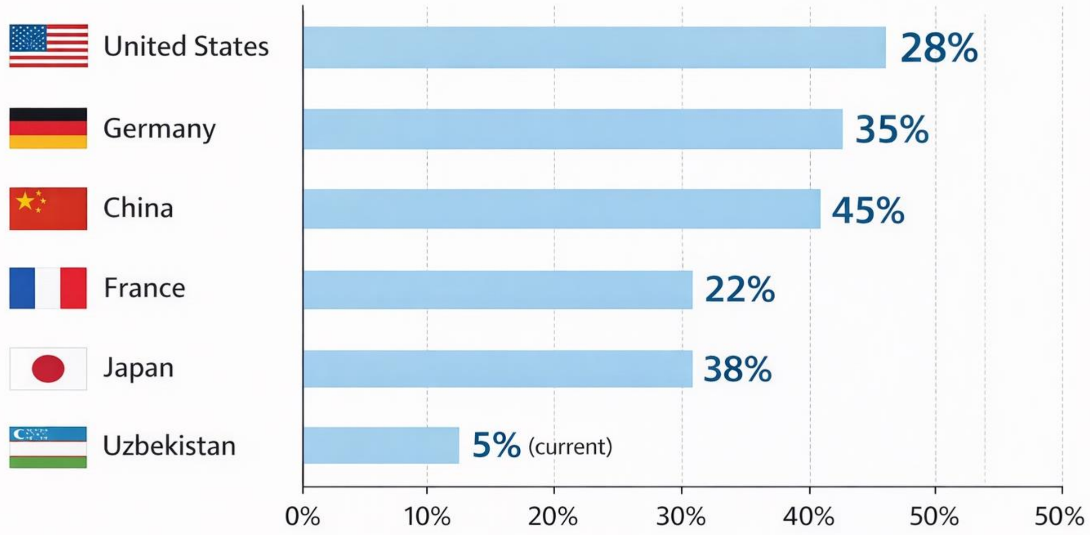


Figure 2. International comparison of rigid pavement adoption in selected national road systems, *showing the share of cement concrete pavements in the total length of each country's national highway network.*

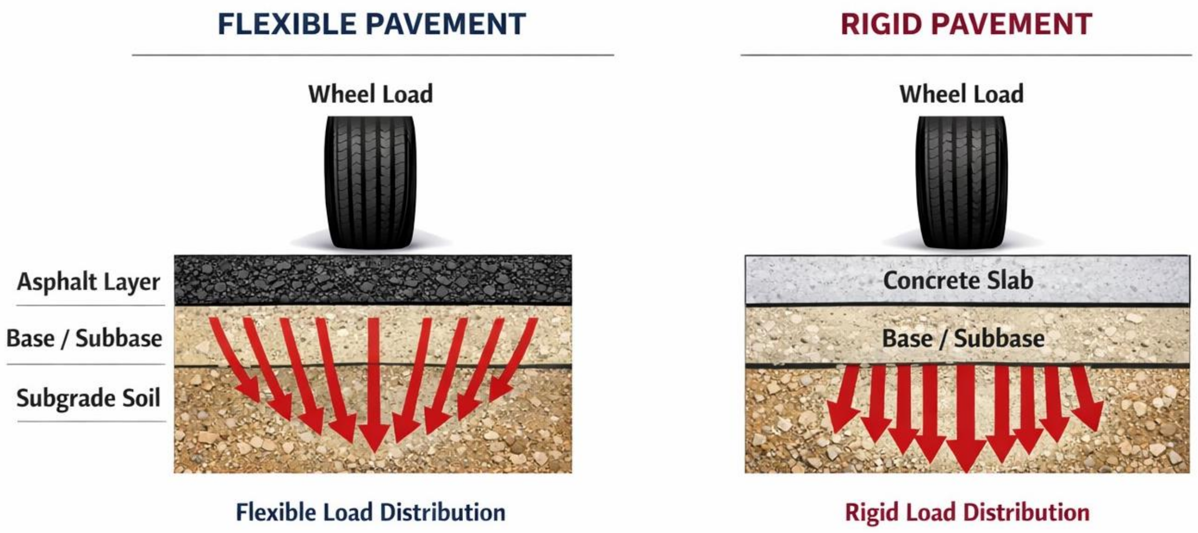


Figure 3. Conceptual load-distribution mechanism in flexible and rigid pavements.

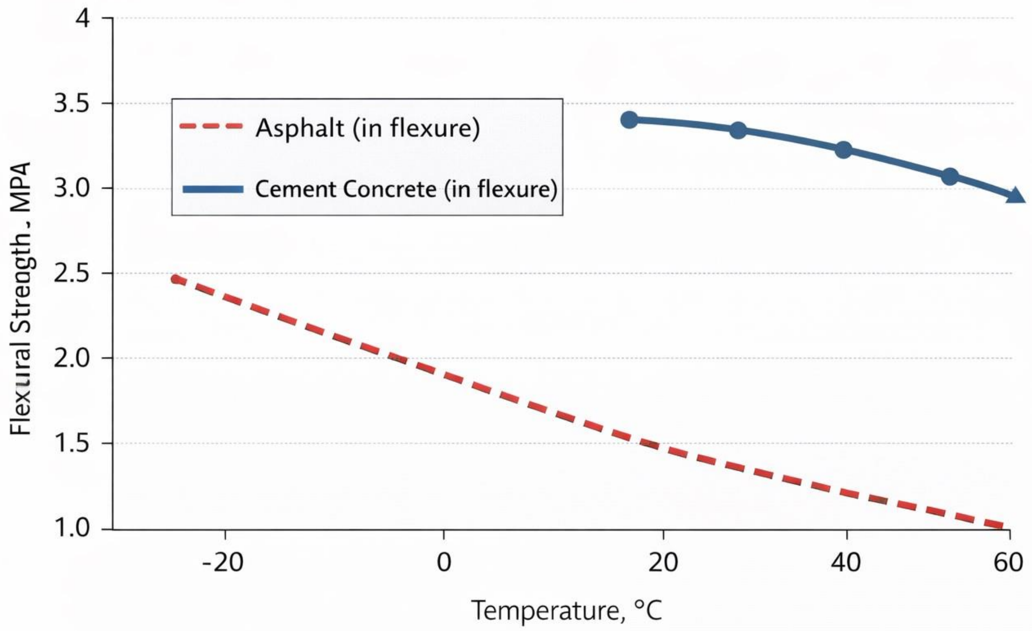


Figure 4. Influence of temperature on the flexural performance of asphalt and cement concrete pavements.

Figure 5. Comparative 30-year life-cycle cost structure

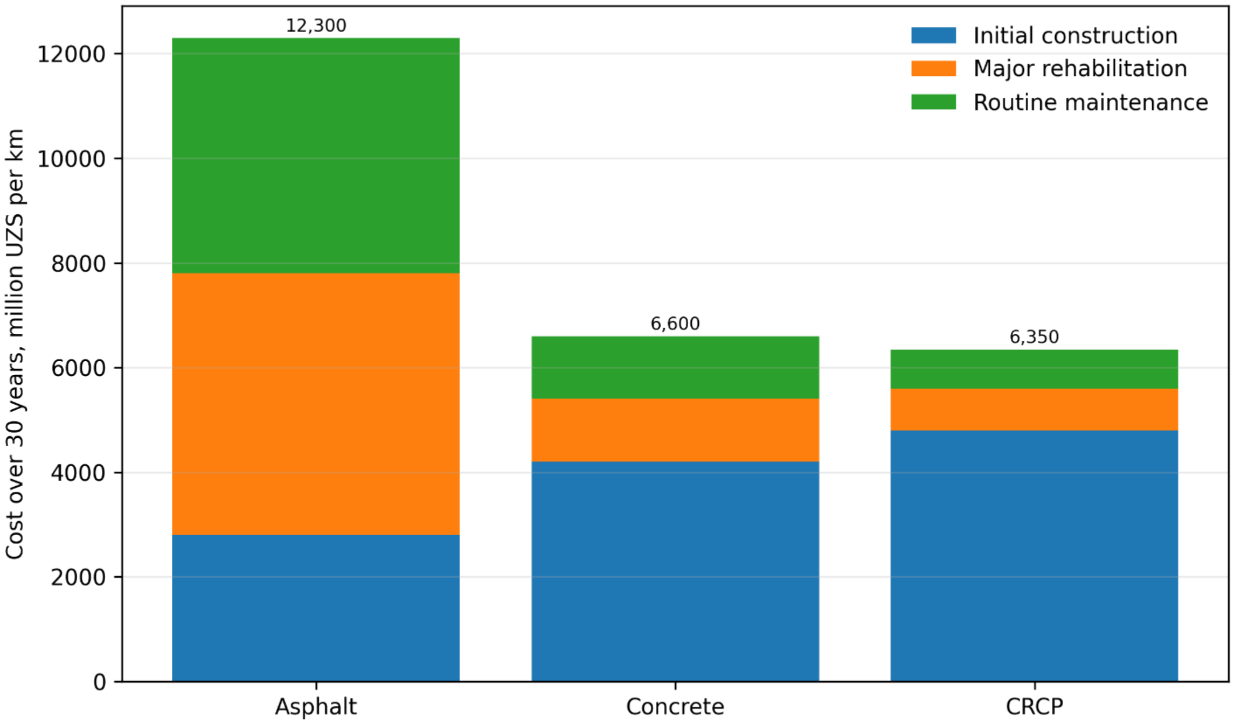
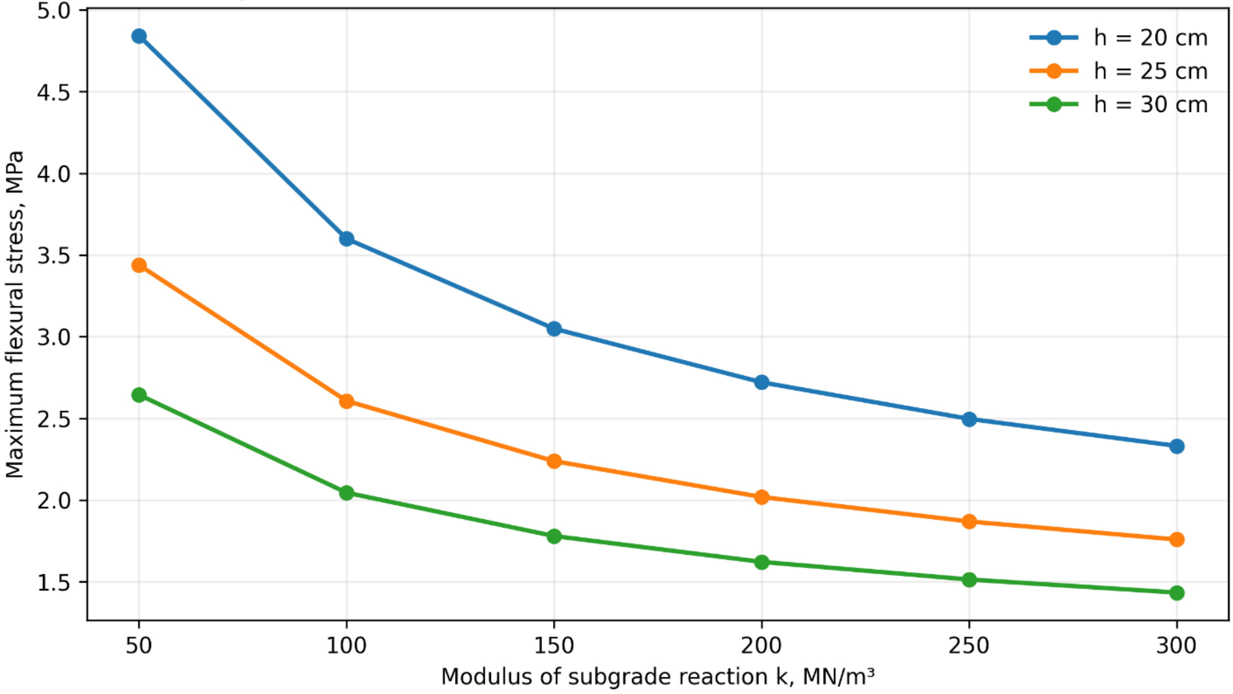
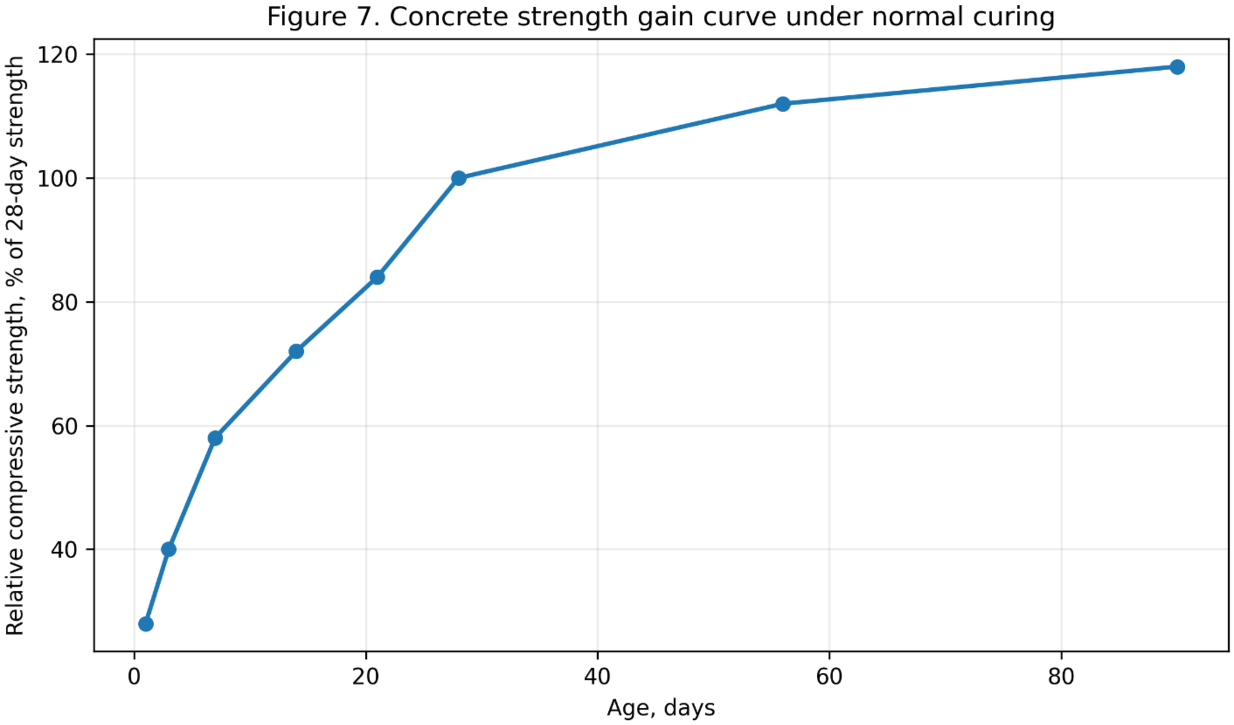


Figure 6. Effect of slab thickness and foundation stiffness on stress





Tables

Table 1. Comparative deformation and mechanical characteristics of asphalt and cement concrete pavements

Indicator	**Asphalt pavement**	**Cement concrete pavement**	**Engineering implication**	**Typical advantage**
Elastic modulus, MPa	1,200–2,000	28,000–35,000	Concrete slab is much stiffer	Concrete
Flexural strength, MPa	2.0–3.0	4.5–6.0	Higher tensile reserve under bending	Concrete
Typical rut depth after 5 years, cm	2.5–4.0	0.2–0.5	Lower permanent deformation	Concrete
Sensitivity to high temperature	High	Low	Shape stability under summer heat	Concrete
Time to traffic opening	1–3 days	7–28 days	Asphalt gains operational readiness faster	Asphalt

Table 2. Surface albedo and functional implications of pavement type

Pavement type	**Albedo coefficient**	**Typical summer surface temperature, °C**	**Lighting / visibility implication**
New asphalt pavement	0.05–0.08	65–70	High lighting demand, low reflectivity
Aged asphalt pavement	0.08–0.12	60–65	Still comparatively dark surface
New cement concrete pavement	0.30–0.40	45–50	Improved reflectivity and visibility
CRCP surface	0.35–0.45	40–45	Best reflectivity among compared options

Table 3. Comparative 30-year life-cycle cost model per 1 km of road (million UZS)

Cost component	**Asphalt pavement**	**Concrete pavement**	**CRCP**	**Comment**
Initial construction	2,800	4,200	4,800	Concrete alternatives require higher initial investment
Major rehabilitation over 30 years	5,000	1,200	800	Concrete requires fewer large interventions
Routine maintenance over 30 years	4,500	1,200	750	User disruption is also typically lower
Total LCC over 30 years	12,300	6,600	6,350	Concrete and CRCP provide the best total-cost outcome
Relative LCC coefficient	1.00	0.54	0.52	Lower is better

Table 4. Finite-element-oriented interpretation of critical stress zones under different loading scenarios

Loading scenario	**Maximum flexural stress, MPa**	**Critical zone**	**Interpretation**
Load at slab center	1.85	Bottom fiber, central region	Moderate response under symmetric support

Loading scenario	**Maximum flexural stress, MPa**	**Critical zone**	**Interpretation**
Load at slab edge	2.42	Bottom fiber, edge zone	Stress rises because support is lost on one side
Joint-adjacent loading	2.68	Bottom fiber near joint	Most critical for jointed pavement systems
Thermal gradient + winter load	2.35	Upper fiber under upward curling	Curling changes, the critical tensile face
Thermal gradient + summer load	2.15	Bottom fiber under downward curling	Combined environment-load action remains significant

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Note

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