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Performance prediction of pavement structures using non-destructive deflection testing and backcalculation

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Highlights

- Sustainable transportation – durable pavement structures
- Non-destructive testing – fast and reliable data acquisition
- Backcalculation – performance-oriented analysis

Abstract

Highway pavement plays a critical role in the economic development of cities and nations, and with proper design and maintenance, it supports sustainable transportation. Performance prediction models help evaluate the efficiency and durability of the road network, assisting in the development of strategies for infrastructure improvements. These predictions are made using computer-aided modeling and simulation techniques, aiming to identify future maintenance needs. Non-destructive testing (NDT) methods are used to assess the condition of existing roadways and provide information about their physical state. These techniques are vital for preserving pavement performance and enhancing traffic safety. NDT methods typically do not damage the materials being tested, and results can be obtained quickly, enabling efficient road maintenance management. Backcalculation problems involve analyzing data obtained from methods such as deflection testing to determine the mechanical properties of pavement structures. These methods play a significant role in enhancing the sustainability and safety of highway networks and contribute to the effective management of roadway maintenance. In this study, the performance prediction of pavement structures is investigated through backcalculation using data obtained from non-destructive deflection testing.

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1. Introduction

Asphalt is a composite material extensively utilized in road engineering, consisting of a bitumen binder and mineral aggregates combined in defined proportions. As a multiphase and structurally heterogeneous material, asphalt exemplifies the foundational concept of composite materials: the integration of components with differing physical or chemical properties to produce a material with enhanced performance characteristics compared to its individual constituents [1]. In asphalt, bitumen imparts elasticity and flexibility, while mineral aggregates contribute stiffness and load-bearing capacity. The interaction between these two phases governs critical performance attributes such as fatigue resistance, deformation behavior, and temperature sensitivity [2,3].

The performance of asphalt can be further optimized through the incorporation of additives such as polymers, fibers, and nanomaterials, which enhance its thermal stability and long-term durability [4,5]. Moreover, the use of recycled materials including reclaimed asphalt pavement (RAP) and plastic waste contributes not only to economic efficiency but also to environmental sustainability by promoting circular material use [6].

Pavement structures are typically constructed as multilayered systems comprising subgrade, sub-base, base, and surface layers. These layers function collectively to distribute traffic loads and must be engineered to perform reliably under diverse climatic and loading conditions. Pavements are generally classified into three categories: flexible, rigid, and composite [7]. Flexible pavements, primarily composed of asphalt layers, are cost-effective, easy to construct, and relatively simple to

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maintain, though they may be less suitable for heavy traffic. In contrast, rigid pavements, typically made of concrete slabs, offer superior durability and load distribution capacity but entail higher construction and maintenance costs. Composite pavements integrate characteristics of both types, providing a balanced approach by enhancing structural performance while maintaining a reasonable cost profile [7].

Highway pavements represent a fundamental component of transportation infrastructure, enabling safe and efficient mobility for vehicles, cyclists, and pedestrians. In addition to supporting mobility, they play a strategic role in urban and national economic development. When integrated with essential infrastructure elements such as road markings, lighting, and traffic control systems, well-designed pavements contribute significantly to road safety, efficiency, and sustainability [8].

To ensure long-term performance and optimize resource allocation, pavement performance prediction has emerged as a key tool in infrastructure management. Computer-aided modeling and simulation techniques allow for the evaluation of pavement behavior under traffic loading, aging processes, and environmental influences. These models assist engineers and planners in identifying future maintenance needs, anticipating structural deficiencies, and assessing the impacts of climate change on pavement systems [9].

In this context, composite pavements offer a particularly effective solution by combining the structural advantages of rigid pavements with the adaptability and smoothness of flexible surfaces. They are especially suitable for regions with weak subgrades and varying traffic demands, offering a cost-effective yet durable alternative for long-term infrastructure needs [10].

Non-Destructive Testing (NDT) methods have become indispensable in modern pavement evaluation. These in-situ techniques enable the assessment of subsurface deformation and structural integrity without compromising the pavement material. By employing surface sensors and real-time data collection, NDT facilitates periodic monitoring of pavement conditions, thereby informing proactive maintenance strategies [11]. Compared to conventional laboratory testing, NDT is faster, more economical, and allows for broader spatial assessment. This is particularly valuable for aging highway networks constructed in the 1960s and 1970s, many of which are nearing or exceeding their design lifespans. By offering detailed insights into existing conditions, NDT supports more efficient resource use and maintenance planning [12].

2. Performance Prediction of Pavement Structures Using Back calculation from NDT

Pavements are fundamental infrastructure components that ensure user comfort and safety. Accurate forecasting of future conditions allows for proper budget planning for maintenance activities. The evaluation of pavement performance involves detailed analysis and is directly related to ride quality and serviceability. Serviceability, which reflects this relationship, considers both the riding comfort and the pavement’s ability to provide service as seen in Figure 1. Overall, pavement performance is commonly associated with driver satisfaction [13].

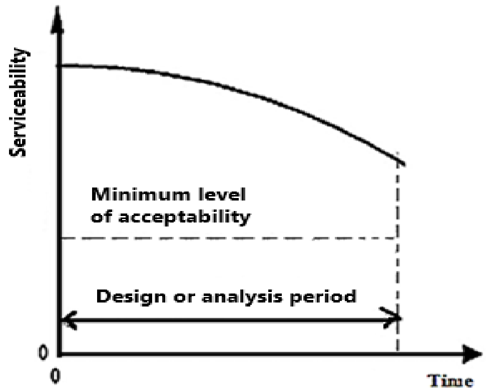

Figure 1. Serviceability degradation [14]

To evaluate the performance of pavement structures, detailed section-level analysis is required. This analysis includes ride quality and traffic data over a specific time period. Pavements are assessed based on user satisfaction or dissatisfaction in terms of ride quality, and the outcomes of these assessments inform decisions regarding maintenance, rehabilitation, or reconstruction.

Various methods have been developed for evaluating structural capacity, which require measurements to estimate the pavement's load-carrying ability and service life. The results of these structural assessments can be used to design improvement projects. Among both destructive and non-destructive structural evaluation methods, deflection measurement techniques are widely used.

Non-destructive techniques are generally preferred due to their lower cost, minimal traffic disruption, and reduced impact on the pavement structure. However, deflection measurements require appropriate equipment and skilled personnel, making structural evaluation a costly process. Therefore, a carefully planned strategy is necessary for effective structural assessment. The structural capacity of pavements can be evaluated non-destructively using various deflection measurement devices. These devices assess the structural response of pavements based on different methods [14].

Highways are the most commonly used mode of transportation worldwide and are designed to function with a certain degree of flexibility over time. However, environmental conditions and mechanical loading can lead to degradation of pavement structures. These deteriorations not only affect traffic safety but also lead to significant economic losses. Efforts to assess pavement performance are carried out within the framework of Pavement Management Systems (PMS) through models such as the Present Serviceability Index (PSI), Pavement Condition Index (PCI), and International Roughness Index (IRI). These models aim to monitor pavement service levels and enable timely interventions [15].

Performance modeling significantly impacts the lifespan, design, and financial aspects of pavement management systems. It constitutes an essential part of analyses conducted both at the network and project levels. Accurately determining pavement performance and deterioration prediction is crucial for maintaining road performance, keeping in mind that progressive deterioration can increase costs over time. Since future conditions cannot be precisely predicted, performance curves are used for estimations at specific points in time. A typical performance curve indicates the timing of maintenance and rehabilitation based on anticipated future pavement deterioration. Specific criteria must be established to compare predicted performance with actual measurements, which are generally based on standards and specifications. The information required to develop prediction models includes databases (such as construction date, IRI value, PSI, RN, AADT, etc.), parameters affecting deterioration, appropriate model selection, and defining certain criteria. Thus, with a suitable database and defined benchmarks, prediction models for pavements can be developed [16].

The existence of systems to manage urban pavements is inevitable. The most challenging step of these systems is to determine the current performance of the pavements. Existing performance can be quantitatively expressed through various techniques and indices, although these methods may require substantial infrastructure investment. In national road networks, pavement performance is generally assessed by device-based measurements. These measurements commonly use the International Roughness Index (IRI). Additionally, deflection data are preferred in pavement evaluations. Researchers often compare surface distress and/or roughness data with vehicle vertical vibration data to determine the current pavement performance [17].

Pavement performance refers to the ability of the pavement to provide ride comfort and safety over time. Performance evaluation requires data on surface characteristics and structural strength. Pavement characteristics are defined as physical properties, including surface type, smoothness, texture, and skid resistance. Pavement performance assessments are conducted by comprehensively evaluating criteria such as ride comfort, safety, surface integrity, structural adequacy, and surface distresses. These evaluations are typically based on pavement management system reports [18].

In recent years, the use of NDT methods has increased significantly in construction and environmental engineering applications. Research into electrical, electromagnetic, optical, and acoustic NDT techniques has accelerated. The potential of these methods has been extensively investigated, and they are widely used across many fields [19].

Continuous monitoring of the pavement network plays an important role in determining the structural performance. In this monitoring process, deflection measurements are commonly used to assess structural capacity. The Non-Destructive Deflection Test is the most widespread method for determining pavement structural condition and detecting variable parameters of the pavement structure. Results from this test help identify the properties of pavement layers. Unlike destructive testing, the Non-Destructive Deflection Test is performed without stopping traffic or damaging the pavement, making it one of the most reliable methods. The simple and fast falling weight deflectometer used in NDT is widely applied to both flexible and rigid pavements [20].

NDT methods are employed to assess existing pavement structures without necessitating subsequent repairs. These methods have two main advantages over destructive testing: first, they allow in-situ evaluation without causing damage or alteration to the materials. Destructive methods may damage underlying layers and require laboratory conditions. Second, non-destructive methods enable faster, more economical testing with less traffic disruption, allowing for a greater number of measurements. These methods are preferred to minimize traffic interruptions and to identify areas for laboratory sample collection for further material property evaluation. The focus is on determining the need for destructive testing, the location of such testing, and on-site measurement of current pavement structural conditions. These methods can assess structural or functional conditions. While data collected by non-destructive methods are objective, data analysis and interpretation may be subjective. Examples include Falling Weight Deflectometer, Dynamic Cone Penetrometer (DCP), Ground Penetrating Radar, and Seismic Method Devices [21].

Figure 2. Falling weight deflectometer [22]

The Falling Weight Deflectometer (FWD) is a device used for evaluating pavement structures. This device which is seen in Figure 2 applies a transient load to the pavement and measures the deflection values that occur under this load. This method is utilized to determine the mechanical properties of the pavement through back-calculation techniques. The DCP is a method used to measure soil strength is seen in Figure 3. However, it can also be employed to identify sudden changes in strength within pavement layers and to measure layer thickness. Ground Penetrating Radar (GPR) seen in Figure 4, is a non-destructive technique used to investigate the composition and extent of materials. It is also used to determine layer thicknesses of various pavements and to explore subsurface areas. Its high-speed data collection capability reduces traffic control needs and enhances safety. The Spectral Analysis of Surface Waves (SASW) method is used to evaluate pavement systems from a seismic perspective. This technique analyzes the travel time and response of Rayleigh waves to determine material properties [23].

These methods enable the integration of experimental approaches that can be used for the evaluation and performance monitoring of pavement structures. One of the NDT methods, the DCP, can determine layer strength without excavation. Similarly, the Lightweight Deflectometer (LWD) is another method used to assess the structural properties and performance of pavement structures [24].

Ground Penetrating Radar test is used to estimate asphalt concrete properties, while density and thickness measurements are performed with the Falling Weight Deflectometer test to assess the elastic modulus and estimate elastic properties using Ultrasonic Pulse Velocity (UPV). A small error and good correlation can be found between NDT methods and standard tests. NDT methods can be repeated numerous times, and with the latest software, surface, subsurface, and volumetric indicators can be detected more quickly and at relatively lower costs.

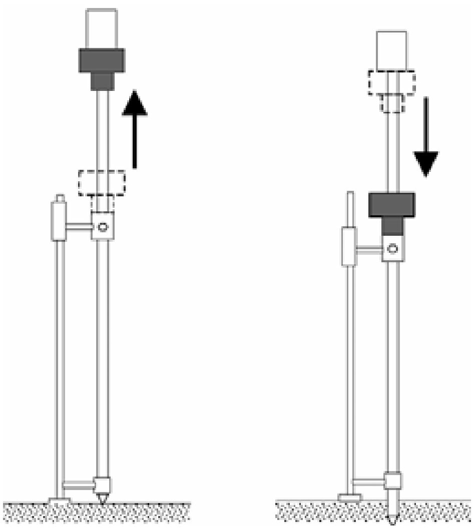

Figure 3. Dynamic cone penetrometer [25]

Figure 4. Ground penetrating radar [27]

In highway transportation, the use of innovative NDT methods for in-situ evaluation of pavement structures is increasing. GPR is a geophysical positioning technique that uses radio waves to capture subsurface images in a minimally invasive manner. It is also used to locate structural objects and evaluate pavement materials, layer thickness, and pavement characteristics.

The Falling Weight Deflectometer is an NDT method that measures the vertical deflection response of pavement layers. Its use is widespread in the pavement design industry for identifying weak pavement areas, back-calculating layer properties, and estimating the remaining service life of the structure. The FWD simulates the effects of wheel loads on concrete by generating impact forces from various drop heights, and geophones and seismometers are commonly used on transducers for various applications following loading [20,26].

A reliable measurement method is necessary to determine the effects of traffic and environmental conditions on pavement structures over time. For this purpose, the Falling Weight Deflectometer or more complex Traffic Speed Deflection Devices can be used as seen in Figure 5. Although FWD is an important tool for structural evaluation, thickness data are also critical as they are required for strain analysis and pavement rehabilitation. In particular, FWD deflections, evaluated together with pavement layer thicknesses, allow for the analysis of the mechanical responses of the pavement, enabling the condition of the pavement to be assessed both individually and overall [28].

NDT aims to determine the physical integrity and quality of the element while preventing deformation. NDT methods can be applied under various conditions based on different physical principles. These methods are faster than destructive techniques and are widely used across many fields. NDT applications can be conducted without interrupting operational processes, and results are generally obtained immediately. Selecting the most appropriate method for testing material safety is crucial and should be done considering various factors [29].

The structural condition of pavement can be determined non-destructively using the FWD. The FWD operates on the principle of transient loading and evaluates the load-carrying capacity of the pavement. In these devices, the force is generated by a guided mass and transmitted to the pavement as an impact load resembling a half-sine wave. Loading is applied within a specific time interval and frequency. The impact effect of the FWD is very close to the effect of standard axle loads, and it provides more reliable results than other NDT methods.

Due to temperature-dependent changes in flexible pavements, the measured deflection values may need to be corrected according to a reference temperature value for accurate evaluation. In flexible pavement systems, the durability of bituminous hot mix (BHM) layers varies depending on factors such as temperature, loading duration, and load magnitude. It should be noted that during deflection measurements, the pavement temperature is an important parameter to monitor. Since the stiffness of asphalt layers changes with temperature, changes in pavement temperature affect the deflections. At higher temperatures, asphalt stiffness decreases, causing deflections to increase [30].

Figure 5. Deflection measurement [11]

NDT utilizes various data acquisition devices and analysis methods. These data are generally used to assess the structural or functional condition of a pavement. Engineers can calculate the strength of pavement layers by using deflection basin data obtained from flexible pavements and rigid center NDT tests. This analysis method is commonly referred to as back calculation because engineers typically perform the inverse of traditional pavement design. Instead of determining the thickness of each pavement layer, back calculation generally solves for the pavement layer moduli based on assumed uniform layer thicknesses.

NDT encompasses various measurement and analysis techniques used to evaluate the current condition of structural materials or components. This method allows examination without altering the composition or shape of the material. In recent years, especially in the fields of civil and mechanical engineering, there has been increasing interest in damage-free methods used to detect defects in materials [31-33].

There are several models for estimating the remaining service life of Bituminous Hot Mix (BHM) pavements. These models are based on NDT methods that utilize material properties. The structural condition of the pavement depends on factors such as the structural capacity of the superstructure, layer thickness, and material properties. A widely used method to determine the structural condition of highway pavements involves measuring surface deflections of the pavement with a NDT device. These data are essential for determining the elastic parameters of pavement layers. To calculate elastic moduli, the parameters affecting deflection values must be known, and the relationship between these parameters and deflection must be established; this process is called back calculation. Deflection measurements provide information about the current condition of the pavement and are important for understanding the relationship between material properties and pavement performance. Data obtained from NDT devices help determine the elastic parameters of pavement layers. However, in addition to deflection tests, data interpretation and analysis are critical and these analyses can be used to identify pavement material properties [11,19,30,34].

NDT methods are generally preferred for evaluating the performance of flexible pavements. Among these methods, the Falling Weight Deflectometer (FWD) technique is the most commonly used. Using this method, time-dependent deflection values caused by applied loads are measured at multiple points along the pavement. Performance evaluation of flexible pavements is typically conducted for two main purposes: to provide information about the physical condition of the existing pavement and to verify the quality of newly constructed pavement layers.

NDT methods are widely preferred for determining mechanical properties because they do not damage the pavement and provide rapid results. Using these methods, the material properties of the pavement layers can be measured at low strain levels. Back calculation problems are considered optimization problems aiming to identify the best model parameters that correspond to known input-output data.

The back calculation process involves the mechanical analysis of surface deflections measured by deflectometers. This process consists of two parts: forward analysis and error correction algorithm. The forward analysis computes deflections, while the error correction algorithm calculates errors and updates the modulus estimates.

For back calculation to be successful, the forward computation model must produce accurate results, as system performance depends on the accuracy of the input and output data used [29,33,35].

To achieve reliable results, a comprehensive analysis of all influencing factors is essential. Factors such as sensor configuration, base layer properties, connection spacing, and temperature conditions must be taken into account when interpreting backcalculation outcomes. The measerement point accuracy as seen in Figure 6 and the distance between the sensors in FWD is also important in backcalculation. For rigid pavements, slab curling has been identified as a critical factor affecting FWD deflection measurements; therefore, its impact should be considered during the interpretation of backcalculation results.

Figure 6. Placement of the falling weight deflectometer on the measurement point [12]

Various backcalculation methods exist for determining base and subgrade moduli or subgrade reaction coefficients (k) in rigid pavements, each possessing distinct strengths and limitations. Inconsistencies among these methods have been recognized as a significant source of variation. Backcalculation procedures typically require the modular ratio as an input parameter, which should be established based on engineering judgment.

Backcalculated parameters for each deflection basin are compared against corresponding average values. If a backcalculated parameter deviates from the average by more than two standard deviations, an appropriate flag is raised. The primary goal of including the base layer in the backcalculation analysis is to account for its structural contribution to the overall pavement stiffness [36,37].

Accurately predicting the remaining service life of existing flexible pavements can lead to substantial savings in maintenance and rehabilitation costs. Backcalculation of structural capacity from non-destructive test data provides an efficient and cost-effective approach. Deflection data obtained from FWD tests are used to estimate the mechanical properties of pavement layers. However, backcalculation algorithms can influence the results, and many highway agencies worldwide still employ simplified methods.

An iterative procedure is typically employed for estimating pavement layer moduli through backcalculation. NDT facilitates the application of a mechanical approach in pavement design and rehabilitation by measuring in-situ material properties using appropriate techniques [38].

In flexible pavement systems, the backcalculation problem primarily involves determining the elastic modulus of individual layers as seen in Figure 7. Within these computational algorithms, the layer thicknesses and Poisson's ratio are considered known parameters. Initially, an elastic modulus value is assigned to each layer. A forward calculation is then performed using these values, and the computed deformation values are compared to the measured data. If the difference exceeds a specified tolerance, the elastic moduli are adjusted and the process repeats iteratively until the results fall within the acceptable tolerance. The initial guesses for elastic moduli significantly affect the convergence rate of the backcalculation procedure. The accuracy of the derived elastic moduli depends on the reliability of known pavement properties, and the goal is to minimize the discrepancy between measured and calculated deformations within a defined tolerance [40,41].

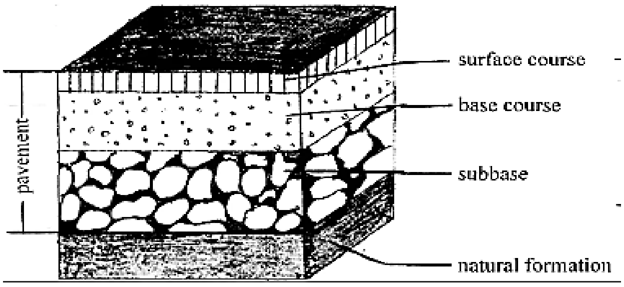

Figure 7. Layers in flexible pavements [39]

In summary, backcalculation is a widely used technique in engineering and materials science. This approach typically involves utilizing experimental data to infer material or structural properties. For instance, data obtained from experimental tests on a structure or material are analyzed via backcalculation algorithms. Through this analysis, structural parameters or material characteristics such as elastic modulus, strength, or thermal conductivity can be determined. Backcalculation is particularly valuable in complex structural systems or materials where direct measurement is challenging [42]. It facilitates understanding and predicting material behavior by analyzing experimental results. Additionally, backcalculation is extensively applied in engineering design and optimization processes, as the insights gained enhance the robustness and evidence-based nature of decision-making.

3. Conclusion

This study focuses on NDT methods employed for evaluating pavement performance. It highlights the significance of NDT approaches and explains how these methods are implemented through various techniques. The non-invasive nature of these tests offers numerous advantages for pavement assessment and performance monitoring. The importance of NDT methods in construction and pavement engineering fields is emphasized.

Among NDT techniques, the Falling Weight Deflectometer is one of the preferred methods for assessing the performance of flexible pavements. The results section underlines the crucial role of NDT methods in effectively evaluating pavement performance. Furthermore, the potential of these methods for future research and practical applications is acknowledged. Ultimately, NDT methods are identified as vital tools for ensuring the safety, durability, and sustainability of pavement structures, and their effective utilization is considered an essential requirement for pavement infrastructure management.

Backcalculation refers to an analytical approach used to determine structural or material properties by processing experimental data in a reverse manner. For example, to identify the elastic characteristics of a material, different loads are applied and the resulting deformations are measured. These experimental measurements are then processed through backcalculation algorithms to estimate properties such as the elastic modulus. This method is particularly useful in cases where direct measurements are difficult, providing a computational means to understand and predict material behavior based on empirical data.

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