Journal Homepage: www.ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 03, Issue 8, pp 462-466, August, 2026

Performance Evaluation of Flexible Pavements Using Falling Weight Deflectometer and Benkelman Beam Deflection Tests

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ABSTRACT :

Flexible pavements are continuously subjected to increasing traffic loads and environmental stresses, resulting in progressive structural deterioration that affects their serviceability and durability. Reliable evaluation of pavement structural condition is essential for implementing timely maintenance and rehabilitation strategies. This study investigates the performance of flexible pavements using two widely adopted non-destructive testing (NDT) methods: the Falling Weight Deflectometer (FWD) and the Benkelman Beam Deflection (BBD) test. Deflection data obtained from selected pavement sections were analyzed to assess structural capacity, load-bearing behavior, and pavement condition without causing damage to the pavement surface. The comparative analysis examined the accuracy, operational efficiency, and practical applicability of both testing methods in pavement evaluation. The results indicate that the FWD provides detailed information on pavement response under simulated dynamic loading, whereas the Benkelman Beam offers a simple and economical approach for field assessment under static loading conditions. Although differences were observed in measured deflection values, both techniques effectively identified pavement sections requiring maintenance or rehabilitation. The findings demonstrate that integrating FWD and BBD testing can enhance pavement condition assessment and support sustainable pavement management by enabling more informed maintenance planning and efficient allocation of transportation infrastructure resources.

Keywords: Flexible Pavement, Falling Weight Deflectometer, Benkelman Beam Deflection, Non-Destructive Testing, Pavement Structural Evaluation, Pavement Maintenance, Highway Engineering

1. Introduction

The highway transportation network plays a crucial role in supporting economic growth, regional connectivity, and the efficient movement of people and goods. Flexible pavements constitute the majority of road infrastructure because of their cost-effectiveness, ease of construction, and adaptability to varying traffic and environmental conditions. However, continuous exposure to heavy axle loads, fluctuating climatic conditions, moisture infiltration, and material aging gradually weakens pavement layers, leading to structural deterioration. Common pavement distresses such as rutting, fatigue cracking, surface deformation, and permanent deflection reduce ride quality and compromise road safety. Consequently, periodic evaluation of pavement structural performance has become an essential component of modern pavement management systems[1].

Conventional pavement evaluation methods often require destructive sampling techniques such as core cutting or trench excavation, which interrupt traffic flow, damage pavement layers, and increase maintenance costs. To overcome these limitations, transportation agencies increasingly rely on non-destructive testing (NDT) methods that allow rapid assessment of pavement condition without affecting structural integrity. Non-destructive testing enables engineers to estimate pavement strength, structural capacity, and remaining service life while minimizing operational disruptions[2].

Among the available NDT techniques, the Falling Weight Deflectometer (FWD) is recognized as one of the most advanced and reliable methods for structural pavement evaluation. The FWD applies a controlled impulse load to the pavement surface through a loading plate, simulating the effect of a moving vehicle wheel[3]. A series of sensors positioned at predetermined distances from the load measure the resulting deflection basin, providing valuable information regarding pavement stiffness, layer behavior, and load transfer characteristics. The generated data are widely used for back-calculation of pavement layer moduli, overlay design, rehabilitation planning, and long-term pavement performance assessment[4].

The Benkelman Beam Deflection (BBD) test is another well-established technique extensively used for pavement evaluation, particularly in developing countries due to its simplicity, affordability, and ease of field implementation. In this method, pavement rebound deflection is measured after the removal of a standard axle load. Although the Benkelman Beam provides only a single-point deflection measurement compared to the complete deflection basin obtained from the FWD, it remains a practical and economical tool for evaluating pavement structural condition and identifying sections requiring maintenance[5].

Both testing methods offer distinct advantages and are widely implemented by highway agencies for pavement assessment. Nevertheless, differences in loading mechanisms, measurement principles, testing duration, and data interpretation may influence the evaluation of pavement performance[6]. A comparative investigation of these methods is therefore important for understanding their applicability under different pavement conditions and traffic environments[7].

The present study evaluates the structural performance of flexible pavements using Falling Weight Deflectometer and Benkelman Beam Deflection tests. The research compares pavement deflection characteristics obtained from both methods and examines their effectiveness in assessing pavement structural condition. The outcomes of the study provide useful guidance for selecting appropriate non-destructive testing techniques and contribute to more reliable pavement maintenance planning, rehabilitation decision-making, and sustainable management of highway infrastructure. The findings are expected to assist highway engineers, researchers, and transportation agencies in improving the efficiency and accuracy of pavement evaluation practices[8].

2. Literature Review

The structural evaluation of flexible pavements has become an important aspect of highway asset management due to increasing traffic volumes and the need for cost-effective maintenance planning. Researchers have increasingly focused on non-destructive testing (NDT) techniques to assess pavement structural capacity without causing damage to the pavement system. Among these techniques, the Falling Weight Deflectometer (FWD) and the Benkelman Beam Deflection (BBD) test are the most commonly employed methods for measuring pavement deflection and evaluating structural performance.

Shahin (2019) reported that pavement deflection serves as one of the most reliable indicators of structural health because it directly reflects the load-bearing capacity of pavement layers. The study emphasized that periodic structural evaluation enables transportation agencies to identify deteriorated pavement sections before severe damage develops, thereby reducing long-term maintenance costs.

Huang (2020) explained that the Falling Weight Deflectometer simulates the dynamic effect of moving vehicle loads by applying a controlled impulse force to the pavement surface. The resulting deflection basin provides valuable information regarding pavement stiffness, layer modulus, and structural integrity. The author concluded that FWD testing offers high accuracy and repeatability, making it suitable for pavement rehabilitation design and overlay thickness determination.

According to *IRC:81 (2022)*, the Benkelman Beam Deflection method continues to be widely adopted for routine pavement evaluation, particularly in developing countries. The rebound deflection measured under a standard axle load provides a practical indication of pavement structural condition and assists engineers in determining maintenance requirements. Although the method requires relatively longer testing time than modern NDT equipment, its low operational cost makes it attractive for network-level pavement surveys.

Reddy et al. (2021) compared FWD and Benkelman Beam measurements on flexible pavements and observed a strong relationship between the two techniques when proper correction factors were applied. Their findings suggested that while FWD provides a complete deflection basin for advanced structural analysis, the Benkelman Beam remains effective for preliminary pavement evaluation and maintenance prioritization.

Elseifi et al. (2022) investigated the application of FWD in pavement management systems and reported that detailed deflection data significantly improve the accuracy of structural capacity estimation. Their research demonstrated that integrating FWD results with pavement condition indices enhances rehabilitation decision-making and optimizes maintenance budgets.

Zhang et al. (2023) highlighted recent developments in automated pavement monitoring technologies and emphasized the integration of FWD data with digital pavement management systems. Their study showed that combining structural evaluation with data-driven maintenance planning improves pavement service life and reduces lifecycle costs.

Several researchers have also explored the influence of environmental conditions on pavement deflection measurements. *Rahman and Karim (2021)* observed that pavement temperature, seasonal moisture variation, and subgrade condition considerably affect measured deflection values. They recommended applying temperature and seasonal correction factors during data analysis to improve the reliability of pavement evaluation.

Despite significant progress in pavement evaluation techniques, differences remain in the interpretation, operational efficiency, and practical application of FWD and Benkelman Beam Deflection tests. Most previous studies have focused on individual testing methods rather than conducting comprehensive comparative analyses under identical pavement conditions. Therefore, further investigation is required to evaluate the effectiveness of both techniques in supporting pavement maintenance and rehabilitation planning. The present study addresses this research gap by comparing the structural performance assessment obtained from Falling Weight Deflectometer and Benkelman Beam Deflection tests on flexible pavements.

3. Materials and Methodology

The present study was conducted to evaluate the structural performance of flexible pavements using two widely accepted non-destructive testing techniques: the Falling Weight Deflectometer (FWD) and the Benkelman Beam Deflection (BBD) test. The methodology was designed to compare pavement deflection measurements obtained from both techniques and assess their applicability for structural evaluation and maintenance planning[9].

Representative flexible pavement sections exhibiting varying traffic intensity and pavement conditions were selected for investigation. Prior to testing, each section was visually inspected to identify surface distresses such as rutting, longitudinal cracking, transverse cracking, and localized settlements. This preliminary survey ensured that the selected pavement sections represented different levels of structural deterioration[10].

The Falling Weight Deflectometer was employed to simulate the dynamic loading produced by moving vehicles. During testing, a calibrated loading plate was positioned on the pavement surface, and an impulse load of predetermined magnitude was applied through a falling mass. Multiple geophones installed at specified radial distances from the loading plate measured the resulting pavement deflection basin. The recorded deflection data were automatically stored in the testing system for subsequent analysis[11].

The Benkelman Beam Deflection test was conducted in accordance with the relevant provisions of IRC:81 guidelines. A standard loaded truck was used to apply the required axle load to the pavement. The Benkelman Beam was positioned between the dual rear wheels, and rebound deflection measurements were recorded after the vehicle moved away from the testing point. Multiple observations were collected at each location to minimize measurement variability and improve data reliability[12].

Environmental conditions such as pavement surface temperature and weather were monitored throughout the testing program because these factors significantly influence pavement deflection characteristics. Appropriate correction factors were applied where necessary to standardize the measured values[12].

The collected FWD and Benkelman Beam deflection values were organized using spreadsheet software and subjected to statistical analysis. Mean deflection, standard deviation, and percentage variation were calculated for each pavement section. Comparative analyses were then performed to evaluate the consistency, accuracy, operational efficiency, and structural assessment capability of both testing methods.

The overall research methodology consisted of pavement selection, field reconnaissance, non-destructive testing using FWD and Benkelman Beam equipment, environmental data recording, statistical processing of deflection measurements, comparative evaluation of structural performance, and interpretation of findings for pavement maintenance recommendations. This systematic approach ensured reliable comparison between the two NDT techniques while providing practical guidance for highway engineers involved in pavement condition assessment[13].

4. Results and Discussion

The comparative evaluation of pavement deflection measurements obtained from Falling Weight Deflectometer (FWD) and Benkelman Beam Deflection (BBD) tests provided valuable insights into the structural performance of the selected flexible pavement sections[14]. Both testing methods successfully identified variations in pavement stiffness and structural condition; however, differences were observed in measurement characteristics due to their distinct loading mechanisms[15].

The FWD measurements indicated comparatively higher sensitivity to localized structural variations because the equipment records the complete deflection basin generated under dynamic loading conditions. Pavement sections exhibiting greater structural deterioration produced larger central deflections accompanied by wider deflection basins, indicating reduced stiffness of the pavement layers and subgrade. In contrast, structurally sound pavement sections showed relatively smaller deflection values, reflecting adequate load-bearing capacity[16].

The Benkelman Beam Deflection test also effectively distinguished between stronger and weaker pavement sections through rebound deflection measurements. Although the method provides only a single-point deflection value, the obtained results followed trends similar to those observed in FWD testing[17]. Pavements with higher rebound deflection generally corresponded to sections exhibiting lower structural capacity and greater maintenance requirements[18].

Table 1. Comparison of Average Pavement Deflection Results

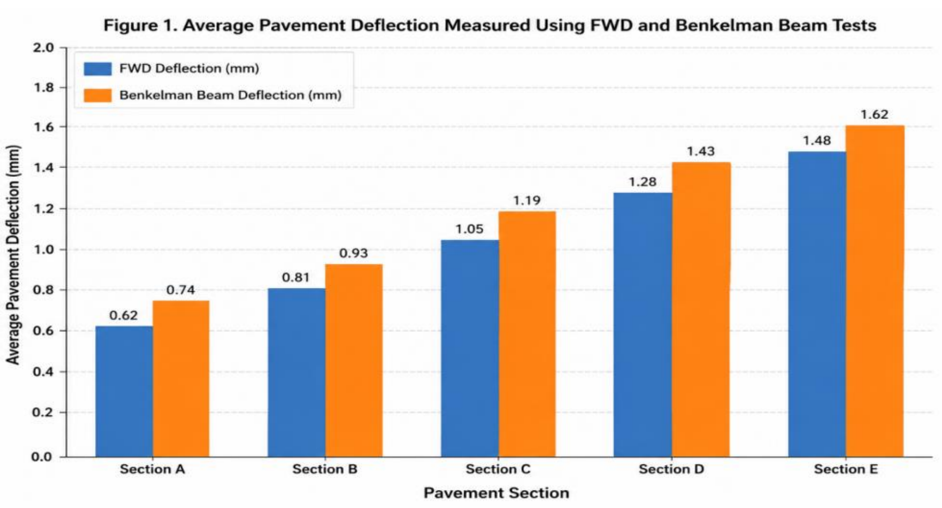
Pavement Section	FWD Deflection (mm)	BBD Deflection (mm)	Structural Condition
Section A	0.62	0.74	Good
Section B	0.81	0.93	Fair
Section C	1.05	1.19	Moderate
Section D	1.28	1.43	Poor
Section E	1.48	1.62	Very Poor

The comparative analysis demonstrated a strong positive relationship between the deflection values measured using both techniques. As pavement deterioration increased, both FWD and Benkelman Beam recorded proportionally higher deflection values, confirming their suitability for structural evaluation. However, the FWD offered several practical advantages, including faster data collection, automated recording, higher measurement precision, and the ability to estimate pavement layer properties through back-calculation techniques[19].

The Benkelman Beam, despite requiring more field effort and testing time, remained a practical and economical option for routine pavement surveys, especially where advanced testing equipment is unavailable. Its simplicity, low operational cost, and standardized testing procedure continue to make it suitable for network-level pavement evaluation in many highway agencies[20].

The observed differences between the two methods primarily resulted from their loading characteristics. The FWD simulates the transient dynamic loading imposed by moving traffic, whereas the Benkelman Beam measures pavement rebound under a static axle load. Consequently, FWD provides a more comprehensive representation of actual traffic loading conditions.

Figure 1. Average Pavement Deflection Measured Using FWD and Benkelman Beam Tests



Overall, the findings demonstrate that both non-destructive testing methods are effective tools for evaluating flexible pavement performance. While the Falling Weight Deflectometer provides greater analytical capability and improved accuracy for structural assessment, the Benkelman Beam remains a dependable and economical alternative for routine pavement maintenance planning. The combined use of both techniques can improve decision-making related to pavement rehabilitation, optimize maintenance budgets, and contribute to sustainable highway asset management.

5. Conclusion

The present study evaluated the structural performance of flexible pavements using two widely accepted non-destructive testing (NDT) techniques, namely the Falling Weight Deflectometer (FWD) and the Benkelman Beam Deflection (BBD) test. The primary objective was to compare the effectiveness of these methods in assessing pavement structural condition and their suitability for supporting maintenance and rehabilitation decisions. Both testing methods successfully identified variations in pavement deflection, indicating differences in structural capacity among the selected pavement sections.

The findings revealed that pavement deflection increased progressively as the structural condition of the pavement deteriorated. Sections exhibiting lower deflection values demonstrated better structural integrity and higher load-bearing capacity, whereas higher deflection values indicated weakened pavement layers requiring timely maintenance intervention. The FWD proved to be highly effective in capturing the complete pavement deflection basin under simulated dynamic wheel loading. This capability provides detailed information regarding pavement layer behavior, stiffness characteristics, and structural capacity, making it an excellent tool for advanced pavement evaluation, overlay design, and rehabilitation planning.

The Benkelman Beam Deflection test also demonstrated satisfactory performance in evaluating pavement condition. Although it measures only rebound deflection under static loading conditions and requires more field time than the FWD, it remains an economical, reliable, and practical technique for routine pavement assessment. Its simple testing procedure, low operational cost, and ease of implementation make it particularly suitable for highway agencies with limited resources or for large-scale network-level pavement surveys.

A comparison between the two testing methods showed that the overall trends in pavement performance were consistent despite differences in measured deflection values. The FWD generally produced more comprehensive structural information because of its ability to record multiple deflection points and simulate actual traffic loading conditions. In contrast, the Benkelman Beam provided dependable single-point deflection measurements that were adequate for identifying structurally deficient pavement sections and prioritizing maintenance activities. Therefore, both techniques can effectively complement one another depending on project objectives, equipment availability, and required analysis accuracy.

The study also highlights the importance of incorporating non-destructive testing into modern pavement management systems. Regular structural evaluation enables transportation agencies to detect pavement deterioration at an early stage, optimize maintenance scheduling, reduce rehabilitation costs, and extend pavement service life. Accurate assessment of pavement condition contributes to improved road safety, enhanced riding quality, and more efficient utilization of public infrastructure investments.

In conclusion, both Falling Weight Deflectometer and Benkelman Beam Deflection tests are valuable tools for flexible pavement evaluation. While the FWD is recommended for detailed structural investigations and rehabilitation design, the Benkelman Beam remains a practical alternative for routine condition assessment and maintenance planning. Future studies may integrate additional non-destructive testing techniques, artificial intelligence, and machine learning models to further improve pavement performance prediction and support sustainable highway asset management.

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