



## High Performance Concretes: A State-of-the-Art Review of Material Behavior, Rigid Pavement under Earthquakes

Noor Adel Ismaeel <sup>1\*</sup>, Adel A. Al-Azzawi<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq

<sup>2</sup>Department of Forensic Engineering, Al-Nahrain University, Baghdad, Iraq

### ARTICLE INFO

#### Article history:

Received	30-04-2026
Revised	30-04-2026
Accepted	12-05-2026,
Available online	14-05-2026

#### Keywords:

Rigid pavement  
HPC  
Fiber reinforcement  
Earthquakes  
Hybrid fiber

### ABSTRACT

High performance concrete can substitute conventional concrete in rigid pavement systems in earthquake-prone regions due to its enhanced mechanical properties, such as high compressive strength, high flexural strength, and durability. An overview of relevant study on HPC material properties, rigid pavement design and performance, the effects of seismic loading on concrete structures in general, as well as specialized materials that include ultra-high-performance concrete (UHPC), engineered cementitious composites (ECC), and fiber-reinforced versions are presented in this review. Engineered cementitious composites (ECC), fiber-reinforced forms, and so forth. Metrics such as loss of energy capacity, crack control ability, load transfer ability, and mechanical–environmental durability are highlighted in the review. Additionally, link slab technology, joint design, and additional cementitious materials for enhancing seismic performance and sustainability are among the subjects addressed. In addition to suggesting future directions for research on seismic optimum of nanomaterials-enabled HPC rigid pavement systems, this report discusses cost, standardizing, and performance data over the service life for HPC rigid pavements.

## 1. Introduction


There are unprecedented challenges in the construction and design of rigid pavement structures due to growing traffic volumes, the effects of climate variability, and seismic activity in earthquake-prone areas [1]. In the past, jointed plain concrete pavements (JPCP) and continuously reinforced concrete pavements (CRCP) were the most common surface types for rigid pavements, which were designed for static and semi-static loading conditions. Nevertheless, new investigations indicate a necessity to consider the dynamic response of pavements subjected to seismic loadings [2], particularly in high-seismic areas. Compared to traditional concrete, the use of High-Performance Concrete (HPC), a notable modification in rigid pavement construction,

greatly improves mechanical characteristics, durability, and structural resilience [3]. The evaluation of high-performance concrete (HPC) as a suitable substitute for rigid pavement systems designed to withstand seismic loads is organized in this literature review, and this also presents constituent characteristics, modelling or designing procedures, performance mechanisms, and research directions for future studies.

The meaning of this study has been shown in both earthquakes and infrastructure disasters, where substandard quality of materials and poor pavement design result in serious infrastructure damage [4]. Superior flexural strength, less permeability, and superior stress-strain behavior—in particular in response to dynamic loading—are the advanced characteristics of High-Performance Concrete. Because of this, its

Corresponding author E-mail address: [nooralneimi1985@gmail.com](mailto:nooralneimi1985@gmail.com)  
<https://doi.org/10.61268/csm1qd40>

This work is an open-access article distributed under a CC BY license (Creative Commons Attribution 4.0 International) under

<https://creativecommons.org/licenses/by-nc-sa/4.0/> 

new research has proven that HPC-based rigid pavements can maximize material consumption and long-term maintenance expenses by minimizing the thickness of the needed slabs by 6–39% while sustaining increased load-carrying capabilities [5]. Furthermore, HPC is a good material for prolonged design life applications in seismic locations due to its generally more durable qualities, such as improved resistance to freeze-thaw cycles, chemical assault, and fatigue.

## 2. High-Performance Concrete's Material Properties and Features

### 2.1 Essential Characteristics of HPC

High compressive strength (over 50 MPa) as well as better workability, durability, and consistency in regard to ordinary concrete are features characteristic of HPC, a unique concrete category [3]. To enhance the microstructure, HPC is made using various amounts of cement, aggregates, specialized admixtures, and supplementary materials (SCM). A significant advancement in the design of HPCs has been the use of additional cementitious materials, such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS), leading to pozzolanic reactions and compacted pore configurations [6]. In addition to improving mechanical qualities, these additives reduce the water-to-cement ratios, resulting in less permeable porous matrices with improved durability. HPC can maintain workability despite reaching a low water-to-cement ratio between 0.25 and 0.40, as opposed to traditional concrete between 0.50 and 0.60, due to high-range water reducers and superplasticizers [7].

HPC beam-column joints have more structural performance, particularly increased load-carrying capacity, minimized deformations, and improved ductility over conventional concrete, according to numerous experimental evaluations [8]. Fibers modify the composite microstructure while providing HPC formulations with better ductility, both of which are good for your application. Research on fibre-reinforced HPC reveals that better failure modes and a higher energy absorption capacity depend on the choice of fibres (steel, synthetic, or basalt) at

appropriate volumes [9]. The variety of imaginative joint designs and structural configurations for rigid pavement applications has been increased by the newly introduced Ultra-High-Performance Concrete (UHPC), which has compressive strengths greater than 150 MPa.

### 2.2 Environmental Performance and Durability

As a result of its tiny microstructure, which considerably reduces moisture entry, sulphate penetration, and chloride diffusion, HPC offers a longer life span [10]. When correctly constructed, HPC formulations with recycled materials can achieve an embodied carbon of roughly 76% lower than typical Portland cement pavements and maintain compressive strengths well into the 65 MPa range [10]. When looking at large-scale pavement designs, where sustainability considerations are significantly included in design procedures, the sustainable aspect is significant. As an example, treatment of recycled concrete aggregates (RCA) with silica fume and metakaolin is being shown to restore some of the mechanical properties lost from secondary use; machine learning models can predict whether modified formulations could restore pristine concrete strength levels with over 95% fidelity [11].

Because HPC has lower capillary porosity as well as greater air-void features [12], it significantly boosts freeze-thaw resistance, an important durability requirement for rigid pavements in seismic zones and cold climates. The use of natural rubber latex in concrete has also been studied as a sustainable alternative; however, excess substitution might have harmful effects on concrete [12]. At recommended dosages (1.0% replacing the weight of cement), both compressive strength and flexural strength are significantly higher than those without, while still meeting the requirements for rigid pavement design criteria [13]. Additionally, to improve mechanical performance in certain conditions, the use of waste materials in HPC formulations, such as sugarcane bagasse ash, wasted coffee grounds, and porcelain tile waste, improves environmental sustainability [14].

### **3. Fundamentals of HPC Applications and Rigid Pavement Design**

#### **3.1 Structure Analysis and Design Process**

Advanced computing methods that take advantage of changes in temperature, dynamic loading conditions, and three-dimensional stress distributions must be utilized for tough pavement design in seismic zones [1]. Modern design approaches like the Pd T-14-2003 method, which is applied throughout Asia, and FAA procedures for runway pavements provide a straightforward framework for computing design slab thickness according to CBR and traffic loading indices. While Westergaard's primary formulas originated for concrete slab design, finite element simulation has led toward their evolution [15]. Based on parametric studies, the assumptions stated under full subgrade support, such as in design, are considerably different in comparison to how concrete pavement behaves to combinations of temperature and traffic loads [15].

When HPC has been employed in the design of rigid pavement, thickness can be minimized while keeping or achieving the structural capacity. Studies additionally indicate that better modal base course materials and slab-base interfaces enable the alteration of pavement foundation properties to be an improved technique for thickness optimization using mechanistic-empirical procedures [17]. HPC-based designs regularly exceed conventional concrete in estimated fatigue resistance and long-term performance forecasting precision for AASHTO 1993, MEPDG, and local requirements, according to comparative studies using different methods of design [17]. It has been established that using modern interlayer materials and surface treatments can improve load transfer efficiency as well as avoid crack propagation in rigid pavements [18].

#### **3.2 The Reaction of Structures to Loads**

The position of the load in the expansion joints, stiffness, and concrete elastic modulus significantly influence the stress-strain state of rigid pavement structure under concentrated loads [19]. Interior loads provide lower maximum stress than edge and corner loadings, as determined by laboratory and computer

analysis [1]. Stress magnification factors have also been found to vary from 1.2 to 2.0, subject to the loading arrangement. The use of HPC alters the basic response characteristics by increasing tensile strength and elastic modulus, which is typically 5–15% larger than that of conventional concrete. However, for optimally designed airfield rigid pavements subjected to aircraft loading, finite element analyses have revealed maximum vertical displacements of 0.94 mm and horizontal displacements of 0.22 mm and maintained stress distributions within acceptable operational limits given the use of recommended materials [1].

Higher stiffness base courses and subbases substantially decrease tension bending stresses and settlements, according to a considerable amount of literature on the influence of foundation materials on rigid pavement response [20]. A well-designed subbase can enhance load distribution characteristics and lower maximum stresses by 20–35%. Because the tensile and flexural enhancement provided by an HPC can only be fully executed when matched with adequate load-transfer mechanisms across all interfaces in the pavement system, HPC-based pavement systems greatly benefit from increased foundation support. Research took place to determine substantial price effectiveness without affecting structural reliability, such as on composite pavement systems with conventional concrete base layers and high-performance concrete (HPC) overlay [21].

### **4. Seismic Performance Class and Anti-Earthquake Mechanism**

#### **4.1 Analysis of Dynamic Action**

As mentioned before, structural damping, mass distribution, and material ductility significantly determine the whole seismic response of concrete structures, including brittle pavements [22]. It has been shown that box-shaped subgrade structures utilized in a high-speed rail respond better, but they remain far more rigid, and components of the structure act in these instances with forces orders that are magnitude shorter than design strength [2]. Reinforcement information, concrete quality, and structural problems that result from decreased stiffness and increased susceptibility to ground motion

amplification all have an important effect on how well reinforced concrete systems respond to earthquakes [22].

When comparing effectively constructed buildings to less durable structures, researchers evaluating code-conforming and standard specifications of concrete in seismic zones identified substantial improvements in story shear, inversion moments, displacement, and energy emitted.

Higher flexural and tensile strength restricts the development and propagation of cracks, a higher elastic modulus increases the initial stiffness, while superior ductility features give a higher deformation capacity without falling apart, all of which contribute to the enhanced seismic performance of HPC [8]. Also, HPC formulations that include additional cementitious materials can bond to reinforcement more successfully than conventional formulations, giving dependable anchorage and, under some circumstances, reduced failure modes during seismic events. When compared to monolithic cast-in-place construction, numerous investigations on precast concrete structures with adjusted connection setups showed that well-designed connections can achieve similar or better seismic performance [23]. The connection details included connectors with friction-damping devices and shape memory alloy components, which minimized the structure's post-seismic permanent deformation while retaining its integrity [24].

#### **4.2 Joint Performance and Load Transfer**

While they must facilitate thermal movement while offering consistent transmission of load capabilities, joints play an important role in the seismic performance of rigid pavement. The traditional dowel bar joint showed limits in preserving load transfer efficiency (LTE) for dynamic seismic loading with crack propagation, with its ability to perform well under static and quasi-static loads [25]. To improve load transfer across JRC with a 70–90% load transfer efficiency, a novel type of ultra-high-performance concrete link slabs was used in place of the traditional dowel bars. This led to limited joint face deflections and lowered relative vertical movements between the

adjacent slabs [25]. Compared with dowelled joints, experimental studies performed on UHPC link slabs indicated ultimate loads ranging up to 23–88% higher and deflection reductions of 56–81% under comparable loading conditions [26].

These parametric studies on UHPC link slab geometry have made it practical to discover the optimum layouts that satisfy constructability and structural efficiency standards. The results showed that slabs with joint widths of 10 mm should have dimensions of length (100 mm) x thickness (50 mm), whereas slabs with joint widths of 20 mm should have dimensions of length (100 mm) x thickness (70 mm), respectively [26]. The average accuracy of the numerical simulation-based expected experimental load-deflection characteristics of UHPC link slab systems was 87% [26]. Instead of employing a single stud connection that exercises the full load-transfer capacity and prevents stress concentrations, the use of shear studs in UHPC link slabs has been adjusted to provide uniform load transfer with improved performance in terms of stress concentration using two studs per side [25].

#### **4.3 Positioning and Detailing of Reinforcement**

For reinforced concrete pavements and supported systems to have adequate seismic performance, adequate reinforcing specifications must be provided. The development length requirements for reinforcement employed here varied from those required for conventional concrete because the bond between concrete and rebar in HPC is made stronger by a somewhat refined microstructure and mineral admixtures [8]. Whereas the role of development length reinforcement in L-section beam-column joints has been proven to increase load capacity while decreasing deflections by more than 20% [8], the design of anchorage substantially highlights the impact on structural reliability. Due to higher levels of confinement that greatly improve ductility and energy dissipation capacity, the inverse relationship between reinforcement diameter and concrete strength has been confirmed across a wider range with the use of HPC. As a result of its high durability and resistance to corrosion, the use of carbon-fiber reinforced polymer (CFRP) reinforcement may

possess greater possibilities in seismic applications [27]. The brittle nature of failure for these materials requires parameter sensitivity and modelling beyond conventional methods, even though CFRP-reinforced concrete columns retain a significant amount of load in flexure [48]. However, this currently enables more than 2.5% drift capacity per CFs in concrete-filled couplings [27]. Deformation capacity and failure modes could be imagined in greater detail with the development of plastic hinge theories for CFRP-reinforced elements, allowing for a more suitable seismic response analysis. Creative Use Cases.

## 5. Methods for Performance Improvement

### 5.1 Joint Innovation and Link Slabs

To solve the problems of typical dowel bars while improving load distribution and durability performance, this study provides a new development in joint design for rigid pavement, particularly on the innovative UHPC link slab. On jointed plain concrete pavements, short ultra-high-performance concrete link slabs, which function as expansion joints while displaying outstanding load distribution characteristics, have been successfully utilized [28]. UHPC specimens displayed improved joint face deflection, proportional end displacement in nearby slab joints, and maximal load capacity (11–23%) in improved lateral tests comparing UHPC link slabs to dowelled joints [28]. In contrast, dowelled joints' performance was greatly impacted by joint width and the load-deflection performance that followed along with it, giving more flexibility in design range and a decrease in slab deformation, which was not seen in UHPC link slabs. For instance, design optimization techniques that may be utilized across different pavement conditions were outlined in the parametric analysis and finite element simulation of UHPC link slab joints done [26]. By improving the distribution of stress (infinite stiffness), it will ultimately reach the tensile strength under load at its bottom face under loading, causing flexural cracking to occur upward from the position where the loads are applied. This will achieve a controlled failure

mode due to flexure while maintaining structural integrity and allowing for movement. It was demonstrated that link slab characteristics, rather than shear stud characteristics, controlled joint performance; vertical stress on studs was maintained below the yield strength level in all configurations.

### 5.2 Fiber-Reinforced and Composite HPC Systems

High-Performance Concrete (HPC) equations have made significant use of fibre reinforcement to improve pavement performance, specifically fatigue resistance and crack control. Compared to control mixes, adding waste tire wire and mine tailings to fiber-reinforced concrete improved its flexural strength by more than 200% and its compressive strength by 18.2% [29]. The material's capability for absorbing energy under impact and cyclic loading had been improved by increases in ductility and a 161% increase in flexural toughness and fracture energy. For stiff pavements designed in seismic zones, where energy absorption power and cracking ability are essential, such mechanical improvements suggest substantial advantages. Based on the successful implementation in rigid pavement slabs and the optimum ratio of sugarcane bagasse ash as a 10% cement replacement weight with the ideal addition of 1% volume macro synthetic fibers, which increased ultimate load-carrying capacity by 34–36% over control mixes, the type of macro synthetic fiber-reinforced HPC was selected [30]. The energy dissipation qualities of fibre reinforcement improved, increasing the service life of cementitious composite materials by distributing stress rather than producing localized damage. It has been shown that HPC reinforced with glass fibers meets seismic requirements for design, although it performs better under cyclic and monotonic loads on beam-column joints [6].

### 5.3 Using Computer Science to Support Eco-Friendly and Sustainable HPC Formulations

HPC waiting formulations utilizing waste, recycled materials, and industrial waste products have shown mechanical performance that is equivalent to or exceeds compositions made of virgin materials while providing a far lower

impact on the environment. In contrast to pavements manufactured from conventional Portland cement, alkali-activated slag concretes utilizing recycled concrete aggregate and waste foundry sand produced compressive strengths above 65 MPa while reducing embodied energy by 43% and embodied carbon by 76% [10]. 10% cement replacement improves permeability and lasting properties because it has been discovered that natural zeolite, as a substitute material, is suitable for structural and sustainability goals [14]. When material selection and mix design are done effectively, the use of recycled coarse aggregates in HPC has been shown to achieve better than 95% strength recovery [11]. However, it must be adjusted for the concrete mixture proportions, additives used, etc. Despite employing more expensive materials at the beginning, HPC-based rigid pavements have proven to be cost-effective over a significant service life (20–40 years) due to their extended, equipment-free periods and lower maintenance costs [14].

#### **5.4 Rehabilitation and Overlay Techniques**

Reliable bonds at the interface are needed to ensure successful and long-term functionality under heavy dynamic loads on rigid airport pavements (Fig. 27-a) [31]. At the same time, ultra-thin concrete overlays have been applied successfully in asphalt pavements as functional rehabilitation measures [10]. While styrene-butadiene rubber modified cement quartz mortar adhesive was necessary for interface treatment preparation, aircraft dynamic simulation investigations in landing, taxiing, and turning proved that the interface failed under the required bond strength in different aircraft operations. The safety factor for tensile failure increased from 0.69 to 1.25 with effective surface preparation and interface treatment, whereas shear resistance values increased from 0.61 to 1.12 [31].

High-performance concrete carpets, in which a thin layer of HPC wearing course is placed on top of typically conventional structural massive layers, are the most used applications [21, 22]. By allowing controlled cracking in both directions and minimizing reflection cracking, this specialized architecture with no bond

between layers (by polymer and geotextile interfaces) propagates damage through greater areas and improves service life.

### **6. Future concerns include performance monitoring and design life.**

#### **6.1 Longevity of Determination**

Detailed long-term (more than 20 years) data collection on concrete pavement performance in the US showed typical trends in degradation and confirmed designs. The Falkenberg concrete pavement laid in Sweden between 1993 and 1996 had very little studded tire wear (5 mm after 20 years), longitudinal cracking was noticed in the outer wheel tracks as a result of base layer erosion and potentially dowel bar position concerns [32]. For long-term stability of structures, this case study highlights the requirement of appropriate drainage, reinforced detailing, and foundation design. Using sustainable preservation techniques like full-depth repair, partial-depth repair, diamond grinding, and joint sealant replacement, the performance of the current concrete pavement restoration techniques, developed from data collected over 22 years, indicated a very acceptable level of ride quality and friction resistance [33].

Rigid pavements' potential to resist freeze-thaw damage is important and significantly impacted by the air-void system's determining characteristics; in fact, void frequency and separation factor have a greater relationship with field performance than air content [12]. Laboratory accelerated freeze-thaw tests (ASTM C 666-type) are more aggressive than real environmental exposure, and actual performance is often better than predicted in the laboratory, as shown in studies published for various concrete pavement projects.

#### **6.2 Climate Change's Impact on the Environment**

The determination of rigid pavements' thermal and flooding resilience has been receiving a lot of attention considering climatic unpredictability and extreme weather events. According to a study employing the FEACONS IV software, performance-related distress (i.e., thermal expansion and contraction cycles) is significantly affected by the weather, especially

annual temperature changes [34]. High temperatures intensify the stress caused by thermal expansion, and flooding conditions saturate the concrete and subgrade layers, which leads to negative effects on long-term performance. However, than in pavements constructed with river gravel or granite<sup>306</sup>, pavements formed with crushable porous limestone aggregates have demonstrated a lower elastic modulus and coefficient of thermal expansion<sup>305</sup>, indicating superior durability under stresses.

Epoch-making computing structural models that contain ductility analysis, pitting mechanisms, and chloride solutions have been utilized in studies on the way corrosion damage and chloride penetration affect seismic behavior of RC structures [35]. The results of this study demonstrated that seismic capacity can be significantly decreased by strength reduction brought on by corrosion of the reinforcement, with building walls less resistant to strength degradation than bridge piers due to the detailed methods used when placing reinforcement. The drop of structural strength and displaced capacity with rising levels of corrosion can be accurately predicted by connecting climate and corrosion models.

### **6.3 Upcoming Technologies and Research Challenges**

In terms of seismic application, future directions for HPC rigid pavements should focus on the following areas: (1) integration of digital twins and smart sensors to allow seamless monitoring, repair, and maintenance systems; (2) new constitutive laws that implement rate dependency and damage evolution into HPC systems; (3) performance evaluation under mainshock-aftershock sequences; and (4) field investigation of novel joint designs and material mixtures over time. [33] The application of artificial neural networks and machine learning to predict pavement performance under varying loading and environments offers significant promise for life-cycle cost analysis and design parameter reduction.

**7. The following comments are presented for developers constructing HPC stiffness pavements in earthquake-prone areas following thorough studies based on recent publications:**

#### **7.1 Materials:**

GGBFS 20–30% for earthquake resilience and silica fume 8–12% for optimal long-term durability are combined to the required concrete strength class C45/55 for significant uses in high seismic locations.

#### **7.2 Joint Design:**

Use UHPC link slab arrangements compared to conventional dowel bars during new construction. Target for load transfer efficiency ratings above 80% and base joint geometry on the outcome of a parametric optimum study (100 mm length × 50-70 mm thickness).

**7.3 Optional base course** supplies with a resilient modulus ( $M_r$ ) of a minimum 150 MPa should be used for slab-base interaction if the CBR is under 6% on the subgrade and micro surfacing is required.

#### **7.4 Reinforcement Detailing:**

Validate that development length measures are suitable for major designs subjected to cyclical seismic loads with confinement reinforcement, considering consideration of the concrete-rebar bond properties of HPC, which allow enhanced anchorage reliability.

#### **7.5 Performance Monitoring:**

Following construction is finished, implement basic structural health tracking programs based on minimally destructive testing methods (ground-penetrating radar, falling weight deflectometer) at five-year intervals.

#### **7.6 Sustainability Approach:**

When standards for performance meet, aim for carbon footprint reductions in the 50–75% range while respecting structural specifications. Wherever appropriate, combine waste from manufacturing and recycled materials.

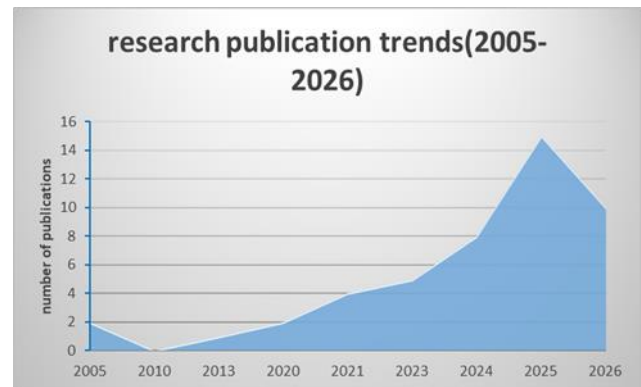
#### **7.7 Thermal Considerations:**

Local environmental variables should be taken into consideration during engineering pavement systems, including provisions for thermal expansion and drainage systems that use thermal cycling to decrease moisture-related deterioration.

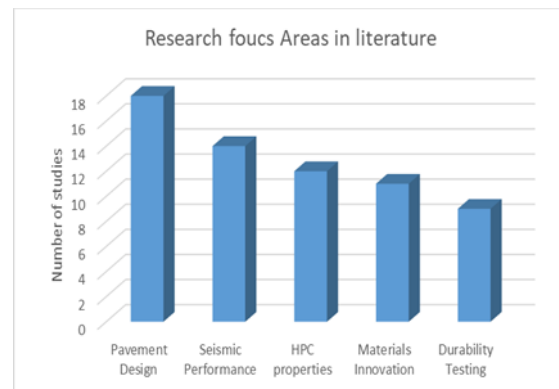
## 8. Conclusions

For rigid pavement mechanisms in seismically hazardous locations, High-Performance Concrete is a revolutionary advancement offering superior mechanical characteristics, durability specifications, and cost-efficiency over a considerable design life. Additionally, all-in-one multi-level earthquake-resistant pavement construction approaches can be obtained using cutting-edge materials with unique UHPC link slab joint designs and efficient foundation engineering [25], [26], [3]. For HPC-based rigid pavements, a low w/cm ratio of 0.3–0.4 and a dry, improvised mix design typically culminate in an accelerated material cost, as indicated by a 40% reduction in overall thickness necessary for satisfactory structural performance and an extended service life of over 40 years, with minimal or no maintenance [5], [14]. Several supplemental mechanisms, which include increased flexural and tensile strength, the fact that limits the range of cracking, increased ductility that raises the deformation capacity, improved energy dissipation properties, and complex microstructure that increases durability under severe environmental conditions, are the reasons for the seismic resistance of HPC rigid pavements [8], [22]. Sustainable compositions for HPC mixes produced with recycled materials showed environmental benefits of more than 76% reduced carbon footprint while achieving structural performance features that meet virgin material standards, according to a new study [10]. By using extensive structural modelling, intelligent joint designs, and real-time structural health assessment technology, generations to come of earthquake-resistant pavement systems may be further enhanced. Innovative seismic elements of design added to HPC rigid pavements represent the most modern engineering solution for supplying long-lasting, environmentally sustainable, and economical pavement infrastructure serving communities safely and consistently over a long time amid extreme environmental and seismic conditions, as growing urbanisation increases the demand on transportation networks and climate change

stresses environmental impacts. Figure (1) isolated literature review data summary.



(a)



(b)

**Figure 1.** (a), (b) High-performance concrete (HPC) for rigid pavement under earthquakes: literature review data summary

## References

- [1] O. Dubyk, O. Chernyshova, I. M. Osovskiy, and D. Yu. Kononenko, "DETERMINATION OF THE STRESS-STRAIN STATE OF THE RIGID PAVEMENT STRUCTURE OF AN AIRFIELD ACCESS ROAD," *Modern construction and architecture*, Mar. 2026, doi: 10.31650/2786-6696-2026-15-34-42.
- [2] Y.-Y. Chen, H. Xiao, X. Song, S. Guo, B. Luo, and M. Nadakatti, "Seismic Response Analysis of Concrete Box-Type Subgrade in High-Speed Railways," *Applied Sciences*, Dec. 2024, doi: 10.3390/app142411899.
- [3] H. H. M. Ali, "Advances in High-Performance Concrete: A Comprehensive Review of Materials, Design, and Applications," *KHWARIZMIA*, Aug. 2023, doi: 10.70470/khwarizmia/2023/013.
- [4] I. Oz and M. Omur, "Evaluating the Seismic Fragility and Code Compliance of Turkish Reinforced

- Concrete Buildings After the 6 February 2023 Kahramanmaraş Earthquake,” *Applied Sciences*, May 2025, doi: 10.3390/app15105554.
- [5] A. Vaitkus, J. Gražulytė, O. Šernas, M. Karbočius, and R. Mickevič, “Concrete Modular Pavement Structures with Optimized Thickness Based on Characteristics of High-Performance Concrete Mixtures with Fibers and Silica Fume,” *Materials*, Jun. 2021, doi: 10.3390/ma14123423.
- [6] C. Kumar, P. Manisha, and P. Sadula, “Behavior of Monotonic Loading for Glass Fibre-based High-Performance Concrete in External Beam-Column Joint using ANSYS. Analysis,” *E3S Web of Conferences*, 2020, doi: 10.1051/e3sconf/202018401088.
- [7] H. Cai, J. Luan, C. Zhou, J. Zhang, and L. Ma, “Admixed high-performance concrete property prediction by novel regression-based models,” *Journal of Intelligent & Fuzzy Systems*, Jun. 2023, doi: 10.3233/JIFS-224343.
- [8] Dr. V. M. Patil, A. C. Lande, and Dr. Mahesh. M. Awati, “Experimental Assessment of Bond Behavior and Structural Performance of High-Strength Concrete Beam-Column Joints under Static Load,” *International Scientific Journal of Engineering and Management*, Jan. 2026, doi: 10.55041/isjem05335.
- [9] T. Ayub, N. Shafiq, and M. Nuruddin, “Mechanical Properties of High-performance Concrete Reinforced with Basalt Fibers,” 2014, doi: 10.1016/J.PROENG.2014.07.029.
- [10] A. Sheshadri, S. Marathe, A. P. Rodrigues, R. Fernandes, and Ł. Sadowski, “Synergy of industrial wastes in eco-friendly, air-cured alkali activated pavement concrete composites: properties, embodied carbon and energy assessment and modelling,” *International Journal on Road Materials and Pavement Design*, Jul. 2025, doi: 10.1080/14680629.2025.2495705.
- [11] T. Alqubaysi et al., “Performance optimization of rigid pavement concrete using metakaolin treated RCA and silica fume with an experimental and machine learning based approach,” *Scientific Reports*, Dec. 2025, doi: 10.1038/s41598-025-31082-2.
- [12] M. Radlinski, J. Olek, M. Arribas, A. Rudy, T. Nantung, and C. M. Byers, “Influence of Air-Void System Parameters on Freeze-Thaw Resistance of Pavement Concrete – Lessons Learned from Field and Laboratory Observations,” *Proceedings of the International Conference on Concrete Pavements*, Jan. 2025, doi: 10.33593/iccp.v9i1.506.
- [13] K. Kantatham et al., “Natural Rubber Latex-Modified Concrete with Bottom Ash for Sustainable Rigid Pavements,” *Civil Engineering Journal*, Aug. 2024, doi: 10.28991/cej-2024-010-08-05.
- [14] T. H. B. Ata and A. T. Ibraheem, “The eco-concrete revolution: Manufacturing a sustainable high-performance rigid pavement with innovative materials,” *Research on Engineering Structures and Materials*, 2025, doi: 10.17515/resm2025-1239ic1110rs.
- [15] C.-L. Wu, M. Tia, and T. J. Larsen, “ANALYSIS OF STRUCTURAL RESPONSE OF CONCRETE PAVEMENTS UNDER CRITICAL THERMAL-LOADING CONDITIONS,” *Proceedings of the International Conference on Concrete Pavements*, Jan. 2025, doi: 10.33593/iccp.v5i1.770.
- [16] S. Saha, F. Gu, X. Luo, and R. Lytton, “Improved Sensitivity of Base Layer on the Performance of Rigid Pavement,” *arXiv.org*, Jan. 2021, [Online]. Available: <https://www.semanticscholar.org/paper/46cab2d56857662516af9aecfe272588b1d3133c>
- [17] C. Pleşcan, E.-L. Pleşcan, M. Stanciu, M. Botis, and D. Taus, “Sensitivity Analysis of Rigid Pavement Design Based on Semi-Empirical Methods: Romanian Case Study,” *Symmetry*, Jan. 2021, doi: 10.3390/sym13020168.
- [18] A. Mateos et al., “Engineering Interlayers for Rigid Bases under Jointed Plain Concrete Pavement Slabs,” *Transportation Research Record*, Oct. 2025, doi: 10.1177/03611981251357926.
- [19] A. Onyshchenko, I. Soloviov, S. Khudolii, and V. Solovyov, “INFLUENCE OF AXIAL LOAD POSITION ON THE STRESS-STRAIN STATE OF CONCRETE SLAB OF RIGID PAVEMENT,” *Automobile Roads and Road Construction*, 2025, doi: 10.33744/0365-8171-2025-117.2-147-159.
- [20] A. M. Shaban, A. Alsabbagh, S. Wtaife, and N. Suksawang, “Effect of Pavement Foundation Materials on Rigid Pavement Response,” *IOP Conference Series: Materials Science and Engineering*, Jan. 2020, doi: 10.1088/1757-899X/671/1/012085.
- [21] F. Larrard, “High-Performance Concrete Carpet: A New Concept of Concrete Pavement,” *SP-228: 7th Intl Symposium on the Utilization of High-Strength/High-Performance Concrete*, Jun. 2005, doi: 10.14359/14515.
- [22] A. Aljaafreh, Y. Alzubi, E. Al-Kharabsheh, and B. Yasin, “Seismic Performance of Reinforced Concrete Structures with Concrete Deficiency Caused by In-situ Quality Management Issues,” *Civil Engineering Journal*, Aug. 2023, doi: 10.28991/cej-2023-09-08-010.
- [23] Z. Wang, G. Xing, J. Huang, Z. Chang, and D. Luo, “Seismic Performance of Precast Concrete Exterior Beam-Column Joint with Disc Spring Devices,” *Journal of earthquake engineering*, Jul. 2024, doi: 10.1080/13632469.2024.2383283.
- [24] A. M. Elnady and H. Jiang, “Seismic Performance of an Earthquake Resilient Self-Centering Precast Reinforced Concrete Rocking Wall with External SMA Rods,” *Journal of earthquake engineering*, Jun. 2023, doi: 10.1080/13632469.2023.2220049.
- [25] H. Al-Jelawy, A. F. Kinaine, M. A. Mousa, and M. Muhaisin, “Advantages of using ultra-high-performance concrete (UHPC) link slabs as an

- alternative to dowel bar joints in rigid road surfaces,” *Roads and Bridges – Drogi i Mosty*, Mar. 2025, doi: 10.7409/rabdim.025.004.
- [26] A. Alzamily, H. Al-Jelawy, and H. Jashami, “Finite element simulation of shear stud jointed plain concrete pavement utilizing UHPC link slabs,” *Discover Civil Engineering*, Mar. 2025, doi: 10.1007/s44290-025-00201-3.
- [27] C. Liu, Y. Zhou, Y. Lu, and L. Qi, “Experimental seismic performance of Carbon FRP-reinforced concrete columns: Experimental evaluation,” *Structural Concrete*, Sep. 2025, doi: 10.1002/suco.70320.
- [28] A. F. Kinaine and H. Al-Jelawy, “Using Short Ultra-High Performance Concrete Link Slab as an Alternative to Steel Dowel Bars in Rigid Pavements,” *IOP Conference Series: Earth and Environment*, Sep. 2023, doi: 10.1088/1755-1315/1232/1/012053.
- [29] M. T. Seferoğlu, Y. S. Aksüt, and A. G. Seferoğlu, “Flexural Behavior and Sustainability of Dual-Waste Fiber-Reinforced Concrete Designed for Pavement Applications,” *Buildings*, Sep. 2025, doi: 10.3390/buildings15193454.
- [30] E. E. Elayouty, S. Ragheb, A. M. Youssef, M. S. El-Bany, and I. Agwa, “Enhancing the performance of rigid pavement slabs using sugarcane bagasse ash and macro synthetic fibers,” *Innovative Infrastructure Solutions*, Feb. 2025, doi: 10.1007/s41062-025-01871-9.
- [31] H. Zhao, Y. Tian, L. Ren, J. Wang, J. Liu, and J. Wu, “Improvements to the bonding condition of ultra-thin concrete overlays for airport rigid pavements,” *International Journal of Pavement Engineering*, Nov. 2024, doi: 10.1080/10298436.2024.2427855.
- [32] E. Dolk, J. Silfwerbrand, and S. Erlingsson, “Concrete pavement Falkenberg, Sweden – a 20 year review,” *Proceedings of the International Conference on Concrete Pavements*, Jan. 2025, doi: 10.33593/iccp.v11i1.320.
- [33] T. Kazmierowski and S. Chan, “Long Term Performance of Sustainable Concrete Pavement Preservation Strategies in Canada,” *Proceedings of the International Conference on Concrete Pavements*, Jan. 2025, doi: 10.33593/iccp.v10i1.405.
- [34] E. Alshammari, M. Tia, O. Alanquri, A. Albogami, A. Alsabbagh, and R. Alrashidi, “Thermal and Flood Resiliency Evaluation of Rigid Pavement Using Various Pavement Characteristics,” *CivilEng*, Apr. 2025, doi: 10.3390/civileng6020022.
- [35] E. Zacchei, R. Houlst, and J. P. D. Almeida, “Influence of chloride and corrosion attack on the seismic resistance of reinforced concrete walls under alternative climate scenarios,” *Structural Concrete*, Mar. 2025, doi: 10.1002/suco.70038.
- [36] J. Fu, “Cost assessment and strength properties estimation of high-performance concrete using a histogram gradient boosting model integrated with individual and ensemble optimisation algorithm,” *International Journal of Pavement Engineering*, Jan. 2025, doi: 10.1080/10298436.2025.2450081.
- [37] G. Afzal and T. Rasool, “Innovative pavement composite using graphene oxide in pervious concrete: durability performance analysis,” *International Journal on Road Materials and Pavement Design*, Feb. 2025, doi: 10.1080/14680629.2025.2463426.