ANALYSIS OF ASPHALT PAVEMENT MATERIALS AND SYSTEMS

EMERGING METHODS

PROCEEDINGS OF THE SYMPOSIUM
ON THE MECHANICS OF FLEXIBLE PAVEMENTS

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Preface

This special publication includes 13 papers on characterization, modeling and simulation of asphalt concrete and subgrade, addressing some timely issues in mechanics of flexible pavements. They include four papers on modeling and simulations of asphalt concrete by incorporating the microscopic structures of the material, the interactions between aggregates, mastics and voids, and the use of Finite Element Method (FEM) and Discrete Element Method (DEM); two papers on the continuum approaches including nonlinear viscoelastic analysis and temperature dependency; two papers on laboratory characterization of asphalt concrete; three papers on the characterization of subgrade soil resilient modulus, incorporation of nonlinear soil behavior into pavement analysis, and the evaluation of the effect of using geogrid; and one paper on pavement evaluation.

Each paper published in this GSP was evaluated by peer reviewers and the editors. The review comments were sent to the authors and they have been addressed to the reviewers and the editors' satisfaction. The ASCE Geo-Institute Pavements Committee and the reviewers are sincerely acknowledged for their time and efforts.

The papers in this GSP include eight papers that were presented in the symposium on Mechanics of Flexible Pavements at the 15th U.S. National Congress of Theoretical and Applied Mechanics, held at Boulder, Colorado, June 25-30 2006 and five papers submitted for publication only. The symposium was supported by the Geo-Institute Pavements Committee, the Inelastic Committee and the Granular Materials Committee of the ASCE Mechanics Division.

The editors of this GSP would like to thank the Board of Governors of the Geo Institute for their approving the symposium and the special publication.

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EFFECT OF THE RELATIVE ROOT-MEAN-SQUARE ERROR ON PAVEMENT RESPONSE

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ABSTRACT: Analysis of flexible pavements using the multilayered elastic theory involves the use of elastic moduli backcalculated from deflection basins measured utilizing the Falling Weight Deflectometer (FWD). Uncertainties associated with the thickness of the elastic layers, seed moduli, and the backcalculation algorithms have been studied to increase the reliability and accuracy of the backcalculated deflection basin by minimizing the relative root-mean-square error (RMSE). Therefore, the RMSE of the backcalculated deflection basin has been used always to assess the validity of the backcalculated set of elastic moduli of the pavement. In this study, the sensitivity of the pavement response to the RMSE is investigated by comparing the response of a pavement section using the exact set of moduli with that using the backcalculated set of pavement moduli with a RMSE less than 1%. The results showed that even when the RMSE in deflections is as low as 0.22%, the pavement response (strain, stress, and therefore fatigue and rutting predictions) using the backcalculated set of moduli can largely be different than that using the exact set of moduli, suggesting more uncertainties to the backcalculated set of moduli.

INTRODUCTION

Elastic modulus is an important property of pavement materials. Different methods have been proposed by researchers to estimate the elastic modulus based on laboratory bending tests and empirical equations (Bonnaure et *al.*, 1997), wave propagation methods (Cho and Lin, 2001), and the Falling Weight Deflectometer (FWD).

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The elastic modulus in pavements cannot be determined accurately based on empirical equations since actual field conditions, loading conditions, and traffic conditions vary. In addition, some of the input parameters in the empirical equations cannot be determined for an existing pavement. Therefore, for practical purposes, elastic moduli need to be determined using in-situ methods to include the effect of different field factors.

The FWD test is currently the most widely used nondestructive method in pavement engineering. The test involves applying impact loads (impulse forces) to a loading plate and measuring the vertical displacement of the pavement surface at different locations using velocity sensors. The FWD system normally uses seven to nine geophones within a distance less than 2 meters with the first sensor below the center of the loading plate. The measured deflections from the FWD test along the pavement surface are then utilized to backcalculate the modulus of elasticity in each layer. This method, however, suffers from different limitations since backcalculating the modulus of elasticity does not always ensure an accurate estimate of the modulus where a seed modulus is required for each layer in the backcalculation procedure. Therefore, the backcalculation of the elastic moduli does not provide a unique solution and in many cases is user-dependent. It is common to assess the accuracy of the backcalculated elasticity moduli by assessing the accuracy between the measured deflection from FWD and the calculated deflection using the backcalculated set of elastic modului.

In this study we investigate the current practice of rejecting and accepting the backcalculated elasticity moduli based on a tolerance value between the measured and calculated deflections.

ERROR TOLERANCE IN BACKCALCULATION PROCEDURE

Backcalculation of elasticity moduli is commonly carried out by assuming a set of pavement-layer moduli (seed moduli) that can produce a deflection basin similar to the measured one from the FWD test. In order to minimize the error between the measured and calculated deflections, the relative root-mean-square error (RMSE) is used to control the convergence of the backcalculated deflections and to assess the acceptance and rejection of the final set of pavement moduli. The RMSE is computed by:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{d_i - D_i}{D_i}\right)^2} \times 100\% \qquad (1)$$

where, $RMSE$ is the relative root-mean-square error, n is the total number of the deflection measurement points, d_i is the backcalculated deflection at point i, and D_i is the measured deflection at point i. When the RMSE value decreases, the accuracy of the backcalculated elasticity moduli is assumed to increase as the error between the measured and calculated deflections decreases.

In the LTPP test sections, a RMSE of 3% was used as an acceptable error (Von Quintus and Simpson, 2002). In addition, Von Quintus and Simpson (2002) showed that selection of a 2% RMSE does not necessarily result in convergence in the backcalculated elasticity moduli in all cases. In general, their results indicated (Von Quintus and Simpson, 2002) that RMSE values less than 3% have little effect on the average backcalculated elastic moduli. In practice, RMSE values larger than 1% can be achieved quickly (Harichandran et *al.* 2000). Therefore, the most commonly used value for the RMSE is between 1% and 3%. However, it is believed that achieving lower RMSE will always enhance the backcalculated elastic moduli and therefore more accurate results can be obtained.

BACKCALCULATION STUDY

The majority of the available research investigates the difference between the RMSE values from different backcalculation programs (Fwa et *al.* 1997), the effect of other factors on the quality of the deflection data (Mehta and Roque 2003), the effect of the seed generation on the RMSE values (Fwa and Rani 2005), and the effect of other factors on the FWD data. To the best of the authors' knowledge, however, the effect of the backcalculated elastic moduli and the associated RMSE on the strain and stress responses of flexible pavements has not been discussed so far.

In this paper, to study the effect of the RMSE on the strains and stresses in flexible pavements, a three-layer pavement section was selected. The flexible pavement section and the backcalculated elastic moduli were reported by Anderson (1988) and were shown in **Tables 1** and **2**. Responses at a total of 11 points (as shown in **Table 4**) were calculated for each case: responses along the ground surface at common locations of the velocity sensors used in the FWD test along the pavement profile (points 1 through 7), at the middle of the AC layer (point 8), at the bottom of the AC layer (point 9), at the middle of the base layer (point 10), and at the top of the subgrade (point 11). For all cases, responses were calculated for a circular load with a radius of 150 mm and a pressure of 690 kPa. The Poisson's ratio for all layers was equal to 0.35.

The pavement response was calculated using the ***MultiSmart3D*** program. The ***MultiSmart3D*** program is a fast and accurate software tool developed by the Computer Modeling and Simulation Group at the University of Akron, and it is based on the innovative computational and mathematical techniques for multilayered elastic systems (Pan 1989a,b; Pan 1990; Pan 1997). The program is capable of analyzing any pavement system regardless of the number of layers, the thickness of each layer, the number of response points, and the shape of the applied pressure at the surface of the pavement.

The RMSE for each case was calculated using **Eq. 1** and shown in **Table 3**. In addition, **Table 3** shows the relative errors using the exact and backcalculated elastic moduli. The relative error is defined as:

$$RE = \left|\frac{Exact - Calculated}{Exact}\right| x100\% \qquad (2)$$

This definition of the relative error is also used to compare the calculated strains and stresses based on the exact and backcalculated models. In other words, *Calculated* is the response using the backcalculated elastic moduli, and *Exact* is the response using the exact elastic moduli.

Pavement responses from the exact and backcalculated elastic moduli (Cases 1 through 5) are shown in **Tables 5** through **10**. In addition, **Tables 5** through **10** show the relative error associated with each response.

TABLE 1. Parameters of the Original (Exact) Layers

Case (1)	AC Thickness (mm) (2)	Base Thickness (mm) (3)	Exact Modulus (MPa)		
			AC (4)	Base (5)	Subgrade (6)
Case 1	381.0	152.4	3447.3785	13789.5140	68.9476
Case 2	381.0	152.4			
Case 3	381.0	152.4			
Case 4	381.0	152.4			
Case 5	381.0	152.4			

TABLE 2. Parameters of the Backcalculated Layers

Case (1)	Backcalculated Modulus (MPa)		
	AC (2)	Base (3)	Subgrade (4)
Case 1	3506.1839	13507.0427	69.0096
Case 2	3359.2980	15717.2743	68.6304
Case 3	3656.5723	12088.8670	69.4302
Case 4	3410.8018	13371.5676	68.7063
Case 5	3657.1101	12017.7062	69.6715

TABLE 3. Relative Errors in Moduli and RMSEs in Deflections between the Exact (TABLE 1) and Backcalculated (TABLE 2) Moduli

Case (1)	AC (%) (2)	Base (%) (3)	Subgrade (%) (4)	RMSE (%) (5)
1	1.71	2.05	0.09	0.24
2	2.55	13.98	0.46	0.22
3	6.07	12.33	0.70	0.65
4	1.06	3.03	0.35	0.69
5	6.08	12.85	1.05	0.85

TABLE 4. Coordinates and Locations of the Response Points

Point (1)	x (mm) (2)	y (mm) (3)	Z (mm) (4)	Location (5)
1	0.0	0.0	0.0	AC Surface
2	304.8	0.0	0.0	
3	609.6	0.0	0.0	
4	914.4	0.0	0.0	
5	1219.2	0.0	0.0	
6	1524.0	0.0	0.0	
7	1828.8	0.0	0.0	
8	0.0	0.0	190.5	Middle of AC Layer
9	0.0	0.0	380.9	Bottom of AC Layer
10	0.0	0.0	457.2	Middle of Base Layer
11	0.0	0.0	533.5	Top of Subgrade Layer

TABLE 5. Exact Responses from the Original (Exact) Pavement Profile

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-57.77	-57.7	-62.49	-677.95	-677.95	-690.00	0.21
2	-7.00	-27.08	18.35	-64.75	-116.02	0.00	0.17
3	-8.44	-18.22	14.35	-58.21	-83.17	0.00	0.16
4	-3.32	-14.08	9.37	-32.39	-59.87	0.00	0.15
5	-0.04	-10.94	5.91	-15.20	-43.02	0.00	0.13
6	1.74	-8.56	3.67	-4.93	-31.24	0.00	0.12
7	2.70	-6.76	2.18	1.32	-22.83	0.00	0.11
8	22.57	22.57	-88.36	-71.10	-71.10	-354.37	0.19
9	1.60	1.59	-21.33	-49.96	-49.97	-108.51	0.18
10	10.32	10.32	-12.91	197.33	197.33	-39.95	0.18
11	21.43	21.43	-85.56	-1.45	-1.45	-6.91	0.18

TABLE 6. Response (Top Row) and Relative Error (Bottom Row in Parenthesis) Using Case 1 Backcalculated Layer Model

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-57.10 (1.173)	-57.10 (1.173)	-61.13 (2.179)	-679.52 (0.232)	-679.52 (0.232)	-690.00 (0.000)	0.21 (0.465)
2	-7.04 (0.592)	-26.87 (0.788)	18.26 (0.505)	-65.72 (1.501)	-117.21 (1.021)	0.00 (0.000)	0.17 (0.223)
3	-8.34 (1.233)	-18.07 (0.777)	14.22 (0.922)	-58.59 (0.651)	-83.88 (0.851)	0.00 (0.000)	0.16 (0.197)
4	-3.27 (1.408)	-13.96 (0.854)	9.28 (0.960)	-32.59 (0.610)	-60.34 (0.794)	0.00 (0.000)	0.15 (0.186)
5	-0.04 (7.515)	-10.84 (0.876)	5.86 (0.901)	-15.32 (0.742)	-43.37 (0.806)	0.00 (0.000)	0.13 (0.171)
6	1.72 (1.039)	-8.49 (0.875)	3.64 (0.833)	-4.99 (1.047)	-31.50 (0.829)	0.00 (0.000)	0.12 (0.158)
7	2.67 (1.054)	-6.70 (0.865)	2.17 (0.739)	1.31 (0.722)	-23.03 (0.858)	0.00 (0.000)	0.11 (0.146)
8	22.16 (1.823)	22.16 (1.823)	-86.76 (1.808)	-71.03 (0.099)	-71.03 (0.099)	-353.91 (0.129)	0.19 (0.317)
9	**1.91** **(19.686)**	**1.91** **(19.686)**	-21.17 (0.742)	-47.60 (4.722)	-47.60 (4.722)	-107.55 (0.879)	0.18 (0.241)
10	10.51 (1.910)	10.51 (1.910)	-13.14 (1.777)	197.19 (0.074)	197.19 (0.074)	-39.50 (1.118)	0.18 (0.255)
11	21.56 (0.611)	21.56 (0.611)	-85.49 (0.089)	-1.42 (1.720)	-1.42 (1.720)	-6.90 (0.248)	0.18 (0.264)

TABLE 7. Response (Top Row) and Relative Error (Bottom Row in Parenthesis) Using Case 2 Backcalculated Layer Model

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-58.31 (0.930)	-58.31 (0.930)	-65.18 (4.306)	-672.90 (0.745)	-672.90 (0.745)	-690.00 (0.000)	0.21 (0.035)
2	-6.75 (3.632)	-27.02 (0.227)	18.18 (0.926)	-62.04 (4.186)	-112.48 (3.051)	0.00 (0.000)	0.17 (0.407)
3	-8.70 (3.091)	-18.23 (0.088)	14.50 (1.039)	-57.74 (0.802)	-81.45 (2.061)	0.00 (0.000)	0.16 (0.307)
4	-3.52 (6.211)	-14.17 (0.660)	9.53 (1.719)	-32.48 (0.265)	-58.97 (1.500)	0.00 (0.000)	0.15 (0.175)
5	**-0.17** **(300.543)**	-11.05 (1.009)	6.04 (2.154)	-15.45 (1.594)	-42.52 (1.180)	0.00 (0.000)	0.13 (0.052)
6	1.66 (4.465)	-8.67 (1.265)	3.77 (2.728)	-5.25 (6.419)	-30.96 (0.894)	0.00 (0.000)	0.12 (0.066)
7	2.66 (1.604)	-6.86 (1.484)	2.26 (3.539)	**0.98** **(25.332)**	-22.69 (0.620)	0.00 (0.000)	0.11 (0.180)
8	23.21 (2.829)	23.21 (2.829)	-91.06 (3.060)	-71.82 (1.021)	-71.82 (1.021)	-356.17 (0.509)	0.19 (0.302)
9	**0.30** **(81.365)**	**0.30** **(81.365)**	-21.15 (0.831)	**-58.94** **(17.970)**	**-58.94** **(17.970)**	-112.31 (3.509)	0.18 (0.468)
10	**9.17** **(11.155)**	**9.17** **(11.155)**	**-11.52** **(10.792)**	199.20 (0.945)	199.20 (0.945)	-41.63 (4.217)	0.18 (0.405)
11	20.15 (5.994)	20.15 (5.994)	-83.18 (2.781)	-1.52 (4.868)	-1.52 (4.868)	-6.77 (2.037)	0.18 (0.350)

TABLE 8. Response (Top Row) and Relative Error (Bottom Row in Parenthesis) Using Case 3 Backcalculated Layer Model

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-55.76 (3.484)	-55.76 (3.484)	-57.53 (7.948)	-685.22 (1.072)	-685.22 (1.072)	-690.00 (0.000)	0.21 (1.228)
2	-7.24 (3.401)	-26.58 (1.870)	18.21 (0.787)	-68.93 (6.460)	-121.30 (4.548)	0.00 (0.000)	0.17 (0.380)
3	-8.02 (5.037)	-17.84 (2.058)	13.92 (3.001)	-59.42 (2.085)	-86.03 (3.444)	0.00 (0.000)	0.16 (0.391)
4	-3.07 (7.473)	-13.71 (2.602)	9.04 (3.532)	-32.78 (1.229)	-61.61 (2.914)	0.00 (0.000)	0.15 (0.457)
5	**-0.05** **(219.214)**	-10.62 (2.883)	5.91/5.69 (3.709)	-15.28 (0.522)	-44.19 (2.703)	0.00 (0.000)	0.13 (0.513)
6	1.75 (0.508)	-8.30 (3.054)	3.53 (3.963)	-4.81 (2.409)	-32.04 (2.539)	0.00 (0.000)	0.12 (0.568)
7	2.66 (1.470)	-6.54 (3.182)	2.09 (4.322)	**1.55** **(17.314)**	-23.38 (2.398)	0.00 (0.000)	0.11 (0.621)
8	21.21 (6.017)	21.21 (6.017)	-82.83 (6.256)	-70.20 (1.260)	-70.20 (1.260)	-352.01 (0.665)	0.19 (0.669)
9	**3.29** **(106.255)**	**3.29** **(106.255)**	-21.23 (0.479)	**-37.34** **(25.253)**	**-37.34** **(25.253)**	-103.77 (4.370)	0.18 (0.394)
10	**11.58** **(12.266)**	**11.58** **(12.266)**	**-14.42** **(11.683)**	195.01 (1.178)	195.01 (1.178)	-37.85 (5.251)	0.18 (0.473)
11	22.58 (5.388)	22.58 (5.388)	-86.86 (1.516)	-1.34 (7.540)	-1.34 (7.540)	-6.97 (0.797)	0.18 (0.533)

TABLE 9. Response (Top Row) and Relative Error (Bottom Row in Parenthesis) Using Case 4 Backcalculated Layer Model

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-58.46 (1.195)	-58.46 (1.195)	-63.09 (0.951)	-678.32 (0.055)	-678.32 (0.055)	-690.00 (0.000)	0.22 (0.860)
2	-7.08 (1.125)	-27.42 (1.238)	18.58 (1.215)	-67.82 (0.116)	-116.20 (0.155)	0.00 (0.000)	0.17 (0.790)
3	-8.48 (0.480)	-18.42 (1.114)	14.48 (0.913)	-58.02 (0.316)	-83.13 (0.046)	0.00 (0.000)	0.16 (0.730)
4	-3.30 (0.460)	-14.22 (0.985)	9.43 (0.709)	-32.18 (0.662)	-59.75 (0.196)	0.00 (0.000)	0.15 (0.671)
5	**0.00** **(100.104)**	-11.03 (0.881)	5.94 (0.495)	-15.01 (1.273)	-42.89 (0.324)	0.00 (0.000)	0.13 (0.614)
6	1.79 (3.007)	-8.63 (0.788)	3.68 (0.221)	-4.77 (3.326)	-31.10 (0.450)	0.00 (0.000)	0.12 (0.557)
7	2.75 (1.993)	-6.80 (0.700)	2.18 (0.161)	1.45 (9.928)	-22.70 (0.577)	0.00 (0.000)	0.11 (0.504)
8	22.84 (1.163)	22.84 (1.163)	-89.29 (1.051)	-70.86 (0.327)	-70.86 (0.327)	-354.14 (0.064)	0.20 (0.841)
9	**1.79** **(12.346)**	**1.79** **(12.346)**	-21.67 (1.604)	-48.76 (2.392)	-48.76 (2.392)	-108.05 (0.417)	0.19 (0.826)
10	10.60 (2.766)	10.60 (2.766)	-13.27 (2.757)	196.66 (0.342)	196.66 (0.342)	-39.78 (0.415)	0.18 (0.816)
11	21.88 (2.097)	21.88 (2.097)	-86.87 (1.524)	-1.45 (0.222)	-1.45 (0.222)	-6.98 (0.968)	0.18 (0.805)

TABLE 10. Response (Top Row) and Relative Error (Bottom Row in Parenthesis) Using Case 5 Backcalculated Layer Model

Point (1)	ε_x (μm/m) (2)	ε_y (μm/m) (3)	ε_z (μm/m) (4)	σ_x (kPa) (5)	σ_y (kPa) (6)	σ_z (kPa) (7)	u_z (mm) (8)
1	-55.77 (3.472)	-55.77 (3.472)	-57.50 (7.988)	-685.30 (1.085)	-685.30 (1.085)	-690.00 (0.000)	0.21 (1.367)
2	-7.23 (3.321)	-26.58 (1.857)	18.21 (0.793)	-68.92 (6.448)	-121.33 (4.570)	0.00 (0.000)	0.17 (0.553)
3	-7.99 (5.284)	-17.83 (2.091)	13.91 (3.102)	-59.33 (1.936)	-85.99 (3.394)	0.00 (0.000)	0.16 (0.588)
4	-3.05 (8.057)	-13.70 (2.679)	9.02 (3.705)	-32.70 (0.946)	-61.55 (2.807)	0.00 (0.000)	0.14 (0.677)
5	**0.07** **(256.180)**	-10.61 (2.996)	5.68 (3.964)	-15.20 (0.007)	-44.12 (2.545)	0.00 (0.000)	0.13 (0.755)
6	1.76 (1.183)	-8.29 (3.202)	3.51 (4.321)	-4.75 (3.761)	-31.97 (2.331)	0.00 (0.000)	0.12 (0.832)
7	2.67 (1.168)	-6.53 (3.363)	2.08 (4.825)	**1.60** **(21.260)**	-23.32 (2.138)	0.00 (0.000)	0.11 (0.906)
8	21.22 (5.981)	21.22 (5.981)	-82.82 (6.270)	-70.10 (1.401)	-70.10 (1.401)	-351.94 (0.685)	0.19 (0.820)
9	**3.35** **(109.897)**	**3.35** **(109.897)**	-21.27 (0.299)	**-36.94** **(26.065)**	**-36.94** **(26.065)**	-103.63 (4.495)	0.18 (0.554)
10	**11.63** **(12.772)**	**11.63** **(12.772)**	**-14.49** **(12.191)**	194.73 (1.320)	194.73 (1.320)	-37.81 (5.352)	0.18 (0.636)
11	22.64 (5.667)	22.64 (5.667)	-86.94 (1.614)	-1.34 (7.575)	-1.34 (7.575)	-7.00 (1.180)	0.18 (0.700)

In **Tables 5** through **10**, values without parentheses are the pavement responses using the backcalculated moduli in **Table 2** (Cases 1 to 5) while values in parentheses are the relative errors compared to responses using the original (exact) pavement profile. Cells that are highlighted with gray show the response with a relative error higher than 2% whilst values in bold show the response with a relative error higher than 10%.

The results in **Tables 3**, and **5** through **9** show that even if the RMSE value is kept less than 1%, the resulting response of strains and stresses can largely differ than the exact response. Cases 1 and 2 (**Tables 6** and **7**, respectively) have relatively the same RMSE in deflection but have different relative errors in strains and stresses. In addition, the magnitude and location of the relative errors vary randomly between Cases 1 and 2. Case 1 showed a relative error of 19.686% in the horizontal strain (ε_x, or ε_y) at the bottom of the AC layer (point 9) while Case 2 showed a higher relative error of 81.365% in the horizontal strain at the same point. On the other hand, at the ground surface (point 5), Case 2 showed a relative error of 300.543% in the horizontal strain which is approximately 40 times the relative error of the horizontal strain at the same point in Case 5 (7.515%). The relative error in Case 1 was higher than 2% in 9.1% of the response points and higher than 10% in 3% of the response points; in Case 2 the relative error was higher than 2% in 48.9% of the response points and higher than 10% in 13.6% of the response points, all indicating a random variation in the error. This high variation in the strain and stress errors can be explained by high relative error of the backcalculated elastic moduli in Case 2 as compared to that in Case 1 (**Table 3**).

Similar random variation in the relative error can be also observed at a higher RMSE for Cases 3 and 4 as shown in **Tables 8** and **9** respectively where the RMSE was almost the same (less than 1%). However, the relative error in Case 3 was higher than 2% in 65.2% of the response points and higher than 10% in 13.6% of the response points while in Case 4 the relative error was higher than 2% in 19.7% of the response points and higher than 10% in 4.5% of the response points, indicating again a random variation in the error. Similarly, the high variation in the strain and stress errors was attributed to the high variation in the relative error of the backcalculated elastic moduli rather than the RMSE values.

Comparing Cases 3 and 5 (**Tables 8** and **10**) one can observe different RMSE values but similar relative errors in the backcalculated elastic moduli. Furthermore, in both cases the magnitude and location of the relative error in the strains and stresses were nearly identical. This finding shows that controlling the RMSE does not necessarily reduce the relative error associated with the pavement response (strains and stresses) at either the surface or along the pavement profile. This would require a better control of the backcalculated moduli. However, controlling the error associated with the backcalculated elastic modulus is not an easy task since the exact modulus is not known. Even with known elastic moduli from lab testing, the variation between the backcalculated and exact moduli can be high. The difference between backcalculated subgrade elastic moduli from the FWD and laboratory elastic moduli has been studied by many researchers (Daleiden et *al.* 1994; Von Quintus and Killingworth 1997). It was found that there is no unique relation between the backcalculated and laboratory measured resilient moduli. The ASSHTO Guide (1993) suggested that the backcalculated modulus is three times the laboratory modulus, whilst Von Quintus and Killingworth (1997) suggested that one could use some correction factors calculated from any multilayered elastic program to match the backcalculated and laboratory moduli. However, the suggested factors are highly dependent on the backcalculation program and should be used with caution. On the other hand, Stolle (2002) showed that the moduli of the base and subgrade layers have the largest contribution to the measured FWD deflection.

It should be noted that in all cases the effect of the backcalculated moduli on the vertical stress (σ_z) was relatively small as compared to their effect on the horizontal strains, vertical strains, and horizontal stresses.

PAVEMENT FATIGUE PREDICTION

The damage of flexible pavements can be assessed by predicting the number of loads needed to initiate cracks (fatigue cracking). The Shell Model (Bonnaure et *al.* 1980) and the Asphalt Institute Model (Shook et *al.* 1982) are frequently used for fatigue cracking in flexible pavements.

The Shell Model is based on two different loading modes, as given by **Eqs. 3** and **4**, below:

Shell Constant Strain Model:

$$N_\epsilon = 13909 A_f K \left(\frac{1}{\epsilon_t}\right)^5 E_s^{-1.8} \qquad \textbf{(3)}$$

and Shell Constant Stress Model:

$$N_\sigma = A_f K \left(\frac{1}{\epsilon_t}\right)^5 E_s^{-1.4} \qquad \textbf{(4)}$$

where N_ε and N_σ are the number of load repetitions to fatigue cracking using the constant strain and constant stress analysis, respectively, A_f and K are material constants, ε_t is the tensile strain at the critical location and E_s is the stiffness of the material (i.e. elastic modulus). The constant strain model is applicable to thin AC layers usually less than 51 mm, whilst the constant stress model is applicable to thick AC layers usually more than 203 mm. The Shell Model was calibrated and generalized for any thickness as given below (MEPDG, 2004):

$$N_f = A_f K F'' \left(\frac{1}{\epsilon_t}\right)^5 E_s^{-1.4} \qquad \textbf{(5)}$$

where N_f is the number of load repetitions to fatigue cracking, and F'' is a constant that depends on the layer thickness and the material stiffness.

The Asphalt Institute Model is given below:

$$N_f = 0.00432 C \left(\frac{1}{\epsilon_t}\right)^{3.291} \left(\frac{1}{E_s}\right)^{0.854} \qquad \textbf{(6)}$$

where, similarly, N_f is the number of load repetitions to fatigue cracking, C is a material constant, ε_t is the tensile strain at the critical location, and again E_s is the material stiffness. The Asphalt Institute Model can be used for any thickness.

It can be seen from the above equations that the critical tensile strain and the stiffness of the AC layer are the main factors affecting the number of load repetitions needed to initiate fatigue failure. The effect of the backcalculated set of elastic moduli on the fatigue in flexible pavements can be studied by finding the ratio between the estimated number of repeated loads (N_f) using the backcalculated set of elastic moduli and that using the exact set of elastic moduli. In other words, the ratio is equal to N_{fb} (backcalculated set of elastic moduli) over N_{fe} (exact set of elastic moduli).

RUTTING DAMAGE

Rutting in flexible pavement is considered as a functional deterioration. Rutting is mainly predicted by calculating the vertical strains at the top of the subgrade and then estimating the allowable load repetitions until a certain rutting threshold is met. For example, Shook et *al.* (1982) assumed a rutting depth of 10 mm in their method, while Potter and Donald (1985) assumed 20-30 mm rutting depth.

Recently, the results from the test sections at MnROAD were used to develop a method to predict the number of allowable load repetitions until rutting failure using a rut depth of 13 mm as shown in the following relation (Skok et *al.*, 2003):

$$N_r = (5.5).10^{15} \left(\frac{1}{\epsilon_v}\right)^{3.929} \qquad \textbf{(7)}$$

where N_r is the number of allowable load repetitions until rutting failure, and ε_v is the maximum compressive strain at the top of the subgrade layer.

It can be seen, from the above equation, that the vertical strain at the top of the subgrade layer is very important to predict the lifetime of the pavement due to rutting. Similar to the fatigue case, the effect of the backcalculated elastic moduli on the rutting can be studied by finding the ratio between the estimated number of repeated loads (N_r) using the backcalculated set of elastic moduli and that using the exact set of elastic moduli. In other words, the ratio is equal to N_{rb} (backcalculated set of elastic moduli) over N_{re} (exact set of elastic moduli).

FATIGUE AND RUTTING PREDICTION

The fatigue and rutting of the pavement are studied for the five cases as summarized in **Tables 1** and **2**, and the results are listed in **Table 11**. It is observed from **Table 11** that, for all cases except Case 2, using either the Shell Model or the Asphalt Institute Model, the fatigue life will be largely underestimated based on the backcalculated moduli as compared to those based on the exact moduli. Furthermore, comparing Case 2 to Case 1 it can be seen that even for the same RMSE the predicted number of repeated loads for fatigue can be largely overestimated rather than underestimated. The fatigue prediction results in **Table 11** also show that even for a small relative error (less than 2.1% in Case 1) in the backcalculated set of elastic moduli the fatigue life of the pavement can be underestimated by 60% using the Shell model and by 45% using the Asphalt Institute Model, indicating a very high sensitivity of the fatigue life to the relative error in elastic moduli rather than the RMSE.

TABLE 11. Comparison of Fatigue Life Using Backcalculated and Exact Pavement Moduli

Case (1)	N_{fb}/N_{fe} Shell (2)	N_{fb}/N_{fe} Asphalt Institute (3)	RMSE (%) (4)
Case 1	0.407	0.554	0.24
Case 2	4449.469	251.951	0.22
Case 3	0.027	0.092	0.65
Case 4	0.559	0.682	0.69
Case 5	0.025	0.087	0.85

The effect of the RMSE value and the relative error in pavement moduli on rutting can be observed from **Table 12**. It can be seen that even for a very small RMSE (Cases 1 and 2 where the RMSE is 0.22% and 0.24%, respectively), the rutting failure prediction based on the backcalculated moduli was overestimated by 11.7% in Case 2 while it was overestimated by 0.3% in Case 1, indicating a high sensitivity of the rutting life on the relative error in moduli. In addition, the results show that as the RMSE (error) increases, the underestimation of the rutting increases, as can be observed by comparing the rutting results in **Table 12** for Cases 2 to 5.

TABLE 12. Comparison of Rutting Failure Using Backcalculated and Exact Pavement Moduli

Case (1)	N_{rb}/N_{re} (2)	RMSE (%) (3)
Case 1	1.003	0.24
Case 2	1.117	0.22
Case 3	0.943	0.65
Case 4	0.942	0.69
Case 5	0.939	0.85

CONCLUSIONS

This study shows that the use of the RMSE is not enough to secure an accurate backcalculation of the pavement elastic moduli. Large discrepancies can exist in the predicted pavement strains and stresses using the backcalculated and exact elastic moduli. As a result, even a RMSE value less than 1% can significantly affects the fatigue and rutting predictions in flexible pavements.

The effect of the RMSE is suitable for controlling the fitness of the backcalculated deflection basin to that measured in the field while the use of the relative error in the elastic moduli is more appropriate. However, the availability of laboratory measured elastic moduli does not guarantee more appropriate backcalculated elastic moduli. This variation adds more uncertainty when dealing with data from the FWD test, and should be the future endeavor in pavement engineering.

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Considerations for Nonlinear Analyses of Pavement Foundation Geomaterials in the Finite Element Modeling of Flexible Pavements

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ABSTACT: Flexible pavements are commonly used for low to high volume roads subjected to many wheel load applications and also for airfields subjected to rather heavy aircraft gear/wheel loads. As the demand for applied wheel loads and number of load applications increase, it becomes very important to properly characterize the behavior of unbound aggregate layers and subgrade soils as the pavement foundation geomaterials. Laboratory studies have shown that resilient responses for these geomaterials follow nonlinear, stress-dependent behavior under repeated loading. Therefore, a finite element (FE) type layered elastic analysis is needed to employ nonlinear resilient material models to predict accurate pavement responses for mechanistic based pavement design. In this study, modulus models well proven over the years to adequately describe the nonlinear pavement geomaterial behavior were programmed in a user material subroutine (UMAT) to perform axisymmetric and three-dimensional (3D) analyses using the general-purpose ABAQUS FE program. The results indicated that modulus characterizations of the nonlinear, stress-dependent base and subgrade layers were essentially needed to reliably predict accurate pavement responses both in axisymmetric and 3D analyses.

Introduction

The various layers of pavement structure have different properties to affect pavement response and overall performance. As the demand for heavier wheel loads and number of load applications increase, nowadays, it becomes even more important to properly characterize the mechanistic response behavior of the unbound granular and subgrade soil layers as the foundation geomaterials of the pavement structure. As properly documented in numerous studies, pavement foundation geomaterials follow nonlinear, stress-dependent modulus characteristics under repeated traffic loading (Brown and Pappin 1981, Thompson and Elliot 1985). Unbound aggregates often

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