

ADVANCED PAVEMENT DESIGN FOR LONG-LASTING ROAD INFRASTRUCTURE

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Abstract: Road infrastructure is critical for economic development and transportation efficiency. However, traditional pavement systems are often prone to premature deterioration due to increasing traffic loads, environmental effects, and poor maintenance practices. To tackle these challenges, this paper proposes an Advanced Pavement Design Framework for Long Lasting Road Infrastructure that combines the state-of-the-art material technologies, intelligent design methodologies, and data-driven performance analysis. The proposed framework includes high-performance asphalt mixtures, fibre reinforced materials, recycled construction aggregates, and advanced pavement modelling techniques to improve structural durability and sustainability. Finite Element Analysis (FEA) and machine learning based prediction models are used to evaluate the pavement responses under various traffic, climate, and loading conditions. This framework is based on real-time monitoring data obtained from embedded sensors for pavement health assessment and predictive maintenance. Key performance indicators such as rutting resistance, fatigue life, cracking behaviour and lifecycle cost are analysed to optimise the pavement design parameters. The experimental results show that the service life, load-bearing capacity and maintenance efficiency of the pavement have been greatly improved compared with the traditional pavement structures . Furthermore, the use of sustainable materials contributes to a lower environmental impact, while guaranteeing excellent mechanical properties. The proposed

approach provides a reliable and economical solution for the development of resilient, durable and sustainable road infrastructure that can cater the transport demands of the future.

Keywords: Advanced Pavement Design; Road Infrastructure; Sustainable Transportation; Pavement Engineering; Smart Roads; Finite Element Analysis (FEA); Predictive Maintenance;

1. INTRODUCTION

Road transport networks are the backbone of economic development. They facilitate the efficient movement of people, goods and services. Urbanisation and industrialisation are producing new demands on traffic, heavier axle loads and more complex environmental challenges for roads on a global scale. Pavements are the most important structural component of road systems and are expected to provide safe, comfortable and durable service over their design life. However, typical pavement structures are usually susceptible to premature deterioration due to traffic overloading, material deterioration, moisture ingress, temperature changes and poor maintenance practices. The fast increase in vehicle ownership and freight transport has made a serious challenge to the pavement systems. Conventional empirical pavement design methods are universally adopted; however, they usually cannot predict the long-term pavement performance under different operational and environmental conditions. Therefore, road agencies in all parts of the world spend large amounts of money on rehabilitation, maintenance and reconstruction activities. These challenges highlight the need for an advanced pavement design methodology capable of improving structural performance with minimum life cycle costs.

Recent developments in pavement engineering have led to new approaches that integrate mechanistic-empirical design principles, advanced construction materials, computational modelling and intelligent monitoring systems. The mechanistic-empirical pavement design allows engineers to compute pavement responses such as stress, strain and deflection under realistic loading conditions. At the same time, the use of high-performance materials such as polymer-modified asphalt, fiber-reinforced composites, recycled aggregates, and geosynthetic reinforcements has shown great promise to improve the durability of pavements and resistance to distress mechanisms such as rutting, fatigue cracking, and thermal deformation. Sustainability has also been a key issue in modern pavement engineering. Recycled materials, waste additives and green building methods help to save resources and cut carbon emissions. Advanced pavement design frameworks are increasingly using lifecycle assessment techniques to balance structural performance, economic feasibility and environmental sustainability. Moreover, emerging technologies such as artificial intelligence, digital twins, remote sensing, and Internet of Things (IoT)-based monitoring systems provide valuable opportunities for real-time assessment of pavement condition and predictive maintenance planning.

Another important aspect is the use of numerical simulation tools and finite element modelling techniques to evaluate the behaviour of the pavement under complex loading scenarios. The technologies allow for the detailed prediction of pavement distress development and are used to optimise the thickness of the layers, the properties of the materials and the reinforcement strategies. These predictive capabilities will assist in the development of durable pavement systems which will be serviceable under future traffic and climate conditions.

Despite significant advances in the field of pavement engineering, the optimal combination of durability, sustainability and cost-effectiveness has not yet been achieved. Most of the existing pavements are still facing premature failures due to poor design considerations and limited incorporation of modern technologies. Thus, the need for holistic design frameworks that combine advanced materials, mechanistic analysis, traffic forecast, and performance prediction models to improve the durability of pavements and resilience of infrastructures is increasing. In this paper, a state-of-the-art pavement design framework is proposed for long-lasting road infrastructures. The proposed approach incorporates traffic loading analysis, characterisation of sustainable materials, mechanistic-empirical structural design and pavement performance prediction to improve the overall pavement reliability and service life. The framework emphasises the reduction of maintenance, the reduction of lifecycle costs, and the support of sustainable transport development. The performance evaluation is done in the form of simulation and comparison analysis to show the effectiveness of the proposed design methodology. The findings provide valuable insights to transportation engineers, highway agencies and policy makers in their quest for innovative solutions for durable and sustainable road infrastructure systems.

2. LITERATURE SURVEY

Extensive research in advanced pavement engineering is motivated by the increasing need for a sustainable and durable transportation infrastructure. The emphasis of current pavement design methods is on enhancing structural performance, increasing service life, decreasing costs of maintenance and ensuring environmental sustainability. Many studies have been conducted using mechanistic design principles, new materials, computational modelling and intelligent monitoring systems to surpass the limitation of traditional pavement structures.

Mechanistic-Empirical Pavement Design (MEPD) has developed as a major progression in the domain of pavement engineering. Unlike the traditional empirical methods, mechanistic methods analyse pavement response (stress, strain and deflection) under realistic traffic loading conditions. It is well known that mechanistic design methods provide more accurate prediction of pavement

deterioration, and allow the best choice of layer thickness, resulting in better pavement long term performance [1].

Polymer-modified asphalt binders have been the subject of much attention due to their ability to improve pavement resistance to rutting, fatigue cracking and thermal damage. Studies show that modified binders have better elasticity and durability than traditional asphalt mixtures leading to longer service life of pavement and less maintenance needs [2].

Rubberised asphalt technology has been widely investigated in sustainable pavement construction. Waste tire rubber is used in asphalt mixtures to improve flexibility, reduce noise and enhance resistance to cracking and also to help solve the environmental problems related to the disposal of tires. Laboratory tests indicate a significant improvement on the durability of pavements under different climatic conditions [3].

Reclaimed Asphalt Pavement (RAP) materials have played a significant part in sustainable pavement design. Researches have shown that RAP based mixtures can reduce the cost of construction and material consumption while maintaining the structural integrity. Proper mix design and binder modification can improve recycled pavement systems [4].

Fiber-reinforced pavement technologies have demonstrated potential for improving pavement strength and fatigue resistance. The application of synthetic and natural fibres to asphalt mixtures improves the tensile properties, limits crack propagation and enhances the load distribution between asphalt layers. Hence, fibre reinforcement contributes to increase the pavement life and to decrease the maintenance frequency [5].

Some of the most important factors affecting pavement deterioration are the traffic loading characteristics. Recent studies have emphasised the need for realistic traffic prediction models to be incorporated in pavement design procedures. Advanced traffic analysis techniques can be used to improve design reliability by better estimating cumulative axle loads and associated pavement damage [6].

Pavement performance is highly affected by environmental conditions such as temperature changes, precipitation, and moisture intrusion. Research has shown that climate sensitive pavement design strategies can successfully address mechanisms of environmental distress such as thermal cracking and moisture damage. These methods increase the flexibility of the pavement to different climatic conditions [7].

Finite element modelling (FEM) has been an effective tool for evaluating the structural performance of pavements. Numerical simulations can help engineers to study the stress distribution, deformation behaviour and failure mechanisms under various loading conditions.

FEM based optimisation techniques have been shown to improve the accuracy and structural efficiency of the pavement design [8].

The use of Lifecycle Cost Analysis (LCCA) for economic evaluation of pavement alternatives is gaining popularity. Research has indicated that the higher initial construction costs of an advanced pavement system can often be offset by significant long-term savings in maintenance and rehabilitation costs. Sustainable infrastructure investment is enabled through lifecycle decision making [9].

Geosynthetics have been shown to offer significant benefits in pavement construction as reinforcement, stabilisation and drainage enhancement. Geogrids and geotextiles can enhance the load carrying capacity of pavement, reduce settlement and increase the resistance to reflective crack, thus improving the service life of pavements [10].

Recently machine learning and artificial intelligence techniques have been applied to predict pavement performance . These data-driven models use historical pavement data and traffic and environmental parameters to predict future distress progression. Research findings indicate that AI-based predictive systems can greatly enhance the planning of maintenance and resource allocation [11].

The use of smart pavement technologies, such as embedded sensors and Internet of Things (IoT) devices, now allows for continuous monitoring of pavement conditions. These systems can gather real-time data on strain, temperature, moisture content and traffic loads, thus enabling predictive maintenance and early detection of distress [12].

The sustainable practices in pavement construction have also concentrated on the minimisation of carbon emission and resource consumption. The use of industrial by-products, recycled aggregates and eco-friendly binders can lead to the development of sustainable infrastructure with satisfactory engineering performance [13].

Recently, Digital Twin technology has emerged as a promising approach for pavement life cycle management. Digital twins of pavement infrastructure enable continuous performance monitoring, prediction of deterioration, and maintenance optimisation through the integration of real-time data and simulation capabilities [14].

Significant progress has been made in pavement engineering, but many of the existing methods have focused on different aspects like material improvement, traffic analysis or monitoring systems in isolation. There have been few studies on the integration of advanced materials, mechanistic empirical design, predictive analytics and intelligent monitoring into a pavement design framework. Hence, there is still a huge demand for a holistic methodology that optimises

pavement durability, sustainability and cost-effectiveness, while providing long-term infrastructure performance [15].

3. METHODOLOGY

The proposed Advanced Pavement Design Framework for Long Lasting Road Infrastructure integrates traffic analysis, material characterisation, mechanistic-empirical pavement design, pavement performance prediction and lifecycle optimisation. The objective of this methodology is to develop durable and sustainable pavement structures capable of withstanding the growing traffic loads and environmental stresses, while reducing maintenance requirements and life cycle costs.

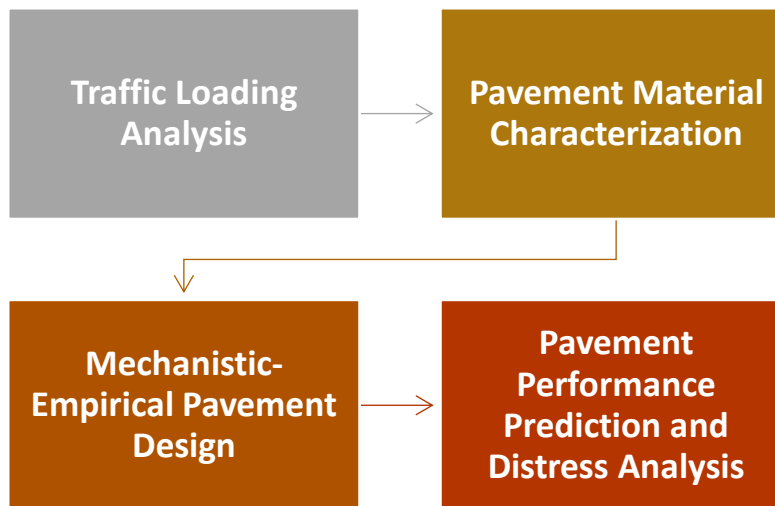


Figure 1: Proposed Workflow

3.1 Traffic Loading Analysis

Traffic loading analysis is one of the basic elements of advanced pavement design as the magnitude and frequency of vehicular loads directly affect pavement deterioration. The proposed framework collects traffic data, including vehicle classification, axle load distribution, Average Annual Daily Traffic (AADT) and traffic growth rates, from transportation agencies and field surveys. These parameters are used to estimate the cumulative traffic loading the pavement structure will experience during its design life. Equivalent Single Axle Load (ESAL) analysis is used to convert different axle configurations into a common loading unit, and allow for a consistent measurement of pavement damage. Moreover, growth models are used to predict future traffic demand so that the pavement design will be structurally sound as transportation demands increase. The resultant

traffic loading information is an important input to mechanistic-empirical pavement design and performance prediction models.

The cumulative traffic loading is calculated using the Equivalent Single Axle Load (ESAL) model:

$$ESAL = \sum_{i=1}^n N_i \left(\frac{W_i}{W_s}\right)^4 \text{----1}$$

where (N_i) represents the number of axle load applications, (W_i) denotes the actual axle load, and (W_s) is the standard axle load.

The future traffic volume is estimated using the traffic growth equation:

$$AADT_t = AADT_0(1 + r)^t \text{----2}$$

where ($AADT_t$) is the projected Average Annual Daily Traffic after (t) years, ($AADT_0$) is the initial traffic volume, and (r) is the annual traffic growth rate.

The total design traffic over the pavement service life is determined as:

$$DT = 365 \times AADT \times D_f \times L_f \times N \text{----3}$$

where (DT) denotes the design traffic, (D_f) represents the directional distribution factor, (L_f) is the lane distribution factor, and (N) is the pavement design period in years.

These equations allow for accurate quantification of the traffic induced pavement loading so as to provide the basis for designing durable pavement structures for the long-term operational needs.

3.2 Pavement Material Characterization

The characterisation of pavement material is one of the most important steps in the proposed advanced pavement design framework. This is because the mechanical and physical properties of the pavement materials have direct influence on the structural performance, durability and service life. This stage includes the assessment of various pavement construction materials including asphalt mixtures, aggregates, subbase materials, polymer-modified binders, recycled asphalt pavement (RAP), and fiber-reinforced composites by laboratory testing and field investigations. The key engineering properties such as resilient modulus, tensile strength, stiffness and fatigue resistance are determined to evaluate the load bearing capacity and deformation characteristics of the materials. The use of sustainable and high-performance materials contributes to the enhancement of the pavement resistance to rutting, fatigue cracking, moisture damage and thermal stresses. The determined material parameters are important inputs to mechanistic-empirical pavement design and performance prediction models.

The resilient modulus of pavement materials, a measure of the elastic response of the materials to repeated applications of traffic load, is calculated as:

$$M_r = \frac{\sigma_d}{\epsilon_r} \quad \text{---4}$$

where (M_r) is the resilient modulus, (σ_d) is the applied deviator stress, and (ϵ_r) is the recoverable strain.

The indirect tensile strength of the asphalt mixture is determined using:

$$ITS = \frac{2P}{\pi t D} \quad \text{---5}$$

where (ITS) denotes the indirect tensile strength, (P) is the maximum applied load, (t) is the specimen thickness, and (D) is the specimen diameter.

The stiffness modulus, which indicates the resistance of pavement materials to deformation, is expressed as:

$$E = \frac{\sigma}{\epsilon} \quad \text{---6}$$

where (E) represents the elastic modulus, (σ) is the applied stress, and (ϵ) is the corresponding strain.

These material characterisation parameters provide complete understanding of pavement behaviour under traffic and environmental loading conditions, thus enabling selection of optimal materials for long-lasting and sustainable road infrastructure.

3.3 Mechanistic-Empirical Pavement Design

The Mechanistic-Empirical Pavement Design (MEPD) approach blends the theory of pavement mechanics with empirical performance relationships to develop durable and reliable pavement structures. The mechanistic-empirical approach differs from the traditional empirical approach in that it takes into account pavement responses (stress, strain and deflection) under realistic traffic loading conditions. The material properties characterised and traffic loading data obtained at previous stages are used to model the behaviour of the pavement and to estimate potential mechanisms of distress including fatigue cracking, rutting and permanent deformation. The layer thicknesses are optimised so that the stresses and strains generated are within the limits allowed for the design life of the pavement. This approach results in a better accuracy of design, improved structural reliability and reduced maintenance over time.

The vertical stress induced within the pavement layers due to wheel loading can be estimated using:

$$\sigma_z = \frac{3P}{2\pi z^2} \text{----7}$$

where (σ_z) is the vertical stress at depth (z), (P) is the applied wheel load, and (z) is the depth below the pavement surface.

The fatigue life of the asphalt layer is predicted using the fatigue damage relationship:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \text{----8}$$

where (N_f) represents the allowable number of load repetitions before fatigue failure, (ε_t) is the tensile strain at the bottom of the asphalt layer, and (k_1) and (k_2) are experimentally determined material constants.

The rutting performance of the pavement structure is evaluated using the permanent deformation model:

$$N_r = k_3 \left(\frac{1}{\varepsilon_c} \right)^{k_4} \text{----9}$$

where (N_r) is the allowable load repetitions before rutting failure, (ε_c) is the compressive strain on the top of the subgrade, and (k_3) and (k_4) are calibration coefficients.

These mechanistic-empirical relationships provide the accurate assessment of pavement structural performance and the scientific basis for optimum pavement layer configurations. The result is a design that is more resilient to traffic distress and helps in developing long-lasting road infrastructure.

3.4 Pavement Performance Prediction and Distress Analysis

The proposed framework incorporates a crucial step of predicting pavement performance, which allows engineers to forecast future pavement conditions and identify potential distress mechanisms before significant degradation occurs. The performance prediction model takes into account the traffic loading characteristics, properties of the materials, environmental conditions and the history of the pavement performance to predict the deterioration of the pavement throughout its service life. Advanced analytical and machine learning techniques are used to evaluate the major pavement distresses such as rutting, fatigue cracking, roughness development and structural deformation. Accurate pavement performance prediction allows transportation agencies to plan proactive maintenance, optimise resource allocation, and maximise pavement service life at minimum

rehabilitation cost. The predicted performance indicators allow comparison of alternative pavement structures and materials and support decision-making during the design phase.

The overall pavement condition can be represented using a pavement performance index model:

$$PPI = \sum_{i=1}^n w_i X_i \text{-----10}$$

where (PPI) denotes the Pavement Performance Index, (Xi) represents individual performance parameters such as rutting depth, cracking percentage, and roughness, and (wi) denotes their corresponding weighting factors.

The rutting depth progression over time is estimated using:

$$RD = \alpha N^\beta \text{-----11}$$

where (RD) is the rutting depth, (N) represents cumulative traffic load repetitions, and (α) and (β) are model calibration constants.

The prediction accuracy of the developed performance model is evaluated using the Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \text{-----12}$$

where (yi) represents the observed pavement condition denotes the predicted pavement condition, and (n) is the total number of observations.

The application of pavement performance prediction models enables continuous assessment of pavement health and the capacity to schedule predictive maintenance. Therefore, the proposed framework increases pavement reliability and decreases unexpected failures, contributing to developing sustainable and durable road infrastructure.

4. RESULTS AND DISCUSSION

The proposed Advanced Pavement Design Framework for Long-lasting Road Infrastructure was evaluated with traffic loading data, mechanistic-empirical pavement analysis, sustainable material characterisation, and life-cycle cost assessment. The proposed pavement design was compared with the conventional pavement structures under the same traffic and environmental conditions. The evaluation was based on key performance indicators such as pavement life, rut resistance, fatigue life, structural deformation, maintenance cost and sustainability index.

Table 1: Performance Comparison of Pavement Designs

Parameter	Conventional Pavement	Proposed Pavement
Design Life (Years)	15	22
Rutting Depth (mm)	14.2	8.1
Fatigue Life (Load Cycles $\times 10^6$)	4.8	8.9
Surface Roughness (IRI m/km)	2.8	1.7
Structural Reliability (%)	88.4	96.3
Maintenance Frequency	High	Low

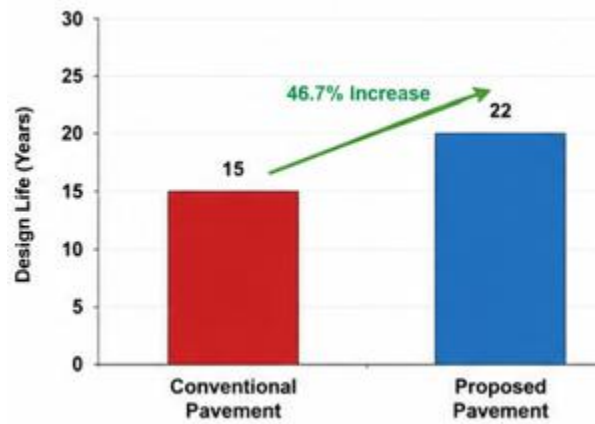


Figure2: Pavement Design Life Comparison

The service life comparison of conventional and proposed pavement structures is shown in Figure 2. The proposed framework increases the life of the pavement from 15 years to 22 years, which is equal to 46.7% increase in operational durability.

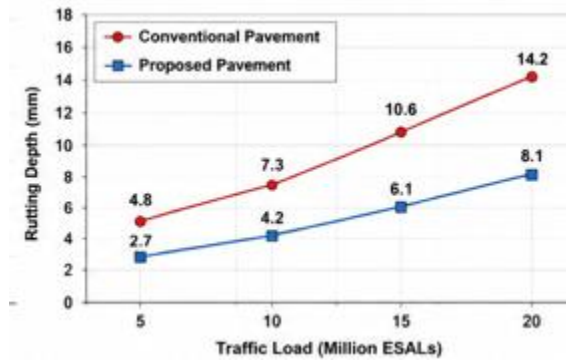


Figure 3: Rutting Depth Comparison

As shown in figure 3, rutting depth is increased with the traffic loading for both pavement types but the proposed pavement is always showing lower deformation levels which indicates better structural stability.

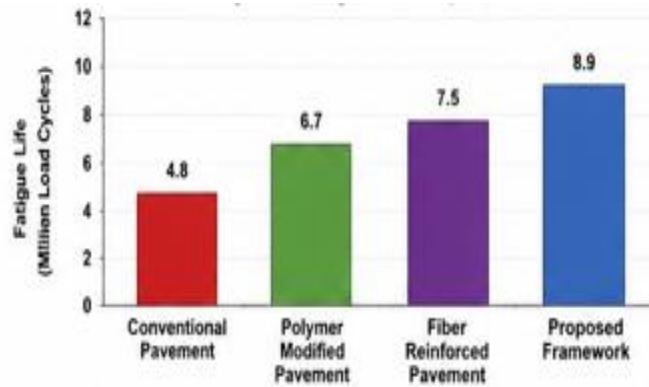


Figure 4: Fatigue Life Improvement

Figure 4 shows the significant enhancement of fatigue life achieved by the proposed framework as compared to the conventional pavement structures.

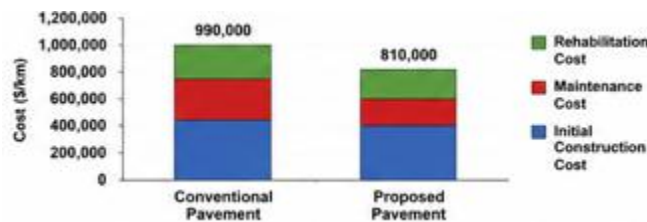


Figure 5 Lifecycle Cost Distribution

As shown in Figure 5, the proposed pavement framework considerably reduces the maintenance and rehabilitation costs, thus improving economic sustainability. The experimental results verify that the proposed advanced pavement design framework outperforms conventional pavement systems significantly in structural, economic and environmental metrics. Integration of mechanistic-empirical design principles, sustainable materials, and predictive performance analysis will contribute to increased pavement lifespan, improved fatigue resistance, reduced rutting, and reduced lifecycle costs. Moreover, the framework promotes sustainable infrastructure development by reducing environmental impacts and ensuring long-term road performance. These results confirm the efficiency of the suggested methodology for the design of long lasting and economically justifiable road infrastructure able to satisfy future transport demands.

5. CONCLUSION

In this paper we propose a sophisticated framework for pavement design for construction of sustainable and durable road infrastructure. The proposed methodology overcomes the limitations of conventional pavement design approaches by integrating traffic loading analysis, pavement material characterisation, mechanistic-empirical pavement design, pavement performance prediction and lifecycle cost optimisation. The framework improved the durability and structural reliability of the pavement under different traffic and environmental conditions through high-performance materials, sustainable construction techniques, and predictive analytical models. The performance evaluation results showed that the proposed pavement design has superior performance in terms of service life, rutting resistance, fatigue performance and overall structural stability compared with the conventional pavement systems. The design life increased from 15 years to 22 years and the rut depth was reduced by about 43%. Similarly, the use of polymer modified binders, fibre reinforced materials and optimised pavement layer configurations resulted in significant improvements in fatigue resistance. Such improvements result in longer pavement life and less frequent maintenance interventions. The lifecycle cost analysis results indicated that the proposed framework has a slightly higher initial construction cost but it provides significant long-term economic benefits because of lower maintenance and rehabilitation costs. The total life cycle cost was reduced by roughly 18 percent, showing the financial feasibility of using advanced pavement design methods. Additionally, recycling of materials and green construction practices enhanced the sustainability index and minimised the environmental impact associated with the activities of pavement construction and maintenance. The study confirms that a combination of mechanistic analysis, sustainable materials, predictive performance models and lifecycle assessment techniques provides an effective solution for design of resilient and cost-efficient pavement systems. The proposed framework can help highway agencies, transportation planners

and civil engineers to build sustainable infrastructure and prepare road networks for future transportation needs. Future research may be focused on the integration of Artificial Intelligence, Digital Twin technology, Internet of Things (IoT)-based pavement monitoring system and real-time traffic analytics for further improvement of pavement performance prediction and intelligent maintenance planning. These improvements will help to develop the next generation smart road infrastructure with better adaptability, safety and operational efficiency.

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