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Prediction of remaining service life for flexible pavement in the Southern Central States using FWD parameters

Abstract

Various Departments of Transportation (DOTs) in the South-Central States and abroad have extensively used Non-Destructive Testing (NDT) surface deflection bowl data. The primary purpose of using deflection-based NDTs in network-level assessment is to identify a section of pavement in need of further investigation at the project level. The falling weight deflectometer (FWD) test is a common NDT-based test that is used by transportation agencies to assess the performance of flexible pavement.This research concentrates on simulating the deflection produced by FWD devices using 3-D Move software. Simulations based on software will decrease the need for lengthy FWD testing in the field. In the study, ninety-seven (97) pavement sections from Arkansas, Louisiana, New Mexico, Oklahoma, and Texas are used for simulation, analysis, and verification of FWD testing. The deflection values produced from software simulations were found to be strongly correlated with field test findings. In addition, the simulated deflection values were used to develop and validate various deflection bowl parameters. In this study, the normalized comprehensive deflection ratio and the normalized comprehensive area ratio are two key characteristics that were validated and produced. Eventually, load-induced impacts using these parameters are effectively analyzed in order to anticipate the remaining service life of flexible pavement structures. The prediction of the remaining service life will be an efficient tool for different DOTs and transportation agencies to initiate the rehabilitation work in time and economically.

Keywords: FWD, deflection basin, deflection parameters, pavement simulation, remaining service life

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Introduction

In the United States, asphalt pavement is the most often used material for highway construction. Most of transportation agencies are primarily concerned with the performance of pavement structures. The functionality of a pavement structure decreases as its age and traffic load increase. Multiple non-destructive methods (NDT) are utilized to assess the routine performance of pavement structures. The Falling Weight Deflectometer (FWD) test is one of the most widely utilized nondestructive testing (NDT) procedures in the United States and worldwide. Being simple and based on real field conditions, the FWD test is one of the most recommended tests to assess the structure of pavements.[1] In the United States, FWD testing has a long history, and it is not uncommon to find vast amounts of data stored in the country's premier database, the Long-Term Pavement Performance (LTPP) database. Using FWD data, a number of studies on the performance monitoring of pavement structures have been done.[2] However, in the majority of transportation agencies, FWD data are typically examined via back-calculations, which are complex and time-consuming. In this research, the thickness and modulus of different LTPP sections in Arkansas, Louisiana, New Mexico, Oklahoma, and Texas are investigated. In addition, the software program 3D-Move Analysis is used to mimic the FWD test deflection. Simulation is necessary to reduce the number of FWD field tests conducted on pavement sections and to analyze pavement structural problems. In addition, simulated deflection bowls are used to develop deflection basin-based parameters in order to decrease the number of field-based testing and cumbersome data analysis procedures. Finally, the remaining service life is predicted using the developed parameters.

Background

A number of nondestructive testing (NDT) methods are used to monitor the performance of all flexible pavement structures. The fundamental benefit of nondestructive testing is that it does not change the structure of the pavement, unlike field cores. La Croix deflect graph, Benkelman Beam, falling weight deflectometer (FWD), Dynaflect, the Road rater system, and the dynamic deflection device are some of the most well-known NDT analyses used in pavement engineering.[3] FWD is considered to be the oldest and most common form of NDT-related testing performed across the globe. The primary idea of FWD testing is applying load to a pavement surface and observing localized deflection. Similarly, the load applied at different drop heights causes geophone sensors installed at certain offsets from the load plate to capture deflection data. The figure below depicts the location of the loading plate and sensor offset in a FWD device.[4]

Notably, in the United States, the FWD test has been one of the most essential monitoring tools for pavement performance. Despite decades of use, FWD measurements need time-consuming back-calculation techniques in order to predict the elastic modulus of pavement layers. Numerous researchers are developing deflection bowl-based criteria to offer transportation agencies with a simpler system.

Using the Benkelman beam test, Haas et al.,[5] created the structural adequacy index (SAI). The index was built with a single, error-sensitive deflection value. In contrast, Haas et al.,[5] offered a 1 to 10-point scale for SAI in a separate study.[6] The characteristics of the pavement and the number of predicted equivalent single axle loads (ESALs) were used to calculate the maximum tolerable deflection (MTD). The system's weakness was that its scale was not fixed, necessitating adjustments whenever it was used to different transportation agencies.

Zhang et al.,[7] focused on developing a structural condition index for the rehabilitation and maintenance of pavement structures at the network level. Structural strength index (StSI) was designed to assess how pavement conditions deteriorated due to the structural deformation of layers and subgrades.

Several falling weight deflectometer data have been collected and stored in the database of the Texas Department of Transportation's Pavement Information Management System (PMIS). As structural estimators, the modulus and structural numbers of the pavement were used, and the assessment was based on the estimators' sensitivity to pavement structure deterioration parameters.

The index was calibrated for use in network maintenance and restoration research. Consequently, it was concluded that the developed index StSI was incapable of representing the performance of the pavement in relation to the accumulated distress. Additionally, the index was calculated using a single deflection measurement[18] inches from the loading plate.

Scullion[8] contributed a new structural strength index to the pavement evaluation system in Texas (PES). Using this method, the Present Serviceability Index (PSI) and visual distresses were the key factors in determining the pavement's condition. Utilizing deflection bowl parameters and a mechanistic approach in the calculation procedure makes this index a more viable way for evaluating the remaining service life of pavement sections at the project level. Under a 9000-pound load level, it was determined that the structural strength index may be utilized to assess network-level pavement structure.

Similarly, Kavussi et al.,[9] were also interested in developing a new method for determining repair and maintenance operations at the network level of pavement management using FWD.[9] The maintenance and repair processes were developed with FWD data. Two regression models were developed utilizing FWD deflection data in order to compute the effective structural number (SNeff) and resilient modulus (Mr) of the subgrades. Using deflection data, a significant relationship was discovered between surface deflection of 60cm from the load plate (D60), SNeff, and Mr. In addition, a network-level pavement management system (PMS) may perform the determination of suitable maintenance and repair technologies utilizing SNeff and Mr derived from the research.

Smith et al.,[10] conducted a research that employed FWD data in the mechanistic and empirical design and analysis of pavement structures. This study examines the rehabilitation procedures for flexible pavement structures utilizing FWD data, as well as the pre-existing systems applied by different transportation agencies. The back-calculation procedure for flexible and composite pavement systems is also reviewed. The study was determined to be equally important for researchers and agencies involved in the rehabilitation and management of pavement structures.[10]

Elbagalati et al.,[11] conducted a study to develop a prediction model for pavement structural capacity at 0.16 km (0.1 mi) intervals using Rolling Wheel Deflectometer (RWD) measurements. In early research investigations, functional parameters like as ride quality and surface distress were used to evaluate pavement conditions. The structural condition index (SCI) of a section of pavement is then calculated by dividing SNeff by the required structural number (SNreq). When sensitivity analysis was done using TXDOT PMS data, it was shown that SCI is very sensitive to pavement deterioration. According to the SCI value, it is evident that fewer sections are in good condition than the expected section, which had asphalt stripping and material deterioration issues. A value of 0.80 for the coefficient of determination (R2) indicated acceptable accuracy. However, the model required recalibration before it could be utilized by other agencies. The research also compared RWD and FWD deflection measurements and found that the mean center deflection differed between the two tests.

Furthermore, Saleh et al.,[12,13] developed more advanced metrics for assessing pavement structural capabilities. Their research examined at the development of the deflection ratio (Dr), normalized deflection ratio (Dr'), area ratios (Ar), and normalized area ratio (Ar') in the deflection bowl across 900mm offsets. Souliman et al.,[2] used broader deflection bowls with 1524 mm offsets to calculate area-based deflection parameters for the state of Texas. Simulated deflection bowls were used to determine the area-based parameters. Significant correlations between deflection and the newly formed area ratio parameter illustrate the metric's dependability. The normalized comprehensive area ratio (CAr') produced from this study is shown in Equation 1.

$$CAr' = \left(\frac{1}{D0 * D0}\right) * \left\{203 * \left(\frac{D0 + D2D3}{2}\right) + 102 * \left(\frac{D2D3 + D3D5}{2}\right) + 152 * \left(\frac{D3D5 + D4D5D7}{2}\right) + 153 * \left(\frac{D457 + D610}{2}\right) + 304 * \left(\left(\frac{D610 + D914}{2}\right)\right) + 610 * \left(\frac{D914 + D1524}{2}\right)\right\} \Big/ 1524 \quad (1)$$

where D_0, D_{203}, D_{305}, D_{457}, D_{610}, D_{914}, and D_{1524} are deflections measured at the center of the plate, 203, 305, 457, 610, 914, and 1524 mm from the center of the load plate, respectively.

In accordance with the research, a number of advanced investigations assessing the structural capabilities of pavements were also conducted. Using area ratio parameters to assess the remaining service life of pavement structures and evaluating pavement sections based on distress conditions were two of the project's most important findings.[14–16] However, the study was limited to pavement sections in Texas, necessitating a larger verification. In this research, complete deflection bowls are used to simplify and validate the various deflection basin parameters. Eventually, a connection is established between the developed parameters and tensile strain, and the remaining service life of the flexible pavement is estimated. For pavement engineers and agencies to establish plans and proposals for repair and maintenance, the estimation of remaining service life might be vital Figure 1.

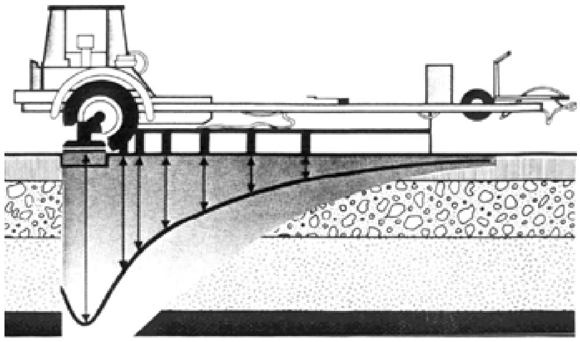

Figure 1 FWD device and sensors.

Description of collected data

This study uses various LTPP sections in five South-Central states to evaluate the proposed Comprehensive Area Ratio parameter developed under project[17] PUTA02 for effective use by various transportation engineers and officials in the early estimation of appropriate pavement rehabilitation and maintenance strategies. Figure 2 depicts the South-Central States and the pavement sections studied for this study.

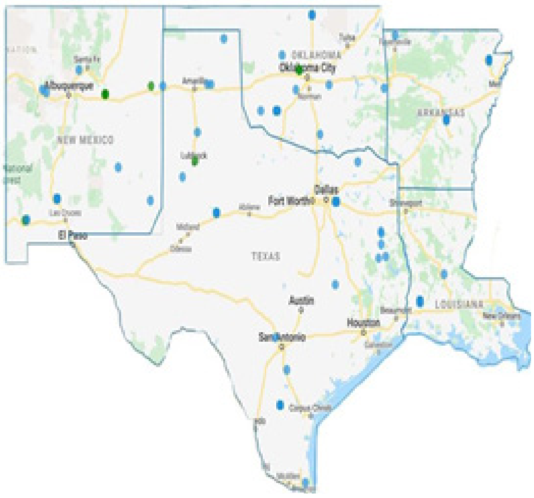

Figure 2 Pavement sections considered in this study in south-central states**.**

Eleven (11) sections from Arkansas, eleven (11) sections from Louisiana, eighteen (18) sections from New Mexico, twenty-two (22) sections from Oklahoma, and thirty-five (35) sections from Texas were analyzed, for a total of ninety-seven (97) sections.. The chosen sections reflect the defined states and their availability of FWD and fatigue cracking at the same time. Utilization was made of the active sections (green) and the non-study sections (blue).The major objective of using both types of sections is to create a state-inclusive classification chart from the pavement section's massive database. Out-of-study sections also provide useful historical data to evaluate pavement conditions at certain timeframes. In addition, the utilized data are associated with pavement deflection through FWD testing conducted over a range of time; hence, both section types can be useful for achieving the study's primary objective. Similarly, as noted previously, the key database for this work is LTPP; hence, it was used to get the layer modulus and layer thickness. The HMA elastic modulus was determined using ANNACAP software.. An estimate was developed to match the age of pavement sections during FWD testing. The characteristics of the base, sub-base, and sub-grade layers were calculated using soil classification data, as indicated in the section on material properties. Various layers were present in the pavement sections used for the study. Others had additional layers, including asphalt layer, treated base, untreated base, treated subbase, untreated subbase, and subgrade.

Field measured FWD deflection bowls computer simulation

FWD tests are performed using a large amount of resources and time; consequently, there is always a need for capturing the behavior of flexible pavement structures without the need to conduct a substantial number of FWD tests, specifically at the network level. Numerous software applications have become useful for estimating the performance of pavement structures and replicating FWD tests. In this research, the 3D- Move Analysis software package is investigated for its ability to efficiently simulate deflection bowls subject to FWD plate loadings. In the analysis of flexible pavements, One of the most often used software programs is 3D-Move Analysis. The next subsections will go through the software tool and how it can be utilized to replicate field-measured deflection bowls.

Simulation of deflection bowls using 3D-Move Analysis Software Packages

One of the most well-known software programs for flexible pavement structure analysis is the 3D Move Software package. The 3D- Move Analysis software package has various benefits, including the capability to manage complex surface loads and non-uniform tire pressures (2). The uses of the 3D-Move software package are not limited to a small number of these functionalities. Furthermore, the 3D-Move software delivers numerous outputs, including strain, stress, and displacement at each given position in the pavement layers. Nonetheless, the major goal of this study is to create and mimic FWD deflection bowls using displacement data. Table 1 displays the deflection of a section of pavement at different sensor locations in Arkansas, Louisiana, New Mexico, Oklahoma, and Texas.

Table 1 Example of deflection output in 3d-move

Sensor Offsets mm	Deflection output through 3D Move (micrometers)				
	AK 0113	LA 0113	NM 0103	OK 0115	TX M310
0	117.34	177.7	318.26	396.11	277.21
203	96.08	143.36	222.69	286.99	181.71
305	82.72	118.54	171.28	235.59	100.25
457	65.62	87.36	114.77	176.37	77.6
610	51.52	63.97	76.18	129.57	59.77
914	31.68	35.9	35.95	68.58	29.44
1524	12.19	14	12.53	20.22	21.31

Comparison between the 3D-Move simulation and the actual FWD test deflection

As previously indicated, the LTPP database records several FWD test results as deflection bowls. Using the simulation capabilities of the 3D-Move software package, a comparable deflection bowl was produced. A comparison chart between the LTPP deflection bowls and the software-simulated bowl is shown. It has been noticed that equivalent software findings have been achieved for deflection. Despite the fact that certain sections exhibit deflection variation, it is evaluable based on temperature and other required modifications.[17] Figure 4 illustrates a comparison between the observed FWD deflection bowl and the FWD simulated using the 3D-Move Analysis software package.

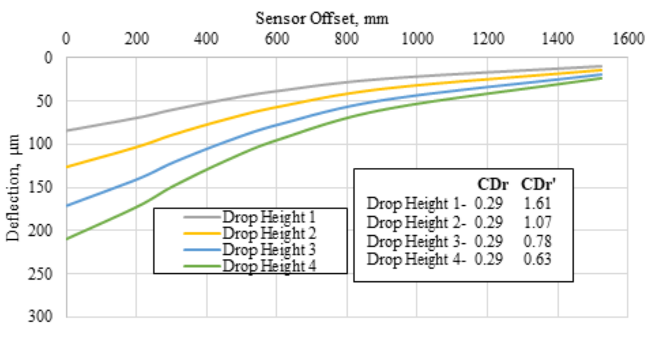

Figure 3 An illustration of the importance of CDr and CDr' based on AK SHRP 0115.

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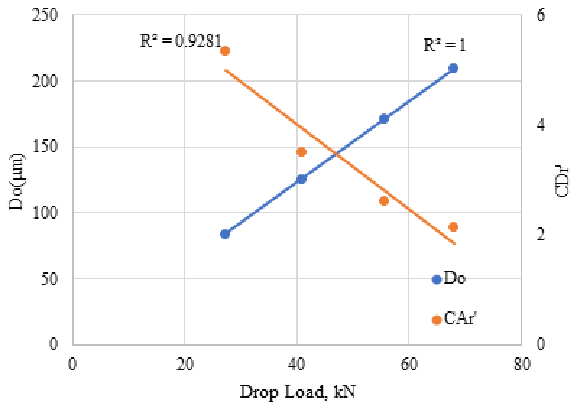

Figure 4 Sensitivity between D_0, CDr' and drop load for AK SHRP section 0115.

The presented results indicate that 3D-Move may be used for FWD-based deflection prediction on a range of pavement structures. Pavement engineers interested in detecting deflection-induced impacts may employ 3D-Move, since virtual replications of pavement and actual FWD testing provided equivalent results.

Comparison of simulated and actualdeflection bowls

Surface deflection values have a key role in determining the structural integrity of pavements, as is widely acknowledged. At various offsets, FWD test deflection values are obtained, which can be used for the early evaluation of flexible pavement structures' conditions. In addition, the deflection value in the center of the load plate is more significant in determining the condition of the pavement This is due to the fact that load plate deflection is highest in the plate's center and decreases as it moves outward. The deflection under the load plates is stated as the central deflection and defined as D0, which corresponds to the actual corresponding deflection (D0) measured during the FWD testing. Figure 5 shows the simulated and actual D0 values for each state (Arkansas, Louisiana, New Mexico, Oklahoma, and Texas). The 3D-Move calculated deflection bowls are compared to the real FWD test, as shown in Figure 6.

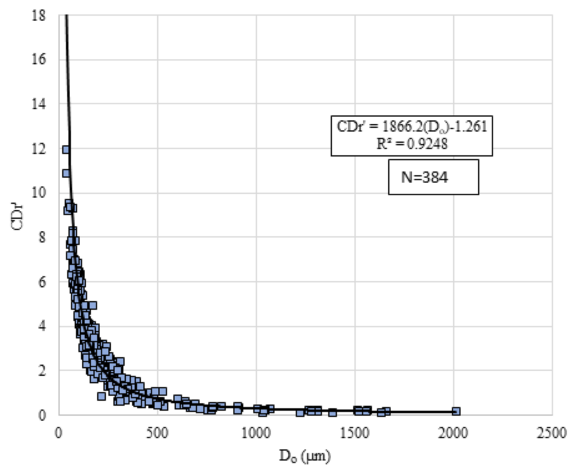

Figure 5 Relationship between normalized comprehensive deflection ratio (CDr') and central deflection (D_0) comprehensive area ratio (CAr).

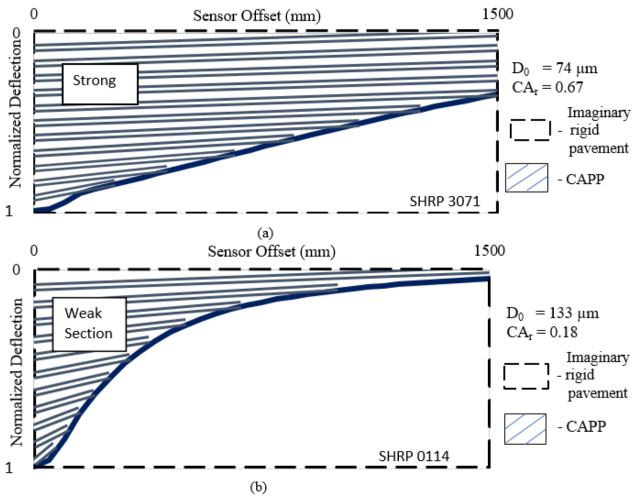

Figure 6 Normalized area of deflection profiles for SHRP sections: (a) 3071 and (b) 0114 normalized comprehensive area ratio (CAr').

The deflection received by 3D-Move Analysis was discovered to be strongly associated with the deflection obtained from the field FWD test. Comparing D0 produced a larger coefficient of determination (R2) than comparing the whole deflection bowls. These enhanced levels of accuracy indicate the reliability of the 3D-Move software for forecasting and simulating the deflection and modeling of deflection bowls.

Simplified deflection parameters

Simulated deflection data is used to provide simplified parameters for assessing a section of pavement. The comprehensive area ratio (CAr) and normalized comprehensive area ratio are key parameters obtained in this study using simulated deflection values.

Comprehensive deflection ratio (CDr) and normalized comprehensive deflection ratio (CDr')

Numerous transportation agencies have commonly employed the deflection ratio (Dr) since it is a straightforward tool that considers the deflection at 250 mm, as shown in equation 2.

$$Dr = D_{250}/D_0 \quad (2)$$

where D_{250} is the deflection at 250 mm offset and D_0 is the central deflection.

However, such a parameter does not covers the full deflection bowl and yields the same results as the center deflection. To solve this problem, the Comprehensive deflection ratio (CDr) metric was developed. The parameter is obtained from the deflection of 600mm and takes into consideration the influence of the base and subbase layers.

$$CDr = D_{600}/D_0 \quad (3)$$

where D_{600} is the deflection at 600mm offset.

Several sections were investigated using the newly developed CDr and Dr. Dr was found to be almost constant for sections with varied central deflection. However, the degree of fatigue cracking differs across pavement sections. Except for CDr, the values were different, indicating that CDr may be used for any of the sections with a lower deflection value.At each of the four drop heights and drop weights, CDr was calculated for each of the South-Central States (27 kN, 40kN, 53kN, and 70kN). For Arkansas section 0115, 3D-Move simulated deflection bowls are plotted. (Figure 3). The slope of the deflection bowl was found to fluctuate with drop load, moving farther away from the center of the load plate, although the predicted CDr remained constant.

Nonetheless, varying drop loads must have various CDr values. The Normalized Comprehensive Deflection Ratio (CDr') was used to assess the impact of load variation. Normalized deflection ratios for the same section were plotted, and it was discovered that normalizing the center deflection ratio caused a progressive change. CDr' demonstrated a substantial association with the central deflection, as shown in Figure 4. (D0). SHRP Section 0115 of Arkansas displays the interpretation based on different target loads in Figure 4. The figures show a significant relationship between Drop loads, Central Deflection, and Normalized Comprehensive Deflection Ratio (CDr'). As a result, CDr' is a revised deflection-based metric for assessing the structural state of any pavement section.

Comprehensive area ratio (CAr)

In this approach, the area under the deflection bowl is partitioned into a number of subdivisions, with the area of each subdivision represented in Equation 4. In this research, as indicated in Equation 4, the trapezoidal region under the deflection bowl is investigated. It is referred to as the Comprehensive Area under Pavement Profile (CAPP).

$$CAPP = \left(\frac{1}{D0}\right) * \{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D914+D1524}{2}\right)\} \quad (4)$$

Similarly, the lowest magnitude of deflections observed at various sensor offsets for a strong pavement section would vary from the deflection reported in the center of the plate. For a section of strong pavement, the deflection is constant over its entire length (i.e., D0 = D203 = D305 =... = D1524). Comprehensive Area under Pavement Profile (CAPP) of a hypothetical pavement section deflection bowl is represented by Equation 5.

$$CAPP = \left(\frac{1}{D0}\right) * \left\{203*\left(\frac{D0+D0}{2}\right) + 102*\left(\frac{D0+D0}{2}\right) + 152*\left(\frac{D0+D0}{2}\right) + 153*\left(\frac{D0+D0}{2}\right) + 304*\left(\frac{D0+D0}{2}\right) + 610*\left(\frac{D0+D0}{2}\right)\right\} = 1524 \text{ mm}^2/\text{mm}. \quad (5)$$

where D0, D203, D305, D457, D610, D914, and D1524 are the deflections measured at the plate's center, 203, 305, 457, 610, 914, and 1524 mm from the center of the load plate, respectively.

Therefore, a comprehensive area ratio (CAr) is determined by dividing the CAPP of the pavement section by the CAPP of the hypothetical pavement. The CAr formula is represented by Equation 6 in a simplified version. A strong section will have a greater area than a weak section, and CAr will be stronger. A weak section may have a CAr value of 0.1, whereas a strong section has a CAr value of 1.0.

$$CAr = \left(\frac{\left(\frac{1}{D0}\right) * \left\{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D917+D1524}{2}\right)\right\}}{1524}\right) \quad (6)$$

As shown in Figure 6, two SHRP pavement sections (0114 and 3071) in the state of Arkansas were compared. It was observed that the area of imaginary rigid pavement covered by SHRP section 0114 was less than that covered by SHRP section 0115; consequently, CAr values of 0.18 and 0.67 were determined for sections 0114 and 3071, respectively.

The area ratio parameter provided a more accurate way for assessing the structural integrity of pavement, considering the fact that it did not account for the different target loads. As a result, a combination of the area ratio and central deflection is offered to illustrate the effect of varied target loads. The parameter was normalized by dividing the area ratio parameter by the central deflection value. It was determined that (Equation 7) is an appropriate method for assessing the structural capabilities of flexible pavements.

$$CAr = \left(\left(\frac{\left(\frac{1}{D0+D0}\right) * \left\{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D917+D1524}{2}\right)\right\}}{1524}\right)\right) \quad (7)$$

The area ratio was unable to account for load changes. Various target load values were found to be insufficient for identifying the structural qualities of pavement sections. Figure 7 depicts the observed deflection bowl for section 0113 in Arkansas. Despite variations in deflection, a consistent CAr was identified regardless of the load levels. According to the statistics, the structural performance of the pavement was insufficient.

Central Deflection has historically been the first parameter considered when monitoring any FWD reaction. In addition, an improved relationship between CAr' and Do is needed. The relationship between CAr' and D0 is depicted using a plot. There is a direct relationship between CAr' and Do, showing that CAr' may be used to assess the structural integrity of pavement sections. The comprehensive area ratio (CAr) parameter does not account for the fluctuation in loading levels, despite the fact that the central deflection was modified. Normalizing area ratio parameter by dividing CAr by D0 was effective with the change in loading level, and CAr' for varied loading levels can be shown on the same graph (Figure 8).

Similarly, the difference between CAr' and D0 is plotted to determine the relationship under four target load levels. In addition, the structure of pavement sections remains the same in all cases, despite the fact that a difference was noticed across all target loads. The interpretation of SHRP Section 0115 of Arkansas is depicted in Figure 9 depending on various target loads. All three factors loads, Central Deflection, and Comprehensive Area Ratio—exhibit a positive correlation in the plots. In addition, the obtained relationships demonstrate that CAr' can be used at any drop load to evaluate pavement performance. The load can be associated with the need of the users, which set forth the newly developed concept in generalizing the other load cases.

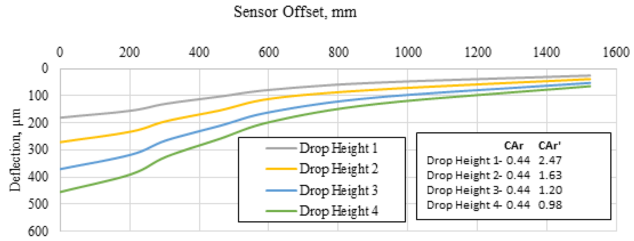

Figure 7 Relationship between comprehensive area ratio CAr' and central deflection D_0.

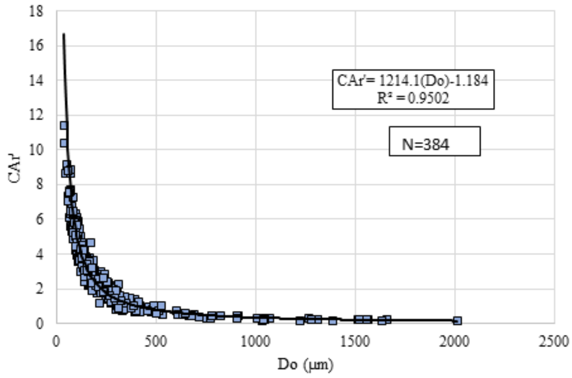

Figure 8 Relationship between CAr' and D_0.

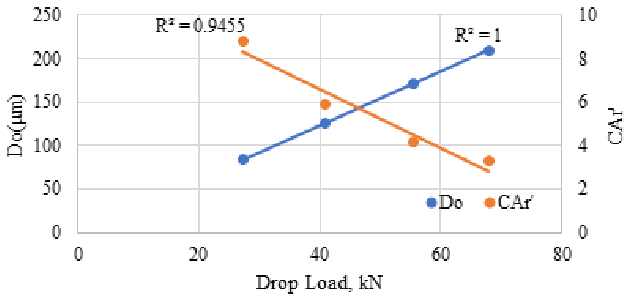

Figure 9 Sensitivity between D_0, CAr' and drop load for AK SHRP 0115.

Similar to CDr', it was observed that the normalized comprehensive area ratio parameter (CAr') was sensitive to the change in target load. In addition, CAr' and CDr' were compared and found to be closely connected (Figures 10 & 11), indicating that CDr' can represent the comprehensive area ratio parameter. Consequently, CDr' and CAr' can be considered as overall parameters for evaluating the structural condition of pavement sections.

Tensile strain based on drop load

Different deflection-related analyses and the development of deflection parameters were performed in the previous section. The drop loads were also highly sensitive to the deflection parameters. Furthermore, the drop load from the FWD can also lead to the formation of tensile strain at the bottom of the HMA layer, which can be utilized to predict the life of pavement structures. Hence, the 3D-Move software package is used to predict the tensile strain at the bottom of the HMA layer. 11 shows the comparison of two sections (0106 and 1003) and tensile strain developed for different drop loads.

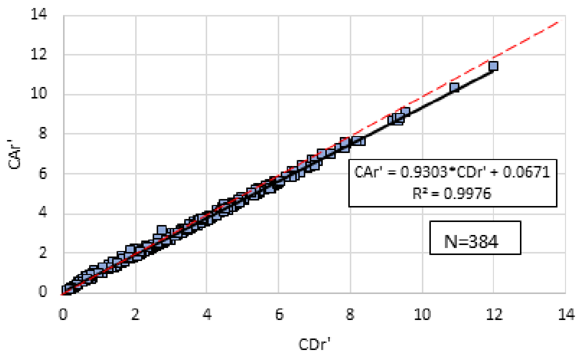

Figure 10 Relationship between normalized comprehensive deflection ratio (CDr') and normalized comprehensive area ratio (CAr').

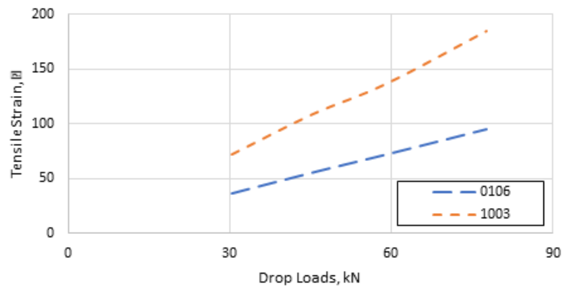

Figure 11 Strain comparison for two different sections based on drop loads.

It is observed that the section, which has a greater tensile strain, corresponds to a category of weak pavement. On the other hand, the section with less developed tensile strain is considered to have greater performance and is classified as a strong pavement. The stiffness of asphalt and base layers is related to the tensile strain developed at the base of the HMA layer. Therefore, the newly produced parameters (CAr' and CDr') and developed strain could be used effectively to assess the structural state of the pavement sections (Figure 12).

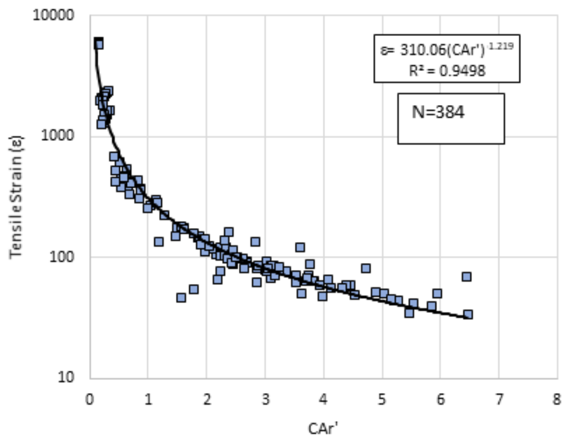

Figure 12 Relationship between tensile strain at the bottom of the HMA and normalized comprehensive area ratio (CAr').

Relationship between tensile strain and parameters developed for the comprehensive deflection ratio

In asphalt pavement structures, the developed tensile strain at the base of the HMA layer correlates strongly with fatigue cracking from the bottom up. For the purpose of assessing the relation between tensile strain and developed parameters, all sections of the

South-Central States were examined. In addition, all four intended loads were used to develop the relationship. A greater coefficient of determination was discovered for the association between CAr,' and CDr' and the developed tensile strain. The results demonstrate a significant relationship between the developed parameter and the tensile strain at the base of the HMA layer. Figures 13 & 14 depict the relationship between these parameters.

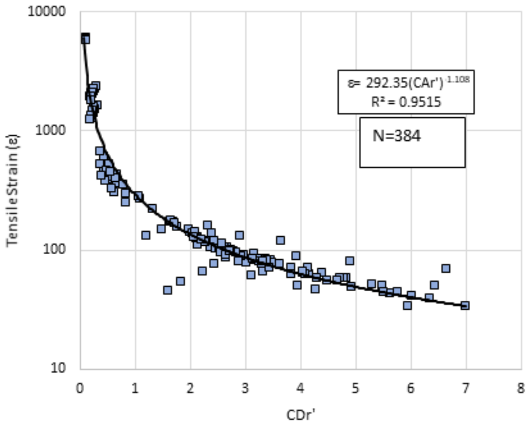

Figure 13 Relationship between tensile strain at the bottom of the HMA and normalized comprehensive deflection ratio (CDr').

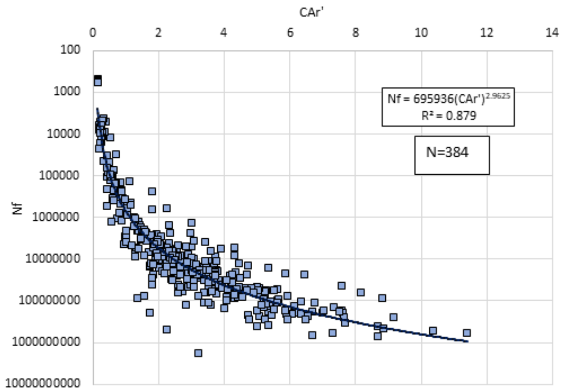

Figure 14 Relationship between Nf and normalized comprehensive area ratio (CAr').

Prediction of remaining service life based on fatigue failure

In the previous section, it was observed that there is a strong link between the tensile strain at the base of the HMA layer and the parameters developed for the comprehensive deflection ratio. The remaining service life of flexible pavement structures may be anticipated using the tensile strain derived from the empirical pavement design fatigue model, which uses the strain and stiffness of the asphalt layer as shown in equation 10.[18] Observations reveal that the number of cycles to failure and tensile strain are inversely related; hence, a greater strain results in fewer load cycles before failure. Load cycles to failure may be used to predict how a pavement will perform under repeated traffic loads.

$$N_f = 0.0795*(1/\varepsilon)^{3.291} * (1/E)^{0.854} \quad (8)$$

Where Nf is the number of load repetitions to failure

ε is the tensile strain developed at the bottom of HMA

E is the modulus of the asphalt layer

Equation 8 can be used to calculate Nf for each of the sections under examination, and the number of cycles to failure has a high relation with CAr' and CDr.' A strong correlation is detected between the developed CAr' and CDr' parameters and the remaining fatigue life of the examined asphalt pavement structures, as shown in Figures 14 & 15.

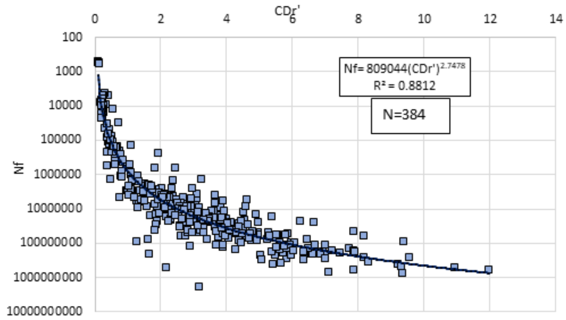

Figure 15 Relationship between Nf and normalized comprehensive deflection ratio (CDr').

As a result, a significant relationship is developed that may accurately forecast the long fatigue service life of a pavement section. The anticipated relationship will be an important tool for assessing pavement conditions for transportation agencies. The newly developed deflection bowl parameters (CAr' and CDr'), which may account for the whole deflection bowl, are more reliable than the previously used parameter based on specific deflection spots.

Conclusions and recommendations

Utilizing FWD tests to evaluate pavement conditions has been a common practice for decades. Frequently, FWD surface deflection bowl data is used to determine the structural condition of flexible pavement sections. Nevertheless, there are only a few straightforward methods for identifying pavement sections using FWD data. In the majority of studies, a single deflection point is used to evaluate pavement conditions, resulting in a limited analysis. Therefore, in this study, 97 LTPP pavement sections and their respective simulated surface deflection bowl data are used to find a simplified deflection-based method. In addition, simulated deflection values are utilized to develop deflection-based parameters.

This study developed and validated the normalized deflection ratio (CDr') and the normalized area ratio (CAr') using 97 pavement sections from the South-Central States. Importantly, these newly developed parameters are the function of the entire deflection bowl (up to 1500mm offsets). Similarly, a tensile strain developed at the base of the HMA layer correlates strongly with normalized deflection ratio (CDr') and normalized comprehensive area ratio (CAr'). The following equations illustrate the relationship between tensile strain and CDr' and CAr'.

$\varepsilon = 292.35* (CDr')^{-1.108}$ $R^2 = 0.9515$

$\varepsilon = 310.06 * (CAr')^{-1.219}$ $R^2 = 0.9498$

Furthermore, the remaining service life of flexible pavement (N_f) was calculated based on the MEPDG *(18)* fatigue failure model. The following equation presents a well-related relationship between N_f, CDr' and CAr' for the entire studied South-Central States.

$N_f = 695936 * CAr'^{(2.9625)}$ $R^2 = 0.879$

$Nf = 809044 * CDr'^{(2.7478)}$ $R^2 = 0.8812$

Therefore, the derived parameter may be a useful tool for determining the remaining service life of flexible pavement for transportation agencies. Based on the suggested process, the most appropriate technique for pavement maintenance and rehabilitation may be simply chosen. The proposed area ratio parameter is a useful tool for network-level analysis of flexible pavement structures using FWD data. The parameter is designed to take use of the voluminous FWD surface deflection bowl data collected by different DOTs and is processed as received. Temperature corrections and corrections for the hard rock effect may improve the correlation between various components. Use of these corrections is strongly suggested for future research.

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Conflicts of interest

There are no conflicts of interest.

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