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UNDERSTANDING IN-SITU PAVEMENT RESPONSES: A COMPARATIVE STUDY OF STATIC AND DYNAMIC ANALYSIS FOR AN INSTRUMENTED PAVEMENT SECTION

Matea Ceric[1], Pejoohan Tavassoti[1], Hassan Baaj[1], Omran Maadani [2]
[1]University of Waterloo, Department of Civil and Environmental Engineering, Waterloo, Ontario, Canada
[2]National Research Council of Canada, Ottawa, Ontario, Canada

Abstract

This paper presents a comprehensive investigation of early-stage pavement deterioration, focusing on comparing the KENPAVE and 3D-Move software tools for predicting pavement response in the Canadian context. To validate the accuracy of these tools, an instrumented test section was implemented on a major roadway in Kitchener, Ontario, with various sensors capturing real-life data. During construction, both KENPAVE and 3D-Move showed discrepancies with field data, resulting in underestimates of stress. However, after a five-month period, accuracy improved for both tools due to stable pavement properties at lower temperatures. 3D-Move provided better estimates of pavement stress deterioration in non-construction scenarios than KENPAVE. The study's findings enhance understanding and application of KENPAVE and 3D-Move in Canadian pavement engineering projects and provide valuable insights for future improvements in predictive capabilities, particularly regarding construction conditions, ultimately aiding pavement maintenance strategies in Canada.

Keywords: KENPAVE, 3D-Move, pavement performance prediction

1 Introduction

Pavement performance prediction is essential for effective maintenance and rehabilitation planning but has traditionally relied on empirical and statistical models. Recently, Artificial Intelligence techniques have improved the accuracy and efficiency of pavement performance analysis in infrastructure management [1]. A recent project in Canada aimed at enabling autonomous monitoring and data collection from instrumented pavement sections to support training Artificial Intelligence models, improve the interpretation of pavement responses, and, ultimately, enable future pavement performance predictions [2, 3]. In addition, the ability to investigate the initial stages of deterioration across the various layers of a pavement structure, as well as the reasons behind it, is valuable for implementing maintenance and rehabilitation methods at the right time. This deterioration is caused by a combination of traffic loads (both static and dynamic) and environmental impacts [4]. Several software tools for predicting pavement response under different loading conditions have been developed. KENPAVE and 3D-Move are examples of such tools that can be used to analyze pavement responses, such as stress, strain, and deflection under a given loading configuration. KENPAVE typically considers static loads [5], whereas 3D-Move, developed at the University of Nevada, Reno, can simulate both static and dynamic pavement structures, accounting for intricate user-defined tire-pavement interactions and vehicle speeds [6].

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Although pavement analysis tools can provide valuable insights into pavement responses under various loading conditions, it is essential to analytically validate calculated responses against in-situ measurements. Literature in the Canadian context examining comparisons between software tools and real-life data, particularly regarding tire loads at different speeds and temperatures is limited. Such investigations are vital for validating and understanding the software's accuracy and reliability in modelling pavement damage under local conditions. To this end, the KENPAVE and 3D-Move software packages were used to compare theoretical with real-life pavement strain and stress responses obtained from an instrumented pavement section in Canada.

2 Instrumented pavement section description

An instrumented flexible pavement test section is installed on a segment of a major arterial roadway in Kitchener, Ontario, enabling dynamic measurement of stress, strain, temperature, and moisture variations at multiple points within the pavement structure. Figure 1 shows the schematics of the instrumented section. The total pavement thickness was 745 mm, including 195 mm of hot-mix asphalt. The sensor array included 8 horizontal asphalt strain gauges (ASG), 4 vertical ASGs, 7 temperature probes, 5 moisture probes, and 8 Total Earth Pressure Cells (TEPC).

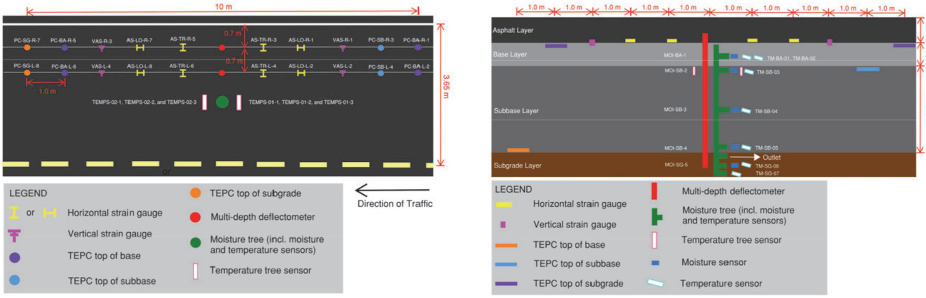


Figure 1 Instrumented section - Top View (left) and Side View (right)

3 Methodology

A combination of numerical analysis and experimental approaches was used in this study to bridge the understanding of the benefits of dynamic pavement response analysis and to improve the understanding of pavement responses under different loading conditions.

3.1 Truck testing

Since its construction in October 2022 and opening to live traffic, the instrumented section has been continuously collecting load and traffic data. Furthermore, several isolated truck tests were performed in which a controlled 14-wheeler truck was driven over the section at different speeds and pavement temperatures. The first set of truck tests (TT#1) was conducted immediately post-construction, when the asphalt concrete mat was cooling, while the second truck testing (TT#2) was performed 5 months after the pavement was opened to traffic in March 2023. TT #1 was performed at three temperatures of 74, 51, and 43°C. At each of these temperatures, a truck with a gross load of 140 kN passed over the section at different speeds of 10, 30, and 45 km/h. On the other hand, TT#2 was performed at a single temperature of 6°C, but at eight different speeds of 5, 10, 20, 30, 40, 50, 60, and 70km/h.

The truck used for TT#2 had a gross load of 348 kN, including a lift axle of 62 kN and Tandem Axles with 106 kN (each). Additional truck tests are scheduled for the future to better understand seasonal variations in pavement responses under controlled loading configurations.

3.2 Input parameters in KENPAVE and 3D-move

Both the immediately post-construction and 5 months after truck testing scenarios were modelled in KENPAVE and 3D-Move using a 4-layer pavement structure. First, the inputs for KENPAVE are shown in table 1. The vertical coordinates (Z-coord.) selected for analysis included the bottom of the AC layer, the top and bottom of the base layer, the top and bottom of the subbase layer, and the top of the subgrade layer, corresponding to the sensor locations. A contact radius of 1.36 cm and a contact pressure of 166.6 kPa were used throughout the analysis. The wheel spacing was set to 0 and 50 cm along the x- and y-axes, respectively.

Table 1 KENPAVE input parameters

Parameter	Post-construction	5 months after
Zcoord [cm]	19.5, 19.503, 34.5, 34.503, 74.5, 74.503	19.5, 19.503, 34.5, 34.503, 74.5, 74.503
Layer	HMA, base, subbase	HMA, base, subbase
Layer thicknesses [cm]	19.5, 15, 40	19.5, 15, 40
Modulus [7]	(Layer No., E in kPa)	(Layer No., E in kPa)
	(1, 3.511E+06), (2, 2.260E+05), (3, 1.450E+05), (4, 7.200E+04)	(1, 3.511E+06), (2, 2.260E+05), (3, 1.450E+05), (4, 7.200E+04)

During the post-construction truck test, individual weights for the lift axle and tandem axles were unavailable, so an average load of 166.6 kPa was calculated for each tire based on a single axle, dual tire "lift" axle on an unloaded truck weighing 140 kN with 14 tires and a tire-pavement interface area of 0.06 m^2 [7]. In the TT#2 scenario, individual weights for various axles were considered, so both the lift axle and one tandem axle (both single-axle dual-tire) were modelled in KENPAVE. The loaded truck weighed 348 kN, with a lift axle load of 62 kN and a tandem axle load of 106 kN. This resulted in 255.4 kPa pressure for the lift axle and 438.25 kPa for the tandem axle, with 14 tires and the same pavement interface area of 0.06 m^2 as in the construction scenario.

In addition to the standard temperature modulus values in table 1, dynamic modulus master curve, based on 30 values from at 6 loading frequencies and 5 testing temperatures were entered in the software. The reference and analysis temperatures were then changed according to the scenario of interest to ensure that the right modulus values are utilized in any given scenario. Table 2 presents some of the required input information for the 3D-Move software. The materials properties. The vehicle suspension was selected as DLC [8] with airbag [9] from the software Database. The critical responses were calculated at the Y-coordinate of 0.138 cm and at different Z-coordinates (0.195, 0.1951, 0.345, 0.3451, 0.745, 0.7451 m).

Table 2 3D-Move input parameters

Parameter	Post-construction	5 Months after
Speed	45 km/h	40 km/h
Tire pressure	166.6 kPa	255.4 kPa
Tire load	10 kN	15.32 kN
Breaking friction coefficient [11]	0.83	0.86
Master curve information (dynamic modulus test inputs)	Unit Weight = 2390 kg/m³ (23.44 kN/ m³), Analysis Temp = 51°C, Reference Temp = 21°C Asphalt Binder = Input Level 2, PG58-28	Unit Weight = 2390 kg/m3 (23.44 kN/ m³), Analysis Temp = 6°C, Reference Temp = 21°C, Asphalt Binder = Input Level 2, PG58-28
Base layer properties	A-1-a, E = 226000 kPa, Poisson's ratio = 0.35, Unit Weight = 15 kN/m³	A-1-a, E = 226000 kPa, Poisson's Ratio = 0.35, Unit Weight = 15 kN/m³
Subbase layer properties	A-1-b, E = 145000 kPa, Poisson's ratio = 0.35, Unit Weight = 15 kN/m³	A-1-b, E = 145000 kPa, Poisson's Ratio = 0.35, Unit Weight = 15 kN/m³
Subgrade layer properties	CH, E = 72000 kPa, Poisson's ratio = 0.325, Unit Weight = 14 kN/m³	CH, E = 72000 kPa, Poisson's Ratio = 0.325, Unit Weight = 14 kN/m³

Using 3D-Move, all nine combinations of asphalt surface layer and truck testing speeds immediately post-construction were modelled. This paper focuses on one of the comparison scenarios, in which the asphalt temperature is 51 °C, and the vehicle speed is 45 km/h. Similarly, this section will discuss one of the eight scenarios conducted during the five-month testing period (i.e., at 40 km/h). A uniform contact pressure model was employed with different magnitudes for TT#1 and TT#2 modelling.

4 Results and discussion

Using the previously presented loading information, material properties, and axle configurations, results from both KENPAVE and 3D-Move software were utilized to compare: 1) tensile strains measured by asphalt strain gauges in the field section with minor principal strain results in KENPAVE and normal strain in the Z-Z direction at the bottom of the asphalt layer in 3D-Move, and 2) the stress measured by TEPCs in the base, subbase, and subgrade layers to vertical stress results in KENPAVE and normal stress in the Z-Z direction within each of the base, subbase, and subgrade layers in 3D-Move. Given the static nature of the analysis in KENPAVE, numerical output values were compared with the maximum values from field dynamic stress and strain curves. On the other hand, 3D-Move can generate dynamic response curves; hence, the results can be directly compared with the measured dynamic responses from field experiments.

4.1 TT #1: Immediately post-construction

Comparing the simulation and measured results, it can be recognized that KENPAVE's pressure and strain results underestimate the in-situ results at the presumed 166.6 kPa contact pressure. Such a discrepancy can be attributed to several factors, including the non-uniform temperature gradient of the newly compacted asphalt concrete layer (immediately post-construction), changes in the tire-pavement interaction and footprint at elevated temperatures while the mat was cooling down from the compaction temperature, and the inherent adjustment of instrumentation right after installation in the pavement structure.

To hypothetically match field conditions, the input load was raised to 900 kPa, focusing on simulating one of the critical pavement response points, the vertical stress/pressure on the subgrade surface as much as possible, considering KENPAVE measures static response. Table 3 presents compressive stress/pressure and tensile strain results for both the software and field results during construction with the 900 kPa pressure input.

Table 3 Peak Compressive Stress and Strain Results during Construction

Metric	KENPAVE	Field
Compressive stress/pressure top of base [kPa]	1.746	9.57
Compressive stress/pressure top of subbase [kPa]	0.811	12.56
Compressive stress/pressure top of subgrade [kPa]	0.357	0.358
Tensile strain bottom of surface layer [με]	-3.427	384.3

For 3D-Move, figure 2 illustrates the field construction data alongside the software output. The plot on the left shows the strain in the transverse direction on the right wheel path at 51 °C with a truck speed of 45 km/h. The plot on the right shows the normal strain response in the Z-Z direction from 3D-Move.

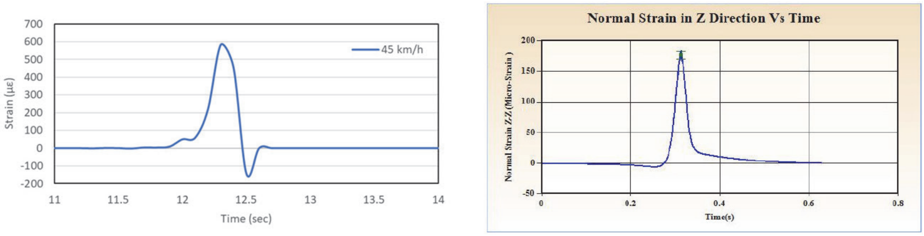


Figure 2 Normal tensile strain at the bottom of the asphalt layer at 51°C and 45km/h from the field results (left) and the 3D-Move software (right)

Comparing the results from KENPAVE and 3DMove reveals that both software tools exhibit discrepancies relative to field data. Regarding KENPAVE, while the compressive stress on the top of the subgrade was set to match the field data, other metrics, such as compressive stress and pressure in the base and subbase, as well as tensile strain at the bottom of the surface layer, are significantly underestimated in the software as compared to the field. On the other hand, for 3D-Move, the peak shapes in the results are similar to those in the field data, but their magnitudes differ notably. The software's outputs underestimate the magnitude of the tensile strain produced. For instance, the tensile strain at the bottom of the asphalt layer in the field was approximately 584 με, whereas 3Dmove showed a value of about 170 με. These discrepancies are reasonable, given that strain impacts during construction are typically more variable and harder to predict than those at cooler temperatures, which are relatively easier for the program to simulate.

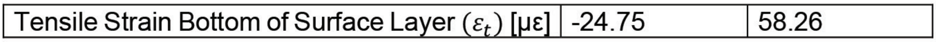
4.2 TT #2: after 5 months in-service testing

During the TT#2 scenario, KENPAVE's load-impact results still underestimated field conditions. To align with the field data, the load was incrementally increased until it matched the software's output. Since both the lift and tandem axles showed similar pavement impacts during testing, their impact loads were comparable.

For clarity, table 4 only presents the results for the lift axle with a contact pressure of 6500 kPa. For 3D-Move, the comparison of tensile strain results is shown in figure 3.

Table 4 Peak Compressive Stress/Pressure and Strain Results 5 Months After

Metric	KENPAVE	Field
Pressure Top of Base Layer [kPa]	12.61	13.93
Pressure Top of Subbase Layer [kPa]	5.86	15.45
Pressure Top of Subgrade Layer [kPa]	2.58	2.54
Tensile Strain Bottom of Surface Layer [με]	-24.75	58.26



Tensile Strain Bottom of Surface Layer (ε_t) [με]	-24.75	58.26

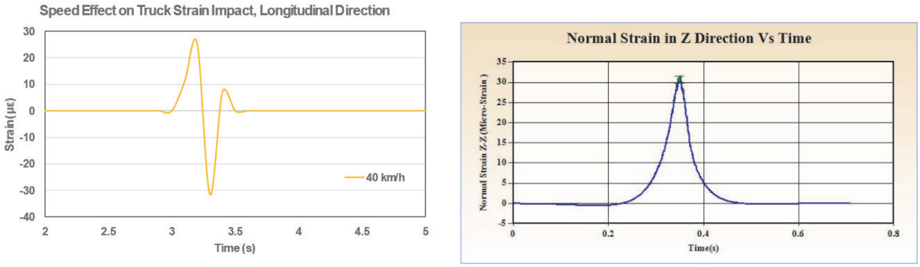


Figure 3 Normal tensile strain at the bottom of the asphalt layer at 6°C and 40km/h from the field results (left) and the 3D-Move software (right)

Both KENPAVE and 3D-Move now yield results that better simulate the field conditions of TT#2. Specifically, the aligned KENPAVE results show greater similarity to the field results after 5 months in service than during construction. This improvement is attributed to more consistent viscoelastic properties resulting from stabilized, lower temperatures, which can affect KENPAVE results, even when comparing static and dynamic results. Similarly, both the field results and those generated by 3D-Move exhibit curves of similar shape and magnitude. While the field data indicated a magnitude of 25.3 με, the software displayed a magnitude of approximately 32 με. This small discrepancy suggests that 3D-Move has a greater capacity to precisely estimate pavement stress deterioration when the field conditions resemble non-construction conditions.

5 Conclusion

This study focuses on the ability of static and dynamic pavement analysis approaches to understand pavement responses by comparing simulation results with in-situ measurements from an instrumented pavement section. KENPAVE and 3D-Move software packages were employed for this purpose. The first set of truck tests (TT#1) provided unique insight into pavement responses immediately after construction. In terms of analysis, considerable discrepancies were observed between the software results and field data. Both tools showed improved accuracy after five months in the second set of truck tests (TT#2), possibly due to more stable, uniform viscoelastic properties and tire-pavement interactions closer to conventional assumptions. However, 3D-Move demonstrated greater precision in estimating pavement stress when field conditions more closely resembled in-service conditions.

This approach can also generate dynamic pavement response curves that can be directly compared with those obtained in the field using truck testing. Further research and validation efforts should continue to improve the predictive capabilities of these software tools to benefit pavement engineering practices, especially under construction conditions.

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