Final Report

Review of ODOT’s Overlay Design Procedure

Volume 1 of 2
HMA Overlays of Existing HMA and Composite Pavements

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ODOT initiated this research study to determine (1) the impact of milling off portions of the existing pavement on the structural capacity of the remaining pavement and (2) whether currently recommended HMA structural coefficients adequately reflect the structural properties of new HMA overlay materials. The study mainly focused on the impact of milling on the design of HMA overlays over existing flexible pavements and composite pavements. This volume (Volume I) of the report deals with this main study focus area. During the course of the study, an additional focus area was added to the project to investigate the impact of completely milling off existing HMA layers in composite pavement systems on unbonded overlay design. Volume II of this report deals with impact of milling on unbonded overlays.

This report describes the structural evaluation of individual flexible and composite pavement projects located at different sites throughout Ohio, as well as an analysis of the evaluation results to develop enhancements to the ODOT HMA overlay design procedure as needed. The report presents detailed descriptions of the projects evaluated, field testing procedures employed, procedures adopted for analyzing field testing data and other data collected, structural evaluation results, analysis of results, and recommendations for improvements of the current ODOT overlay design procedure.
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REVIEW OF ODOT’S OVERLAY DESIGN PROCEDURES

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# TABLE OF CONTENTS

LIST OF FIGURES ..................................................................................................................... ix

LIST OF TABLES ........................................................................................................................ xiv

CHAPTER 1. INTRODUCTION ................................................................................................ 1

Overview..................................................................................................................................... 1
Current ODOT HMA Overlay Design Procedures ..................................................................... 2
Suggested Areas for Improvement to ODOT HMA Overlay Design Procedure ...................... 5
Structural Evaluation of Selected Flexible and Composite Pavement Projects ...................... 7

CHAPTER 2. PROJECT ERI-6 .............................................................................................. 21

Overview of Project ERI-6 ....................................................................................................... 21
Rehabilitation and Structural Evaluation Activities for Project ERI-6 ..................................... 21
Data Analysis for Project ERI-6 ............................................................................................... 25
Summary ................................................................................................................................... 30

CHAPTER 3. PROJECT FAY-71(N) ..................................................................................... 31

Overview of Project FAY-71(N) .............................................................................................. 31
Rehabilitation and Structural Evaluation Activities for Project FAY-71(N)............................ 31
Data Analysis for Project FAY-71(N) ...................................................................................... 35
Summary ................................................................................................................................... 38

CHAPTER 4. PROJECT FAY/MAD-71(S) ........................................................................... 40

Overview of Project FAY/MAD-71(S) .................................................................................... 41
Rehabilitation and Structural Evaluation Activities for Project FAY/MAD-71(S).................. 41
Data Analysis for Project FAY/MAD-71(S) ............................................................................ 45
Summary ................................................................................................................................... 49

CHAPTER 5. PROJECTS GRE-4(N) .................................................................................... 51

Overview of Project GRE-4(N) ................................................................................................ 51
Rehabilitation and Structural Evaluation Activities for Project GRE-4(N)......................... 51
Data Analysis for Project GRE-4(N) ........................................................................................ 55
Summary ................................................................................................................................... 59

CHAPTER 6. PROJECT JEF-7 .............................................................................................. 60

Overview of Project JEF-7 ........................................................................................................ 61
Rehabilitation and Structural Evaluation Activities for Project JEF-7 ..................................... 61
Data Analysis for Project JEF-7 ............................................................................................... 69
Summary ................................................................................................................................... 73
# TABLE OF CONTENTS (CONT.)

## CHAPTER 7. PROJECT MOT-4(S)
- Overview of PROJECT MOT-4(S) ................................................................. 75
- Rehabilitation and Structural Evaluation Activities for Project MOT-4(S) ............ 75
- Data Analysis for Project MOT-4(S) ............................................................... 78
- Summary ....................................................................................................... 82

## CHAPTER 8. PROJECT MOT-40 (04)
- Overview of Project MOT-40 (04) ............................................................... 85
- Rehabilitation and Structural Evaluation Activities for Project MOT-40 (04) ......... 85
- Data Analysis for Project MOT-40 (04) ......................................................... 91
- Summary .................................................................................................... 95

## CHAPTER 9. PROJECT ROS-35
- Overview of Project ROS-35 ..................................................................... 97
- Rehabilitation and Structural Evaluation Activities for Project ROS-35 ............... 97
- Data Analysis for Project ROS-35 ............................................................... 105
- Summary .................................................................................................. 109

## CHAPTER 10. PROJECT WAY-30
- Overview of Project WAY-30 ................................................................. 111
- Rehabilitation and Structural Evaluation Activities for Project WAY-30 .......... 111
- Data Analysis for Project WAY-30 .......................................................... 115
- Summary .................................................................................................. 118

## CHAPTER 11. PROJECT CLA-68
- Overview of Project CLA-68 ..................................................................... 121
- Rehabilitation and Structural Evaluation Activities for Project CLA-68 ........... 121
- Data Analysis for Project CLA-68 .............................................................. 126
- Summary .................................................................................................. 130

## CHAPTER 12. PROJECT GAL-35
- Overview of Project GAL-35 .................................................................... 133
- Rehabilitation and Structural Evaluation Activities for Project GAL-35 .......... 133
- Data Analysis for Project GAL-35 .............................................................. 140
- Summary ................................................................................................. 144

## CHAPTER 13. PROJECT GRE-72
- Overview of Project GRE-72 .................................................................... 145
- Rehabilitation and Structural Evaluation Activities for Project GRE-72 .......... 145
- Data Analysis for Project GRE-72 .............................................................. 153
- Summary ................................................................................................. 157
# TABLE OF CONTENTS (CONT.)

## CHAPTER 14. PROJECT JAC-32 ................................................................. 159
- Overview of Project JAC-32 ........................................................................... 159
- Rehabilitation and Structural Evaluation Activities for Project JAC-32 .......... 159
- Data Analysis for Project JAC-32 ................................................................. 166
- Summary ....................................................................................................... 170

## CHAPTER 15. PROJECT LIC-70 ............................................................... 171
- Overview of Project LIC-70 ........................................................................... 171
- Rehabilitation and Structural Evaluation Activities for Project LIC-70 .......... 171
- Data Analysis for Project LIC-70 ................................................................. 175
- Summary ....................................................................................................... 179

## CHAPTER 16. PROJECT MOT-40 (05) ...................................................... 181
- Overview of Project MOT-40 (05) ................................................................. 181
- Rehabilitation and Structural Evaluation Activities for Project MOT-40(05) .. 181
- Data Analysis for Project MOT-40 (05) .......................................................... 188
- Summary ....................................................................................................... 191

## CHAPTER 17. PROJECT ROS-35 (MM 9.15) AND ROS-35 (MM 10.0) ....... 193
- Overview of Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0) ................... 193
- Rehabilitation and Structural Evaluation Activities for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0) .......................................................... 193
- Data Analysis for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0) .......... 200
- Summary ....................................................................................................... 207

## CHAPTER 18. FWD DATA ANALYSIS .................................................... 209
- ROS-35 (MM9.15) ......................................................................................... 209
- ROS-35 (MM10) .......................................................................................... 211
- JAC-32 ........................................................................................................ 213

## CHAPTER 19. FLEXIBLE PAVEMENT ANALYSIS AND FINDINGS ........ 219
- Introduction .................................................................................................. 219
- Summary and Observations ......................................................................... 219
- Implications of Observations ....................................................................... 223
- Adjustment of SN_{eff} to Account for the Effect of Milling ......................... 224
- Impact of New HMA Materials on aOL ..................................................... 231

## CHAPTER 20. COMPOSITE PAVEMENT ANALYSIS AND FINDINGS ........ 233
- Introduction .................................................................................................. 233
- Summary and Observations ......................................................................... 233
- Implications of Observations ....................................................................... 237
- Adjustment of D_{eff} to Account for the Effect of Milling ............................ 237
TABLE OF CONTENTS (CONT.)

CHAPTER 21. SUMMARY, CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK .......................................................... 244

Summary ....................................................................................................................................................... 245
Conclusions ................................................................................................................................................. 247
Recommendations for Future Work and Additional Data Needs ................................................................. 248

REFERENCES ............................................................................................................................................. 249
LIST OF FIGURES

Figure 1. Overview of ODOT’s HMA/HMA overlay design process and potential issues that need further investigation................................................................. 6
Figure 2. Overview of ODOT’s HMA/Composite overlay design process and potential issues that will need further investigation............................................... 7
Figure 3. Map of projects selected for detailed structural evaluation................................................. 9
Figure 4. Configuration of Dynaflect deflection testing equipment load wheels and geophones. ............................................................................................................ 18
Figure 5. Typical deflection basin/profile from a Dynaflect deflection test. ....................................... 18
Figure 6. Historical pavement performance characterized using PCR for ERI-6................................. 23
Figure 7. Historical traffic application for ERI-6............................................................................. 23
Figure 8. Photos of cores extracted from ERI-6 in 2005.................................................................. 25
Figure 9. Plot showing S1 profiles for ERI-6.................................................................................. 27
Figure 10. Plot showing SPR profiles for ERI-6........................................................................... 28
Figure 11. Historical pavement performance characterized using PCR for FAY-71(N).................. 33
Figure 12. Historical traffic application for FAY-71(N)................................................................. 33
Figure 13. Plot showing S1 profiles for FAY-71(N)....................................................................... 36
Figure 14. Plot showing SPR profiles for FAY-71(N).................................................................... 37
Figure 15. Historical pavement performance characterized using PCR for FAY/MAD-71(S)........... 43
Figure 16. Historical traffic application for FAY/MAD-71(S).......................................................... 43
Figure 17. Plot showing S1 profiles for FAY/MAD-71(S)............................................................... 46
Figure 18. Plot showing SPR profiles for FAY/MAD-71(S)............................................................ 47
Figure 19. Historical pavement performance characterized using PCR for GRE-4(N)..................... 53
Figure 20. Historical traffic application for GRE-4(N).................................................................... 53
Figure 21. Plot showing S1 profiles for GRE-4(N)......................................................................... 56
Figure 22. Plot showing SPR profiles for GRE-4(N)...................................................................... 57
Figure 23. JEF-7 windshield survey (photo 1).............................................................................. 62
Figure 24. JEF-7 windshield survey (photo 2)............................................................................. 62
Figure 25. JEF-7 windshield survey (photo 3) showing moderate-severity “transverse” reflection cracking. .................................................................................. 63
Figure 26. JEF-7 windshield survey (photo 4) showing-low severity “longitudinal” reflection cracking (from the JRCP lane to lane joint). ........................................... 63
Figure 27. Historical pavement performance characterized using PCR for JEF-7............................. 65
Figure 28. Historical traffic application for JEF-7.......................................................................... 65
Figure 29. Cores extracted from JEF-7.......................................................................................... 67
Figure 30. Picture of cores extracted from JEF-7.......................................................................... 68
Figure 31. Plot showing S1 profiles for JEF-7................................................................................ 70
Figure 32. Plot showing SPR profiles for JEF-7............................................................................. 71
Figure 33. Historical pavement performance characterized using PCR for MOT-4(S)................... 77
Figure 34. Historical traffic application for MOT-4(S)................................................................... 77
Figure 35. Plot showing S1 profiles for MOT-4(S)........................................................................ 79
Figure 36. Plot showing SPR profiles for MOT-4(S)..................................................................... 81
LIST OF FIGURES (CONT.)

Figure 37. Historical pavement performance characterized using PCR for MOT-40 (04) ....... 87
Figure 38. Historical traffic application for MOT-40 (04) ......................................................... 88
Figure 39. Photos of cores extracted from MOT-40 (04) in 2004 ............................................... 90
Figure 40. Photos of verification cores extracted from MOT-40 (04) in 2006 ............................. 91
Figure 41. Plot showing $S_1$ profiles for MOT-40 (04) ............................................................ 92
Figure 42. Plot showing SPR profiles for MOT-40 (04) ............................................................. 93
Figure 43. ROS-35 windshield survey (photo 1) showing moderate-severity reflection “transverse” cracking .......................................................... 98
Figure 44. ROS-35 windshield survey (photo 2) showing high-severity reflection “transverse” cracking ........................................................................ 98
Figure 45. ROS-35 windshield survey (photo 3) showing high-severity reflection “transverse” cracking and patching ..................................................... 99
Figure 46. ROS-35 windshield survey (photo 4) showing moderate-severity reflection “transverse” cracking .......................................................... 99
Figure 47. Historical pavement performance characterized using PCR for ROS-35 .................. 100
Figure 48. Historical traffic for ROS-35 ................................................................................. 101
Figure 49. Photos of cores extracted from ROS-35 in 2005 ..................................................... 102
Figure 50. Photos of cores extracted from ROS-35 in 2005 ..................................................... 103
Figure 51. Photos of verification cores extracted from ROS-35 in 2006 ................................. 104
Figure 52. Plot showing $S_1$ profiles for ROS-35 ................................................................. 106
Figure 53. Plot showing SPR profiles for ROS-35 ................................................................. 107
Figure 54. Historical pavement performance characterized using PCR for WAY-30 ............. 113
Figure 55. Historical traffic for WAY-30 ................................................................................. 113
Figure 56. Photo of cores extracted from WAY-30 ................................................................. 115
Figure 57. Plot showing $S_1$ profiles for WAY-30 .................................................................. 116
Figure 58. Plot showing SPR profiles for WAY-30 ................................................................. 117
Figure 59. Cross-section of the southbound lane for CLA-68 ................................................... 122
Figure 60. Historical pavement performance characterized using PCR for CLA-68 ............ 124
Figure 61. Historical traffic for CLA-68 ................................................................................. 124
Figure 62. Photos of cores extracted from CLA-68 in 2006 ................................................... 126
Figure 63. Plot showing $S_1$ profiles for CLA-68 ................................................................. 127
Figure 64. Plot showing SPR profiles for CLA-68 ................................................................. 128
Figure 65. GAL-35 windshield survey (photo 1) showing moderate-severity cracking (longitudinal, transverse, and alligator) .................................................... 134
Figure 66. GAL-35 windshield survey (photo 2) showing high-severity cracking (longitudinal, transverse (reflection), and alligator).................................................. 134
Figure 67. GAL-35 windshield survey (photo 3) showing high-severity alligator cracking .... 135
Figure 68. GAL-35 windshield survey (photo 4) showing moderate-severity reflection “transverse” cracking .......................................................... 135
Figure 69. Historical pavement performance characterized using PCR for GAL-35 .......... 137
Figure 70. Historical traffic application for GAL-35 ............................................................... 137
Figure 71. Cores extracted from GAL-35 in 2004 ................................................................. 138
LIST OF FIGURES (CONT.)

Figure 72. Cores extracted from GAL-35 in 2005 ................................................................. 140
Figure 73. Plot showing S1 profiles for GAL-35 ................................................................. 141
Figure 74. Plot showing SPR profiles for GAL-35 ................................................................. 143
Figure 75. GRE-72 windshield survey (photo 1) ................................................................. 146
Figure 76. GRE-72 windshield survey (photo 2) showing high-severity alligator cracking ... 146
Figure 77. GRE-72 windshield survey (photo 3) showing patching ..................................... 147
Figure 78. GRE-72 windshield survey (photo 4) showing high-severity alligator cracking ... 147
Figure 79. Historical pavement performance characterized using PCR for GRE-72 ............. 148
Figure 80. Historical traffic application for GRE-72 ............................................................. 149
Figure 81. Cores extracted from GRE-72 in 2006 ................................................................. 150
Figure 82. Cores extracted from GRE-72 in 2005 ................................................................. 151
Figure 83. Cores extracted from GRE-72 in 2006 ................................................................. 152
Figure 84. Plot showing S1 profiles for GRE-72 ................................................................. 154
Figure 85. Plot showing SPR profiles for GRE-72 ................................................................. 155
Figure 86. JAC-32 windshield survey (photo 1) showing high-severity transverse cracking. 160
Figure 87. JAC-32 windshield survey (photo 2) showing high-severity transverse cracking. 160
Figure 88. JAC-32 windshield survey showing longitudinal & transverse cracking .......... 161
Figure 89. JAC-32 windshield survey (photo 4) showing high-severity transverse cracking. 161
Figure 90. Historical pavement performance characterized using PCR for JAC-32 ............ 162
Figure 91. Historical traffic application for JAC-32 ............................................................. 163
Figure 92. Cores extracted from JAC-32 ............................................................................. 164
Figure 93. Cores extracted from JAC-32 ............................................................................. 166
Figure 94. Plot showing S1 profiles for JAC-32 ................................................................. 167
Figure 95. Plot showing SPR profiles for JAC-32 ................................................................. 168
Figure 96. Historical pavement performance characterized using PCR for LIC-70 ............. 173
Figure 97. Historical traffic application for LIC-70 ............................................................. 173
Figure 98. Cores extracted from LIC-70 in 2005 ................................................................. 175
Figure 99. Plot showing S1 profiles for LIC-70 ................................................................. 177
Figure 100. Plot showing SPR profiles for LIC-70 ............................................................... 178
Figure 101. MOT-40 (05) windshield survey showing patched longitudinal cracking ....... 183
Figure 102. MOT-40 (05) windshield survey showing moderate levels of alligator cracking. 183
Figure 103. MOT-40 (05) windshield survey showing high-severity alligator cracking ...... 184
Figure 104. MOT-40 (05) windshield survey showing severity transverse cracking .......... 184
Figure 105. Historical pavement performance characterized using PCR for MOT-40 (05) ... 185
Figure 106. Historical traffic application for MOT-40 (05) .................................................. 185
Figure 107. Cores extracted from MOT-40 (05) in 2005 ....................................................... 187
Figure 108. Cores extracted from MOT-40 (05) in 2006 ....................................................... 187
Figure 109. Plot showing S1 profiles for MOT-40 (05) .......................................................... 189
Figure 110. Plot showing SPR profiles for MOT-40 (05) ........................................................ 190
Figure 111. ROS-35 (4.38) windshield survey showing alligator and transverse cracking .... 195
LIST OF FIGURES (CONT.)

Figure 112. ROS-35 (4.38) windshield survey (photo 2) ............................................................... 195
Figure 113. ROS-35 (4.38) windshield survey (photo 3) showing low-severity cracking ................................. 196
Figure 114. ROS-35 (4.38) windshield survey (photo 4) showing low-severity alligator cracking. ........................................................ 196
Figure 115. Historical pavement performance characterized using PCR for ROS-35 (MM 9.15) and ROS-35 (MM 10.0) ................................................................. 198
Figure 116. Historical traffic application for ROS-35 (MM 9.15) and ROS-35 (MM 10.0) ................................................................. 198
Figure 117. Cores extracted from ROS-35 (MM9.15). ............................................................................. 200
Figure 118. Cores extracted from ROS-35 (MM10.0). ............................................................................. 201
Figure 119. S1 profile for ROS-35 (MM 9.15) .................................................................................. 202
Figure 120. S1 profile for ROS-35 (MM 10.0) .................................................................................. 202
Figure 121. SPR profile for ROS-35 (MM 9.15) ............................................................................... 204
Figure 122. SPR profile for ROS-35 (MM 10.0) ............................................................................... 204
Figure 123. Comparison of backcalculated Ep from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15 ............. 210
Figure 124. Comparison of backcalculated Mr from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15 ................................................................. 210
Figure 125. Comparison of backcalculated SNeff from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15 ................................................................. 211
Figure 126. Comparison of backcalculated Ep from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM10. ................................................................. 212
Figure 127. Comparison of backcalculated Mr from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM10. ................................................................. 212
Figure 128. Comparison of backcalculated SNeff from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM10. ................................................................. 213
Figure 129. Comparison of backcalculated Ep from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32 ................................................................. 214
Figure 130. Comparison of backcalculated Mr from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32 ................................................................. 214
Figure 131. Comparison of backcalculated SNeff from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32 ................................................................. 215
Figure 132. ODOT relationship between subgrade Mr versus Dynaflect’s S5. .............................................. 217
Figure 133. Summary of observed trends in maximum deflections for HMA-overlaid flexible pavements. ................................................................. 219
Figure 134. Summary of observed trends in SPR for HMA-overlaid flexible pavements. ................. 220
Figure 135. Summary of observed trends in S5 for HMA-overlaid flexible pavements. .................. 220
Figure 136. Summary of observed trends in Ep for HMA-overlaid flexible pavements. ................................................................. 221
Figure 137. Summary of observed trends in Mr for HMA-overlaid flexible pavements. ................................................................. 221
LIST OF FIGURES (CONT.)

Figure 138. Summary of observed trends in SNeff for HMA-overlaid flexible pavements. ................................................................. 222
Figure 139. Plot showing predicted versus measured SNeff. ................................................................. 226
Figure 140. Relationship between S1 effective and SNeff. ................................................................. 227
Figure 141. Relationship between before and after milling S1. ............................................................. 228
Figure 142. Plot of measured and predicted after milling S1 ................................................................. 229
Figure 143. Plot showing the effect of milling depth and PCR on adjusted SNeff for a 9-in-thick existing pavement................................................................ 230
Figure 144. Plot showing the effect of milling depth and PCR on adjusted SNeff for a 12-in-thick existing pavement................................................................. 230
Figure 145. Plot showing the effect of milling depth and PCR on adjusted SNeff for a 15-in-thick existing pavement.............................. 230
Figure 146. Summary of observed trends in maximum deflections for HMA-overlaid composite pavements. ................................................................. 231
Figure 147. Summary of observed trends in SPR for HMA-overlaid composite pavements. ................................................................. 233
Figure 148. Summary of observed trends in AREA for HMA-overlaid composite pavements. ................................................................. 234
Figure 149. Summary of observed trends in EP for HMA-overlaid composite pavements. ................................................................. 235
Figure 150. Summary of observed trends in k-value for HMA-overlaid composite pavements. ................................................................. 235
Figure 151. Summary of observed trends in Deff for HMA-overlaid composite pavements. ................................................................. 236
Figure 152. Plot showing predicted versus measured SNeff. ................................................................. 239
Figure 153. Relationship between S1 effective and SNeff. ................................................................. 240
Figure 154. Plot of measured and predicted after milling S1. ................................................................. 242
Figure 155. Plot showing the effect of milling depth and PCR on adjusted Deff for a max. deflection (before milling) of 0.2 mils................................. 242
Figure 156. Plot showing the effect of milling depth and PCR on adjusted Deff for a max. deflection (before milling) of 0.5 mils................................. 243
Figure 157. Plot showing the effect of milling depth and PCR on adjusted Deff for a max. deflection (before milling) of 1.82 mils................................. 243
LIST OF TABLES

Table 1. General description of the pavement projects selected for evaluation ........................................ 10
Table 2. ODOT PCR scale (ODOT 1999) .................................................................................................. 12
Table 3. Detailed description of pavement structural evaluation and rehabilitation activities ..................... 14
Table 4. Description of project specific structural evaluation/rehabilitation activities ............................... 15
Table 5. Interpretation of Dynaflect data on continuous pavement (Edwards et al. 1989) ......................... 19
Table 6. Timeline showing significant historical construction and M&R events for ERI-6 ......................... 22
Table 7. Summary of analysis of variance results for maximum deflections (ERI-6) ................................. 27
Table 8. Summary of analysis of variance results for SPR (ERI-6) ........................................................... 28
Table 9. Summary of analysis of variance results for AREA (ERI-6) ....................................................... 29
Table 10. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for ERI-6 .......................................................... 29
Table 11. Timeline showing significant historical construction and M &R events for FAY-71(N) ............... 32
Table 12. Summary of analysis of variance results for maximum deflections (FAY-71(N)) ................. 36
Table 13. Summary of analysis of variance results for SPR (FAY-71(N)) ............................................... 37
Table 14. Summary of analysis of variance results for AREA (FAY-71(N)) ................................................ 38
Table 15. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for FAY-71(N) ............................................................................. 39
Table 16. Timeline showing significant historical construction and M&R events for FAY/MAD-71(S) .... 42
Table 17. Summary of analysis of variance results for maximum deflections ........................................ 46
Table 18. Summary of analysis of variance results for FAY/MAD-71(S) .................................................. 47
Table 19. Summary of analysis of variance results for AREA (FAY/MAD-71(S)) ................................. 48
Table 20. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for FAY/MAD-71(S) ...................................................... 48
Table 21. Timeline showing significant historical construction and M &R events for GRE-4(N) ................ 52
Table 22. Summary of analysis of variance results for maximum deflections (GRE-4(N)) ......................... 56
Table 23. Summary of analysis of variance results for SPR (GRE-4(N)) ............................................... 57
Table 24. Summary of analysis of variance results for AREA (GRE-4(N)) ................................................ 58
Table 25. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for GRE-4(N) .......................................................... 59
Table 26. Timeline showing significant historical construction and M &R events for JEF-7 ....................... 64
Table 27. Summary of analysis of variance results for maximum deflections (JEF-7) ............................... 70
Table 28. Summary of analysis of variance results for SPR (JEF-7) ...................................................... 71
Table 29. Summary of analysis of variance results for AREA (JEF-7) ..................................................... 72
Table 30. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for JEF-7 .......................................................... 72
Table 31. Timeline showing significant historical construction and M &R events for MOT-4(S) ............... 76
Table 32. Summary of analysis of variance results for maximum deflections (MOT-4(S)) .................... 80
Table 33. Summary of analysis of variance results for SPR (MOT-4(S)) .............................................. 81
LIST OF TABLES (CONT.)

Table 34. Summary of analysis of variance results for AREA (MOT-4(S)) ................................. 82
Table 35. Summary of backcalculated layer moduli, effective thickness and required HMA
overlay thickness for MOT -4(S). .................................................................................. 82
Table 36. Timeline showing significant historical construction and M&R events for
MOT-40 (04)............................................................................................................. 86
Table 37. Summary of analysis of variance results for maximum deflections (MOT-40 (04)) ... 92
Table 38. Summary of analysis of variance results for SPR (MOT-40 (04)). .............................. 93
Table 39. Summary of analysis of variance results for AREA (MOT-40 (04)). .......................... 94
Table 40. Summary of backcalculated layer moduli, effective thickness and required HMA
overlay thickness for MOT-40 (04). ............................................................................. 94
Table 41. Timeline showing significant historical construction and M&R events for ROS-35. 100
Table 42. Summary of analysis of variance results for maximum deflections (ROS-35) ........ 106
Table 43. Summary of analysis of variance results for SPR (ROS-35)...................................... 107
Table 44. Summary of analysis of variance results for AREA (ROS-35) ................................. 108
Table 45. Summary of backcalculated layer moduli, effective thickness and required HMA
overlay thickness for ROS-35..................................................................................... 108
Table 46. Timeline showing significant historical construction and M & R events for WAY-30 ........ 112
Table 47. Summary of analysis of variance results for maximum deflections (WAY-30) .............. 117
Table 48. Summary of analysis of variance results for SPR (WAY-30). ..................................... 117
Table 49. Summary of analysis of variance results for AREA (WAY-30). ................................. 119
Table 50. Summary of backcalculated layer moduli, effective thickness and required HMA
overlay thickness for WAY-30................................................................................... 119
Table 51. Timeline showing significant historical construction and M & R events for CLA-68 ......... 123
Table 52. Summary of analysis of variance results for maximum deflections (CLA-68) .......... 127
Table 53. Summary of analysis of variance results for SPR (CLA-68)....................................... 129
Table 54. Summary of analysis of variance results for S5 deflections (CLA-68) ....................... 129
Table 55. Summary of backcalculated layer moduli and effective structural number for
CLA-68. ...................................................................................................................... 130
Table 56. Timeline showing significant historical construction and M&R events for GAL-35. 136
Table 57. Summary of analysis of variance results for maximum deflections (GAL-35) .......... 142
Table 58. Summary of analysis of variance results for SPR (GAL-35)....................................... 143
Table 59. Summary of analysis of variance results for S5 deflections (GAL-35) ................. 143
Table 60. Summary of backcalculated layer moduli and effective structural number for
GAL-35. ...................................................................................................................... 143
Table 61. Timeline showing significant historical construction and M&R events for GRE-72. 148
Table 62. Summary of analysis of variance results for maximum deflections (GRE-72) .......... 154
Table 63. Summary of analysis of variance results for SPR (GRE-72)....................................... 155
Table 64. Summary of analysis of variance results for S5 deflections (GRE-72) ....................... 156
Table 65. Summary of backcalculated layer moduli and effective structural number for
GRE-72. ...................................................................................................................... 156
<table>
<thead>
<tr>
<th>Table No.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>Timeline showing significant historical construction and M&amp;R events for JAC-32.</td>
<td>162</td>
</tr>
<tr>
<td>67</td>
<td>Summary of analysis of variance results for maximum deflections (JAC-32).</td>
<td>167</td>
</tr>
<tr>
<td>68</td>
<td>Summary of analysis of variance results for SPR (JAC-32).</td>
<td>168</td>
</tr>
<tr>
<td>69</td>
<td>Summary of analysis of variance results for S₅ deflections (GAL-35).</td>
<td>169</td>
</tr>
<tr>
<td>70</td>
<td>Summary of backcalculated layer moduli, and SNₐ (GAL-35).</td>
<td>170</td>
</tr>
<tr>
<td>71</td>
<td>Timeline showing original construction and significant M&amp;R events for LIC-70.</td>
<td>172</td>
</tr>
<tr>
<td>72</td>
<td>Summary of analysis of variance results for maximum deflections (LIC-70).</td>
<td>177</td>
</tr>
<tr>
<td>73</td>
<td>Summary of analysis of variance results for SPR (LIC-70).</td>
<td>178</td>
</tr>
<tr>
<td>74</td>
<td>Summary of analysis of variance results for S₅ deflections (LIC-70).</td>
<td>178</td>
</tr>
<tr>
<td>75</td>
<td>Summary of backcalculated layer moduli and SNₐ (LIC-70).</td>
<td>179</td>
</tr>
<tr>
<td>76</td>
<td>Cross-section of Eastbound lane of MOT-40 (05) in 2005 before major rehabilitation.</td>
<td>182</td>
</tr>
<tr>
<td>77</td>
<td>Summary of analysis of variance results for maximum deflections (MOT-40 (05)).</td>
<td>189</td>
</tr>
<tr>
<td>78</td>
<td>Summary of analysis of variance results for SPR (MOT-40 (05)).</td>
<td>190</td>
</tr>
<tr>
<td>79</td>
<td>Summary of analysis of variance results for S₅ deflections.</td>
<td>190</td>
</tr>
<tr>
<td>80</td>
<td>Summary of backcalculated layer moduli and effective structural number for MOT-40 (05).</td>
<td>191</td>
</tr>
<tr>
<td>81</td>
<td>Timeline showing significant historical construction and M&amp;R events for ROS-35 (MM 9.15).</td>
<td>194</td>
</tr>
<tr>
<td>82</td>
<td>Timeline showing significant historical construction and M&amp;R events for ROS-35 (MM 10.0).</td>
<td>194</td>
</tr>
<tr>
<td>83</td>
<td>Summary of analysis of variance results for maximum deflections (ROS-35 (MM 9.15)).</td>
<td>203</td>
</tr>
<tr>
<td>84</td>
<td>Summary of analysis of variance results for maximum deflections (ROS-35 (MM 10.0)).</td>
<td>203</td>
</tr>
<tr>
<td>85</td>
<td>Summary of analysis of variance results for SPR (ROS-35 (MM 9.15)).</td>
<td>205</td>
</tr>
<tr>
<td>86</td>
<td>Summary of analysis of variance results for SPR (ROS-35 (MM 10.0)).</td>
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</tr>
<tr>
<td>87</td>
<td>Summary of analysis of variance results for S₅ deflections.</td>
<td>205</td>
</tr>
<tr>
<td>88</td>
<td>Summary of analysis of variance results for S₅ deflections.</td>
<td>205</td>
</tr>
<tr>
<td>89</td>
<td>Summary of backcalculated layer moduli and SNₐ eff for ROS-35 (MM 9.15).</td>
<td>206</td>
</tr>
<tr>
<td>90</td>
<td>Summary of backcalculated layer moduli and SNₐ eff for ROS-35 (MM 10.0).</td>
<td>206</td>
</tr>
<tr>
<td>91</td>
<td>ANOVA results for Ep, Mr, and SNₐ eff for ROS-35 MM 9.15 project.</td>
<td>211</td>
</tr>
<tr>
<td>92</td>
<td>ANOVA results for Ep, Mr, and SNₐ eff for ROS-35 MM 10.0 project.</td>
<td>213</td>
</tr>
<tr>
<td>93</td>
<td>ANOVA results for Ep, Mr, and SNₐ eff for JAC-32 project.</td>
<td>215</td>
</tr>
<tr>
<td>94</td>
<td>Last sensor deflection statistics comparison—Dynaflect versus FWD.</td>
<td>216</td>
</tr>
<tr>
<td>95</td>
<td>ANOVA results for comparison of methods 1 and 2.</td>
<td>225</td>
</tr>
<tr>
<td>96</td>
<td>Selected projects for comparison of SNₐ eff before rehab and after HMA overlay.</td>
<td>232</td>
</tr>
<tr>
<td>97</td>
<td>Summary of ANOVA results for comparison of SNₐ eff before rehabilitation and after HMA overlay placement.</td>
<td>232</td>
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<tr>
<td>98</td>
<td>ANOVA results for comparison of methods 1 and 2.</td>
<td>238</td>
</tr>
</tbody>
</table>
CHAPTER 1. INTRODUCTION

Overview

The Ohio Department of Transportation’s (ODOT’s) *Pavement Design and Rehabilitation Manual* describes milling in combination with other repair types and hot-mix asphalt (HMA) overlays as *minor pavement rehabilitation*. ODOT designs HMA overlays for minor pavement rehabilitation using a deflection-based pavement design procedure. This procedure basically is a modified version of the structural deficiency HMA overlay design approach presented in the 1993 *AASHTO Guide for Design of Pavement Structures* (AASHTO 1993). ODOT’s procedure for minor pavement rehabilitation has been coded into the software DOITOVER.

The ODOT HMA overlay design procedure does not directly address the impact of pre-overlay repair activities (such as milling off portions of the existing pavement) in the process of determining HMA overlay thickness. Also, the procedure does not fully consider the consequences of replacing existing bituminous materials with potentially superior asphalt materials (e.g., Superpave or polymer modified asphalt).

ODOT initiated this research study to determine (1) the impact of milling off portions of the existing pavement on the structural capacity of the remaining pavement and (2) whether currently recommended HMA structural coefficients adequately reflect the structural properties of new HMA materials. The study mainly focused on the impact of milling on the design of HMA overlays over existing flexible pavements and composite pavements. This volume (Volume I) of the report deals with this main study focus area. During the course of the study, an additional focus area was added to the project to investigate the impact of completely milling off existing HMA layers in composite pavement systems on unbonded overlay design. Volume II of this report deals with impact of milling on unbonded overlays.

ODOT defines flexible pavements as (1) new conventional HMA, (2) deep strength HMA, (3) full-depth HMA, and (4) HMA over rubblized rigid (portland cement concrete [PCC]) pavement. Composite pavements are described as HMA over intact rigid pavements.

The objectives of the study were achieved by reviewing the ODOT HMA overlay design procedure, performing theoretical analysis, and conducting a detailed structural evaluation of several ODOT pavement projects. The structural evaluation of selected HMA-surfaced pavements was conducted prior to, during, and after rehabilitation in order to characterize (1) pavement structural capacity at various stages of the rehabilitation process and (2) the strength of the new “superior” HMA materials. Specifically, structural evaluation was performed to gather information on the following:
• The effect of milling off portions or the entire existing HMA surface layer on existing pavement structural capacity.
• The structural contribution of superior HMA materials (i.e., is it significantly higher than the structural contributions of conventional HMA mixes to warrant the use of high HMA structural coefficients?)

This report describes the structural evaluation of individual flexible and composite pavement projects at different sites throughout Ohio and the analysis of the evaluation results to develop any necessary enhancements to the ODOT HMA overlay design procedure. The report presents detailed descriptions of the projects evaluated, field testing procedures, procedure for analyzing field test and other collected data, structural evaluation results, analysis of results, and recommendations for improvements of the current design procedure.

Current ODOT HMA Overlay Design Procedures

HMA Overlays over Existing HMA Pavements

For structural HMA overlays over existing HMA pavements, the required HMA overlay thickness is determined as follows (ODOT 1999):

$$SN_{OL} = SN_{req} - SN_{eff}$$  \hspace{1cm} Eq. 1

where,
- $SN_{OL}$ = required overlay structural number
- $SN_{req}$ = structural number required to carry future traffic
- $SN_{eff}$ = effective structural number of the existing pavement

The required HMA overlay thickness is determined as follows:

$$D_{OL} = \frac{SN_{req} - SN_{eff}}{a_{OL}}$$  \hspace{1cm} Eq. 2

where,
- $a_{OL}$ = structural coefficient of the HMA overlay
- $D_{OL}$ = required overlay thickness, in

$SN_{req}$ is computed using future (12 years) traffic estimates and the pavement subgrade resilient modulus backcalculated using deflection test data. The effective structural number should theoretically be determined from the layer properties of the existing pavement as follows:

$$SN_{eff} = \sum_{i=1}^{n} h_i a_i$$  \hspace{1cm} Eq. 3
where $h_i$ and $a_i$ are the in situ thickness and structural coefficients of each layer within the entire pavement structure. However, typically, for HMA overlay design based on deflection testing, individual structural layer coefficients cannot be estimated.

Thus, $SN_{ef}$ is computed using a backcalculated composite elastic modulus, $E_p$, representing all layers above the subgrade. The composite layer modulus, $E_p$, representing all layers above the subgrade, is estimated from the deflection test data. Note that the deflections obtained from testing are corrected for the effects of HMA layer temperature during backcalculation to obtain a more standardized and reasonable estimate of $E_p$. The equation for computing $SN_{ef}$ is as follows:

$$SN_{ef} = 0.0045 \times h_p \times (E_p)^{0.33}$$

Eq. 4

Finally, $SN_{OL}$ is determined from equation 1 based on the estimated $SN_{ef}$ and $SN_{req}$. The required HMA overlay thickness can then be estimated from $SN_{OL}$ using the structural coefficients representative of the proposed HMA overlay material.

**HMA Overlays over Existing Composite Pavements**

The ODOT procedure considers any asphalt-surfaced pavement (i.e., conventional HMA, deep strength HMA, full-depth HMA, HMA over PCC, HMA over rubblized PCC) with an Edwards ratio of less than 3 as a composite pavement (ODOT 1999). A rigid pavement is considered as a special case of a composite pavement with surface layer thickness, $h_{AC}$, equal to zero. This is a valid assumption since the structural behavior of most composite pavements is dominated by the underlying PCC slab.

The required overlay thickness to increase structural capacity to carry future traffic is determined using the following equation (ODOT 1999):

$$D_{OL} = A(D_{req} - D_{eff})$$

Eq. 5

where,

- $D_{OL}$ = required HMA overlay, in
- $A$ = factor to convert PCC thickness deficiency to asphalt concrete (AC) overlay thickness
- $D_{req}$ = slab thickness to carry future traffic
- $D_{eff}$ = effective equivalent PCC slab thickness of existing pavement

To determine the effective thickness of composite pavement, the existing pavement is compared with a new composite pavement having the same layer thickness as the existing composite pavement. The effective thickness of the new composite pavement can be estimated as follows:

$$D_{eff} = \frac{D_{new}}{(E_{eff} / E_p)^{0.33}}$$

Eq. 6
D_{new} is the effective PCC thickness of the composite pavement and is calculated as follows:

\[ D_{new} = \frac{h_{AC}}{2} + h_{PCC} \]  

where, \( h_{AC} \) is the thickness of the existing bituminous layers and \( h_{PCC} \) is the thickness of the existing PCC layer.

\( E_P \) is the effective elastic modulus of the existing pavement (combination of all layers above the subgrade) and is determined through backcalculation using deflection test data and the AREA method. No temperature correction is applied to the raw deflection test data. AREA is computed using all five Dynaflect sensors and, thus, reflects the structural contributions of both the HMA and PCC layers, along with any other layers in the pavement system:

\[ AREA = \frac{1}{S_1} (2.81*S_1 + 8.0*S_2 + 10.87*S_3 + 11.515*S_4 + 5.835*S_5) \]  

\( E_{eff} \) is the effective elastic modulus of the combined HMA and PCC layers and can be determined based on the equivalent rigidity concept, as illustrated in the following discussion.

Modulus of rigidity of a plate or slab, \( R \), is defined as:

\[ R = \frac{EI}{1 - \nu^2} = \frac{Eh^3}{12(1 - \nu^2)} \]  

where \( E \), \( \nu \), \( I \), and \( h \) are the modulus of elasticity, Poisson’s ratio, moment of inertia, and plate thickness. For a bonded two-layer system (HMA/PCC), the rigidity of each layer is as follows:

\[ R_1 = \frac{E_{AC}\left(\frac{h_{AC}^3}{12} + h_{AC}(0.5h_{AC} + h_{PCC} - b)^2\right)}{1 - \nu_{AC}^2} \]  

\[ R_2 = \frac{E_{PCC}\left(\frac{h_{PCC}^3}{12} + h_{PCC}(b - 0.5h_{PCC})^2\right)}{1 - \nu_{PCC}^2} \]  

\[ b = \frac{\left(\frac{E_{AC}}{E_{PCC}}\right)h_{AC}(0.5h_{AC} + h_{PCC})^2 + 0.5h_{PCC}}{\left(\frac{E_{AC}}{E_{PCC}}\right)h_{AC} + h_{PCC}} \]
where,
\[
R_1 = \text{rigidity of the HMA layer} \\
R_2 = \text{rigidity of the PCC layer} \\
h_{AC} = \text{thickness of the HMA layer} \\
h_{PCC} = \text{thickness of the PCC layer} \\
E_{AC} = \text{elastic modulus of the HMA layer} \\
E_{PCC} = \text{elastic modulus of the PCC layer} \\
\nu_{AC} = \text{Poisson’s ratio of the HMA layer} \\
\nu_{PCC} = \text{Poisson’s ratio of the PCC layer}
\]

The combined rigidity of the two bonded layers can be calculated as:
\[
R_t = R_1 + R_2 = \frac{E_{\text{eff}} h^3}{12(1 - \nu^2)}
\]
Eq. 13

where \( h = h_{AC} + h_{PCC} \) and \( \nu \) is the equivalent Poisson’s ratio for the composite layer. Therefore, \( E_{\text{eff}} \) can be calculated as follows:
\[
E_{\text{eff}} = \frac{12(1 - \nu^2)(R_1 + R_2)}{h^3}
\]
Eq. 14

Finally, as shown in equation 5, the HMA overlay thickness is determined using \( D_{\text{req}}, D_{\text{eff}}, \) and “A.” The “A” factor is used to convert PCC thickness deficiency to an equivalent HMA overlay thickness. It is defined as follows:
\[
A = 2.2233 + 0.0099(D_{\text{req}} - D_{\text{eff}})^2 + 0.1534(D_{\text{req}} - D_{\text{eff}})
\]
Eq. 15

Suggested Areas for Improvement to ODOT HMA Overlay Design Procedure

HMA Overlays of Existing HMA Pavements

Figure 1 presents a simplified flow diagram of ODOT’s design process for HMA overlay over existing flexible pavement and indicates areas that were reviewed to meet the study objectives:

- **Issue #1: Temperature Adjustment of Surface Deflections.** The ODOT procedure for adjusting the maximum pavement deflection, \( S_1 \), to a standard temperature of 68 °F for estimating layer moduli is based on the procedures documented in the AASHTO 1993 Guide. This procedure was evaluated to examine its sensitivity and reasonableness.
- **Issue #2: Impact of Milling on SN_{\text{eff}}.** In the ODOT procedure, SN_{\text{eff}} is derived from both \( h_p \) and \( E_p \) (equation 4). In the simplest case, an adjustment to \( h_p \) to account for the milled depth would appear to be sufficient to account for the effect of milling on SN_{\text{eff}}. However, it is possible that milling could also impact \( E_p \), depending on the condition of the existing pavement (in terms of both structural and durability distress) and the depth of...
milling relative to the existing pavement section. Another side effect of milling is the
damage caused to the existing structure by the milling operation itself, which could affect
$E_p$. Therefore, the impact of milling on both $h_p$ and $E_p$ and eventually $SN_{eff}$ was
evaluated.

- **Issue #3: Impact of New HMA Materials on $a_{OL}$.** The appropriate structural layer
coefficient, $a_{OL}$, for the newer HMA materials used in the overlay layers was
investigated, as it directly affects the $D_{OL}$ term (equation 2). In a straightforward scenario,
the $a_{OL}$ will be a simple function of the effect of the paving material on performance
(cracking, raveling, and rutting) and serviceability.

![Diagram of the ODOT’s HMA/HMA overlay design process]

Figure 1. Overview of ODOT’s HMA/HMA overlay design process and potential issues that
need further investigation.
HMA Overlays over Existing Composite Pavements

Figure 2 presents a simplified flow diagram of ODOT’s design methodology for overlays over existing composite pavements and highlights areas that need to be reviewed to meet the study objectives:

- **Issue #1: Impact of Milling on $D_{eff}$**: As with HMA overlays of existing HMA pavements, partial milling of the HMA layers in a composite pavement structure can affect the backcalculated $E_p$. The relative impact of milling in composite pavements may not be as great as for HMA overlays of existing HMA pavements. However, this was investigated to ascertain how reasonable this hypothesis is.

- **Issue #2: Impact of Milling on $E_{eff}$**: It is obvious from equation 13 that milling the HMA layer can affect the computed $E_{eff}$—a key input for estimating the existing composite pavement’s effective thickness.

```
Obtain Dynaflect Deflections

Compute $E_p$, $k$

Compute $D_{eff}$

$D_{eff} = \frac{D_{new}}{(E_{eff}/E_p)^{1/3}}$

Estimate $D_{req}$

$h_{OL} = A(D_{req} - D_{eff})$

$A = f(D_{req}, D_{eff})$
```

Figure 2. Overview of ODOT’s HMA/Composite overlay design process and potential issues that will need further investigation.
Structural Evaluation of Selected Flexible and Composite Pavement Projects

Selection of HMA/HMA and HMA/Composite Pavement Projects for Structural Evaluation

The projects for detailed structural evaluation to verify ODOT’s overlay design process were selected by ODOT personnel. The criteria used for selection were as follows:

- The selected project must currently be undergoing rehabilitation or have just undergone rehabilitation (this allowed detailed project-specific data to be collected).
- The selected project should be representative of typical ODOT flexible, rigid, and composite pavement designs (layer thicknesses, material types, etc.).
- Pre-overlay repairs should as much as possible represent typical ODOT practices (milling, patching, etc.).
- The selected projects collectively must represent ODOT site conditions (i.e., traffic, climate, and subgrade).
- The structural condition of the individual projects prior to rehabilitation must represent that of typical ODOT pavements prior to rehabilitation (e.g., a pavement in moderate to poor condition with a Pavement Condition Rating [PCR] ranging from 55 to 65).

Of the 25 projects identified, 17 were selected for detailed evaluation. Reasons for selecting the 17 projects included the availability of detailed data for pavement evaluation, ability to satisfy project objectives, and consistency in pavement type throughout the rehabilitation process. For example, the pavement “type” for some projects changes as they go through the rehabilitation process (e.g., composite-to-rigid-to-flexible). Such projects were not considered for analysis because it makes it difficult to compare the structure prior to, during, and after rehabilitation. Only those projects where the pavement type is maintained at least for two of the three rehabilitation stages were selected and included in analysis.

Detailed descriptions of the selected projects are presented in table 1. Figure 3 shows the geographical locations of these 17 selected projects:

- HMA/PCC (or composite) pavements.
  - ERI-6 Westbound (remains composite through all 3 stages of rehabilitation)
  - FAY 71 Northbound (composite pavement prior to and after overlay)
  - FAY/MAD 71 Southbound (composite pavement prior to and after overlay)
  - GRE-4 Southbound (composite pavement prior to and after overlay)
  - JEF-7 Northbound (remains composite through all 3 stages of rehabilitation)
  - MOT-4 Northbound (composite pavement prior to and after overlay)
  - MOT-40 (04) Westbound (remains composite through all 3 stages of rehabilitation)
  - ROS-35 Northbound (remains composite through all 3 stages of rehabilitation)
  - WAY-30 Westbound (remains composite through all 3 stages of rehabilitation)
Figure 3. Map of projects selected for detailed structural evaluation.
Table 1. General description of the pavement projects selected for evaluation.

<table>
<thead>
<tr>
<th>Project Number</th>
<th>Site ID</th>
<th>Project ID</th>
<th>Project Location</th>
<th>ODOT District No.</th>
<th>County</th>
<th>Route Type</th>
<th>Route No.</th>
<th>Site Begin Station</th>
<th>Site End Station</th>
<th>Original Pavement Type</th>
<th>Pavement Type During Rehabilitation</th>
<th>Pavement Type after Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ERI-6</td>
<td>1</td>
<td>Westbound (1,500-ft)</td>
<td>3</td>
<td>Erie</td>
<td>U.S. 6</td>
<td>—</td>
<td>—</td>
<td>Composite*</td>
<td>Composite*</td>
<td>Composite*</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>FAY-71</td>
<td>N</td>
<td>Northbound (5,280-ft)</td>
<td>6</td>
<td>Fayette</td>
<td>Interstate 71</td>
<td>726+63</td>
<td>779+43</td>
<td>Composite*</td>
<td>Rigid*</td>
<td>Composite*</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>FAY/MAD-71</td>
<td>S</td>
<td>Southbound (5300-ft)</td>
<td>6</td>
<td>Fayette &amp; Madison</td>
<td>Interstate 71</td>
<td>35+00</td>
<td>88+00</td>
<td>Composite*</td>
<td>Rigid*</td>
<td>Composite*</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>GRE-4</td>
<td>N</td>
<td>Northbound (5,499-ft)</td>
<td>8</td>
<td>Greene</td>
<td>State 4</td>
<td>105+50</td>
<td>160+49</td>
<td>Composite*</td>
<td>Rigid*</td>
<td>Composite*</td>
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<tr>
<td>5</td>
<td>JEF-7</td>
<td>1</td>
<td>Northbound (1,500-ft)</td>
<td>11</td>
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<td>351+65</td>
<td>Composite*</td>
<td>Composite*</td>
<td>Composite*</td>
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<td>6</td>
<td>MOT-4</td>
<td>S</td>
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<td>7</td>
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<td>Rigid*</td>
<td>Composite*</td>
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<td>7</td>
<td>MOT-40 (04)</td>
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<td>Westbound (800-ft)</td>
<td>7</td>
<td>Montgomery</td>
<td>U.S. 40</td>
<td>—</td>
<td>—</td>
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<td>Composite*</td>
<td>Composite*</td>
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<tr>
<td>8</td>
<td>ROS-35</td>
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<td>Northbound (1,500-ft)</td>
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<td>Ross</td>
<td>U.S. 35</td>
<td>1214+36</td>
<td>1229+36</td>
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<td>9</td>
<td>WAY-30</td>
<td>1</td>
<td>Westbound (1,500-ft)</td>
<td>3</td>
<td>Wayne</td>
<td>U.S. 30</td>
<td>1271+92</td>
<td>1286+92</td>
<td>Composite*</td>
<td>Composite*</td>
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</table>

*Used in analysis.
Table 1. General description of the pavement projects selected for evaluation, continued.

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<th>Site ID</th>
<th>Project ID</th>
<th>Project Location</th>
<th>ODOT District No.</th>
<th>County</th>
<th>Route No.</th>
<th>Route Type</th>
<th>Site Begin Station</th>
<th>Site End Station</th>
<th>Original Pavement Type</th>
<th>Pavement Type During Rehabilitation</th>
<th>Pavement Type after Rehabilitation</th>
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<tbody>
<tr>
<td>10</td>
<td>CLA-68</td>
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<td>Southbound (1,550-ft)</td>
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<td>Clark</td>
<td>68</td>
<td>U.S.</td>
<td>—</td>
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<td>Flexible HMA/HMA*</td>
<td>Flexible HMA/HMA*</td>
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<td>11</td>
<td>GAL-35</td>
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<td>Gallia</td>
<td>35</td>
<td>U.S.</td>
<td>158+29</td>
<td>173+29</td>
<td>Flexible HMA/Rubblized PCC*</td>
<td>Flexible HMA/Rubblized PCC*</td>
<td>Flexible HMA/Rubblized PCC*</td>
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<td>12</td>
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<td>Greene</td>
<td>72</td>
<td>U.S.</td>
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<td>Flexible HMA/HMA*</td>
<td>Flexible HMA/HMA*</td>
<td>Flexible HMA/HMA*</td>
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<td>JAC-32</td>
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<td>Eastbound (1,500-ft)</td>
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<td>Jackson</td>
<td>32</td>
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<td>1171+46</td>
<td>1186+46</td>
<td>Flexible HMA/HMA*</td>
<td>Flexible HMA/HMA*</td>
<td>Flexible HMA/HMA*</td>
</tr>
<tr>
<td>14</td>
<td>LIC-70</td>
<td>1</td>
<td>Eastbound (1,500-ft)</td>
<td>5</td>
<td>Licking</td>
<td>70</td>
<td>Interstate</td>
<td>1137+51</td>
<td>1152+51</td>
<td>Flexible HMA/Rubblized PCC*</td>
<td>Flexible HMA/Rubblized PCC*</td>
<td>Flexible HMA/Rubblized PCC*</td>
</tr>
<tr>
<td>15</td>
<td>MOT-40</td>
<td>05</td>
<td>Eastbound (800-ft)</td>
<td>7</td>
<td>Montgomery</td>
<td>40</td>
<td>U.S.</td>
<td>—</td>
<td>—</td>
<td>Flexible*</td>
<td>Flexible*</td>
<td>Flexible*</td>
</tr>
<tr>
<td>16</td>
<td>ROS-35</td>
<td>MM 9.15</td>
<td>Westbound (750-ft)</td>
<td>9</td>
<td>Ross</td>
<td>35</td>
<td>U.S.</td>
<td>—</td>
<td>—</td>
<td>Flexible*</td>
<td>Flexible*</td>
<td>Flexible*</td>
</tr>
<tr>
<td>17</td>
<td>ROS-35</td>
<td>MM 10.0</td>
<td>Westbound (1,500-ft)</td>
<td>9</td>
<td>Ross</td>
<td>35</td>
<td>U.S.</td>
<td>—</td>
<td>—</td>
<td>Flexible*</td>
<td>Flexible*</td>
<td>Flexible*</td>
</tr>
</tbody>
</table>

*Used in analysis.
- HMA/HMA (or flexible) pavements.
  - CLA-68 Southbound (HMA overlay of existing HMA pavement)
  - GAL-35 Westbound (remains HMA/rubblized through all 3 stages of rehabilitation)
  - GRE-72 Northbound (HMA overlay of existing HMA pavement)
  - JAC-32 Eastbound (HMA overlay of existing HMA pavement)
  - LIC-70 Eastbound (HMA overlay of existing HMA/Rubblized PCC)
  - MOT-40 (05) Eastbound (HMA overlay of existing HMA through all 3 stages of rehabilitation)
  - ROS-35 MM 9.15 (remains flexible through all 3 stages of rehabilitation)
  - ROS-35 MM 10 (remains flexible through all 3 stages of rehabilitation)

Project Rehabilitation Activities and Structural Evaluation (Field and Lab Testing)

Rehabilitation of existing flexible and composite pavements consisted of (1) milling off portions or the entire existing HMA layer (all projects), (2) patching of the deteriorated portions of the pavement, and (3) the placement of HMA overlays (all projects). Structural evaluation consisted of several different activities, including (1) windshield survey prior to rehabilitation and records review, (2) extraction of cores, examination of cores for distress/damage, and layer thickness measurements, and (3) nondestructive deflection testing.

For this study, ODOT personnel performed the windshield survey to characterize the pavement’s visual condition prior to rehabilitation. During the windshield survey, the general condition of the pavement was rated in accordance with standard ODOT rating methods. The overall condition of the pavement was characterized using the PCR index (see table 2). Also, photo logs of distressed areas within a project were taken and provided to the project team. The result of the windshield survey was the assembly of reliable data on the condition of the projects selected prior to rehabilitation.

Table 2. ODOT PCR scale (ODOT 1999).

<table>
<thead>
<tr>
<th>PCR Scale</th>
<th>Condition Rating</th>
<th>Description of Pavement Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 to 100</td>
<td>Very good</td>
<td>Perfect pavement with no observable distress</td>
</tr>
<tr>
<td>75 to 90</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>65 to 75</td>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>55 to 65</td>
<td>Fair to poor</td>
<td></td>
</tr>
<tr>
<td>40 to 55</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>0 to 40</td>
<td>Very poor</td>
<td>All distresses present at their “High” levels of severity and “Extensive” levels of extent</td>
</tr>
</tbody>
</table>

Coring was performed under ODOT supervision. The extracted cores were evaluated in the laboratory to determine layer thicknesses, material type, and layer material condition/damage. Information from the cores was used to define pavement type and to determine as-constructed layer types and thicknesses, which are key inputs for structural analysis.
Nondestructive deflection testing was performed using a Dynamic Deflection Determination System (Dynaflect) for all 17 projects. Additional deflection tests were performed for 7 of the projects using a Falling Weight Deflectometer (FWD). Dynaflect is a trailer mounted device which induces a total of 1,000 lb of dynamic load at a frequency of 8 Hz on a pavement and measures the resulting pavement deflections using five geophones placed at approximately 12-in intervals from the center of the loads. The FWD is capable of applying dynamic loads to the pavement surface, similar in magnitude and duration to that of a single heavy moving wheel load. The response of the pavement system is measured in terms of vertical deformation, or deflection, over a given area using geophones. For the standard FWD, load can be applied at four levels, ranging typically from 1,500 to 24,000 lb. Deflections are measured using seven geophones placed at 0-, 8-, 12-, 18-, 24-, 36-, and 60-inches apart, with the first geophone placed at the center of the loading plate.

Although nondestructive deflection testing has numerous applications, for this study, measured deflections were used to (1) individually or together to compute various indices that are commonly used to characterize pavement structural condition and (2) backcalculate layer elastic moduli, which were then used to characterize pavement structural capacity.

Table 3 presents a detailed description of the activities that were performed as part of both pavement rehabilitation and structural evaluation, while table 4 presents details of the actual rehabilitation and structural evaluation performed for each selected project.

Analysis of Field and Laboratory Testing Results

Structural analysis consisted of analyzing field test data along with theoretical analysis to evaluate the key aspects of ODOT HMA overlay design listed below:

- **HMA overlays of existing flexible pavements**
  - Temperature adjustment of surface deflections.
  - Impact of milling on $S_{\text{Neff}}$.
  - Impact of milling on $a_{\text{OL}}$.
- **HMA overlays over existing composite pavements**
  - Impact of milling on $h_{\text{AC}}$.
  - Backcalculation of $E_p$ (compressibility in HMA overlay).
  - Impact of milling on $D_{\text{eff}}$.
  - Impact of milling on $E_{\text{eff}}$.
  - Impact of milling on $a_{\text{OL}}$. 
Table 3. Detailed description of pavement structural evaluation and rehabilitation activities.

<table>
<thead>
<tr>
<th>Activity Number</th>
<th>Activity Name</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Windshield distress survey and record review</td>
<td>Windshield survey consisted of a drive through the entire pavement section at traffic speed. A record of distresses present and general pavement condition was made during the drive. Significant distresses observed were photographed. Records review consisted of assembling and evaluating historical pavement design, construction, performance, and maintenance &amp; rehabilitation (M&amp;R) information available in ODOT pavement management system databases and files. Specific information reviewed was related to (1) pavement type, (2) pavement structure, (3) subgrade soil type, (4) past maintenance and rehabilitation history, (5) pavement performance history (from windshield surveys, PCR, etc.), and (6) traffic.</td>
</tr>
</tbody>
</table>
| 2               | First structural evaluation         | (1) Coring  
(2) Laboratory inspection and thickness measurement of cores  
(3) Deflection testing of pavement—This was done using Dynaflect or FWD testing equipment. Testing was typically done over the entire project section. Appropriate temperature corrections were applied to the actual deflection test data. The reference temperature for adjustments was 68°F. |
| 3               | Pre-overlay repair activities       | Flexible  
(1) Milling of significant portions of the existing HMA surface layer  
Composite  
(1) Milling of significant portions of the existing AC surface layer |
| 4               | Second structural evaluation       | (1) Deflection testing after milling. |
| 5               | HMA overlay placement               | HMA overlays were placed after pre-overlay repairs to complete pavement rehabilitation. This was done for all 18 projects evaluated |
| 6               | Third structural evaluation        | (1) Coring  
(2) Laboratory inspection and thickness measurement of cores  
(3) Deflection testing of pavement |
### Table 4. Description of project specific structural evaluation/rehabilitation activities.

<table>
<thead>
<tr>
<th>Section ID</th>
<th>ARA Project No.</th>
<th>Final Pavement Type</th>
<th>Windshield Survey</th>
<th>First Structural Evaluation</th>
<th>Significant Pre-overlay Repairs&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Second Structural Evaluation</th>
<th>Placement of HMA Overlay&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Third Structural Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERI-6</td>
<td>1</td>
<td>Composite</td>
<td>No</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>1.5-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>FAY-71</td>
<td>2</td>
<td>Composite</td>
<td>No</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 2.9-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>8.5-in HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>FAY/MAD-71</td>
<td>3</td>
<td>Composite</td>
<td>No</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 2.9-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>8.5-in HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>GRE-4</td>
<td>4</td>
<td>Composite</td>
<td>No</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 2.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>6.0-in HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>JEF-7</td>
<td>5</td>
<td>Composite</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect</td>
<td>Milling off 3.25-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>5.0-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>MOT-4</td>
<td>6</td>
<td>Composite</td>
<td>No</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 2.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>6.0-in HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>MOT-40 (04)</td>
<td>7</td>
<td>Composite</td>
<td>No</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 2.0-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>2.0-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>ROS-35</td>
<td>8</td>
<td>Composite</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect</td>
<td>Milling off 1.75-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>3.25-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>WAY-30</td>
<td>9</td>
<td>Composite</td>
<td>No</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>3.25-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
</tbody>
</table>

1. Layer thicknesses are average computed from cores or obtained from ODOT records.
Table 4. Description of project specific structural evaluation/rehabilitation activities, continued.

<table>
<thead>
<tr>
<th>Section ID</th>
<th>Project ID</th>
<th>Final Pavement Type</th>
<th>Windshield Survey</th>
<th>First Structural Evaluation</th>
<th>Significant Pre-overlay Repairs&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Second Structural Evaluation</th>
<th>Placement of HMA Overlay&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Third Structural Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA-68</td>
<td>10</td>
<td>HMA over existing HMA</td>
<td>Yes</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>1.8-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>GAL-35</td>
<td>11</td>
<td>HMA over rubblized PCC</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>1.5-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>GRE-72</td>
<td>12</td>
<td>HMA over existing HMA</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>1.5-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>JAC-32</td>
<td>13</td>
<td>HMA over existing HMA</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 1.5-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>3.3-in HMA</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>LIC-70</td>
<td>14</td>
<td>HMA over rubblized PCC</td>
<td>No</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 1.75-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>1.75-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>MOT-40 (05)</td>
<td>15</td>
<td>HMA over existing HMA</td>
<td>No</td>
<td>Deflection testing using Dynaflect</td>
<td>Milling off 1.25-in of existing HMA</td>
<td>Deflection testing using Dynaflect</td>
<td>2.0-in HMA</td>
<td>Coring and deflection testing using Dynaflect</td>
</tr>
<tr>
<td>ROS-35 MM 9.15</td>
<td>16</td>
<td>HMA over existing HMA</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 2.8-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>3.1-in HMA</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
</tr>
<tr>
<td>ROS-35 MM 10.0</td>
<td>17</td>
<td>HMA over existing HMA</td>
<td>Yes</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
<td>Milling off 1.9-in of existing HMA</td>
<td>Deflection testing using Dynaflect and FWD</td>
<td>3.2-in HMA</td>
<td>Coring and deflection testing using Dynaflect and FWD</td>
</tr>
</tbody>
</table>

1. Layer thicknesses represent average values along the project length.
The analysis was divided into three parts, as follows:

1. Preliminary analysis of field deflection data (reviewing trends in raw deflection data along with computed structural indices to determine the effect of milling and HMA overlay on pavement structural capacity).
2. Detailed analysis of field data (backcalculating layer moduli and determining the effect of milling and HMA overlay on pavement structural capacity).
3. Theoretical analysis (using layer elastic analysis to simulate pavement responses).

*Preliminary Structural Analysis*

Preliminary analysis consisted of reviewing trends in deflections and computed indices that are indicative of overall pavement, pavement upper layer, and subgrade structural capacity, as appropriate. The structural indices to characterize pavement structural condition were as follows (Attoh-Okine and Roddis 1994; FHWA 2000; Edwards et al. 1989):

- Maximum deflection, $S_1$: a measure of overall pavement structural capacity.
- Spreadability (SPR): a measure of pavement upper layers structural capacity.
- AREA: a measure structural capacity of the load carrying layers of a rigid or composite pavement system.
- Subgrade deflection, $S_5$: a measure of subgrade strength.

Maximum deflection is an indicator of overall pavement structural capacity, and it is the deflection reported by the sensor closest to the applied load. For Dynaflect, the closest sensor is 10 inches away from the applied load, as shown in figure 4. Figure 5 shows a typical deflection profile/basin obtained from Dynaflect deflection testing with sensor 1 reporting the highest deflections. Table 5 describes a typical range of maximum deflection values that corresponds to various levels of overall pavement structural condition (Edwards et al. 1989). As shown in table 5, an increase in maximum deflection value implies a decrease in the overall pavement structural capacity.

Spreadability (SPR) is a parameter used to determine the strength of the upper pavement layers (HMA for flexible pavements, PCC for rigid pavements, and HMA/PCC for composite pavements). SPR is computed using the following equation (Attoh-Okine and Roddis 1994):

$$SPR = \frac{100\sum W_1 + W_2 + W_3 + W_4 + W_5}{5W_1}$$

Table 5 describes a typical range of SPR values that corresponds to various levels of pavement upper layers structural condition. As indicated in table 5, higher values of SPR indicate increased pavement upper layer strength.

For composite pavements, the AREA method estimates the radius of relative stiffness of the plate as a function of the AREA computed from the deflection basin (equation 8). This estimation is used for the subsequent calculation of modulus of subgrade reaction, $k$, and slab modulus of elasticity, $E$, (using simple closed form equations). The AREA method for
computing E and k is based on Westergaard’s solution for the interior loading of a plate consisting of a linear elastic, homogeneous, and isotropic material resting on a dense-liquid foundation (AASHTO 1993). A higher AREA value indicates weaker pavement foundation and strength.

Subgrade deflection $S_5$ is an indicator of subgrade strength and is used in closed form equations to compute subgrade resilient modulus. A high $S_5$ value indicates weaker pavement foundation and strength.

For preliminary analysis, $S_1$ and SPR profiles were developed for each project before, during, and after rehabilitation. The profiles of $S_1$, $S_5$, and SPR were evaluated by (1) reviewing the plots to observe trends and changes in values for the different stages of rehabilitation and (2) performing a statistical analysis of variance (ANOVA) to determine if there were significant changes in mean values of the indices for the different rehabilitation stages (Ott and Longnecker, 2001). The level of significance used in statistical analysis was 5 percent. Additionally, multiple comparison procedures were used to determine which means are different from each other.

Figure 4. Configuration of Dynaflect deflection testing equipment load wheels and geophones (ODOT 1997).

Figure 5. Typical deflection basin/profile from a Dynaflect deflection test (Attoh-Okine and Roddis 1994).
Table 5. Interpretation of Dynaflect data on continuous pavement (Edwards et al. 1989).

<table>
<thead>
<tr>
<th>Pavement Structural Condition</th>
<th>Flexible Pavement</th>
<th>Rigid and Composite Pavements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S₁ (mils)</td>
<td>SPR (percent)*</td>
</tr>
<tr>
<td>Excellent</td>
<td>&lt;0.5</td>
<td>&gt;72</td>
</tr>
<tr>
<td>Good</td>
<td>0.5 to 0.7</td>
<td>62 to 72</td>
</tr>
<tr>
<td>Fair</td>
<td>0.71 to 0.90</td>
<td>52 to 61</td>
</tr>
<tr>
<td>Poor</td>
<td>&gt;0.90</td>
<td>&lt;52</td>
</tr>
</tbody>
</table>

*Range varies with pavement thickness and subgrade deflection.

Detailed Structural Analysis

Detailed structural analysis consisted of the following steps:

- **Assemble data:** Loading, deflection, future traffic estimates, ambient test temperature, and layer thickness/material type data were assembled for detailed structural analysis. Loading and corresponding deflection data were obtained from deflection testing using Dynaflect test equipment and FWD equipment where available. Layer thickness/material type data were assembled from cores collected as part of structural evaluation and supplemented by data available in ODOT records.

- **Backcalculate pavement layer moduli using ODOT DOITOVER software:** The assembled data were used to backcalculate pavement layer moduli using the DOITOVER program. DOITOVER assumes a two-layer pavement system to model flexible and composite pavements. The first layer consists of the entire pavement structure above the subgrade, and the second layer is the subgrade. The two-layer system was adopted because of its simplicity and the availability of closed-form equations that can be used to backcalculate layer modulus for such a system (ensures stable results). Details of the ODOT backcalculation procedure and the DOITOVER program have been presented in other references (ODOT 1997).

- **Determine SNeff or Deff and HMA overlay thickness needed to carry future traffic:** DOITOVER determines SNeff or Deff as appropriate and HMA overlay thickness needed to carry future traffic using the AASHTO structural deficiency approach. Full details of the ODOT HMA overlay thickness determination procedure for existing flexible and composite pavements have been presented in several ODOT references (ODOT 1997).

- **Evaluate results:** SNeff or Deff as appropriate and HMA overlay thicknesses required to carry future traffic obtained from DOITOVER for the different rehabilitation stages were compared for each project. The goal was to answer the following:

  - For the different stages of rehabilitation, is there a statistical difference in 1) mean SNeff or Deff as appropriate and 2) HMA overlay thickness required to carry the same future traffic?
  - Is SNeff or Deff (if significantly different) in agreement with engineering theory and mechanistic principles? That is:
    - Is there a difference in structural capacity of the original pavement and the original pavement after milling?
Is there a difference in the structural capacity of the original pavement and the pavement after rehabilitation (i.e., after milling, other pre-overlay repairs and placement of new HMA overlay)?

For mill and fill projects, did the use of new and/or superior HMA materials enhance structural capacity?

The results of the preliminary and detailed structural analysis for the projects evaluated are presented in chapters 2 through 18 of this report.

Theoretical Analysis

BISAR and DIPLOMAT, computer programs based on Layered Elastic Theory (LET), were used to simulate pavement responses when subjected Dynaflect loading at various stages of rehabilitation (e.g., after milling, after the placement of HMA overlay) for flexible and composite pavements, respectively (De Jong et. al., 1973; Khazanovich and Ioannides, 1995). Multi-layer elastic theory was selected for theoretical analysis, as it is the most common method used for estimating pavement response to vehicular loading. Layer elastic theory and analysis assumed that the pavement layers were:

- Homogeneous, isotropic, and elastic.
- Consisted of weightless materials.
- Infinite layers horizontally.
- Finite layer vertically with defined thicknesses except for subgrade.
- Subjected to static loading over a circular area.

Inputs required by BISAR and DIPLOMAT for theoretical analysis was obtained from ODOT records, field testing, and backcalculation. Specifically, the following inputs were used in analysis:

- Elastic modulus for each layer (backcalculated using Dynaflect and FWD deflection test data).
- Poisson’s ratio for each layer (assumed).
- Layer thicknesses (from extracted cores or obtained from ODOT records or both).
- Dynaflect load plate radius: 1.63 in.
- Applied load: 500 lb per wheel.

With these inputs, relevant pavement responses before, during, and after rehabilitation were computed. The theoretical deflections (pavement response) were then compared to actual measured Dynaflect or FWD deflections. The theoretical analysis results were used to establish expected trends in pavement responses when subjected to various kinds of treatments (e.g., milling, HMA overlay placement, etc.).

The trends established were used to determine reasonableness of actual trends observed from the structural evaluation of the 17 projects. Although the actual theoretical analysis results are not presented, deviations from expected trends obtained from theoretical analysis are discussed throughout this report.
CHAPTER 2. PROJECT ERI-6

Overview of Project ERI-6

Project ERI-6 is a 1,500-ft-long composite (HMA over PCC) pavement section located in the westbound lane of U.S. Route 6, Erie County (ODOT District 3). ODOT historical records indicate that it was constructed as a jointed plain concrete pavement (JPCP) in 1947. The original JPCP was overlaid with HMA in 1972. In 1990, a second HMA overlay (1.5-in HMA overlay consisting of 1.0-in ODOT Item 404 over 0.5-in ODOT Item 403) was placed after milling off approximately 1.25 inches of the 1972 HMA overlay. Significant rehabilitation was performed in 2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project ERI-6

A six-step rehabilitation/structural evaluation program was implemented in 2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project ERI-6

A comprehensive search of ODOT records was performed to obtain historical information pertaining to project ERI-6 original design and construction, subsequent maintenance and rehabilitation (M&R), and performance history. Specific information gathered was as follows:

- Historical pavement condition characterized using PCR. PCR data were available for the years 1986 through 2004. Detailed distress information from visual windshield surveys was not available.
- Historical traffic.
- Design plans describing layer thicknesses, material types, and so on.

The information was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. A summary of information assembled from ODOT records and confirmed through coring is presented in table 6. Presented in figures 6 and 7 are plots of historical pavement performance and traffic.

The PCR data plotted in figure 6 show a PCR of approximately 80 prior to the 1990 rehabilitation, suggesting an existing pavement in relatively good condition. The 1990 HMA overlay probably was placed to improve the functionality of the pavement. The PCR value reported in 1992 was nearly 100. Between 1992 and 2004, there was a steady decline in pavement condition, leading to a PCR of 66 (existing pavement in poor to fair condition) being reported in 2004.

The historical traffic information presented in figure 7 shows that traffic levels have not changed significantly since the early 1990’s. Annual Average Daily Traffic (AADT) just prior to the 2004 rehabilitation was estimated to be 11,404. ODOT records indicated that approximately 3.6 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2004 was estimated to be approximately 416.
Table 6. Timeline showing significant historical construction and M&R events for ERI-6.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Placement of a 5.5-in HMA</td>
<td>Stage A (Milling off 1.25-in of existing HMA layer)</td>
<td>Stage A (Milling off 1.5-in of existing HMA layer)</td>
</tr>
<tr>
<td></td>
<td>4.3-in HMA</td>
<td>1.5-in HMA (404)</td>
<td>1.5-in HMA (446)</td>
</tr>
<tr>
<td></td>
<td>6.9-in JPC</td>
<td>4.3-in HMA</td>
<td>4.3-in HMA</td>
</tr>
<tr>
<td></td>
<td>6-in Aggregate Base</td>
<td>6.9-in JPC</td>
<td>6.9-in JPC</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 2004 rehabilitation and specifically for this study.
Figure 6. Historical pavement performance characterized using PCR for ERI-6.

Figure 7. Historical traffic application for ERI-6.
Historical traffic growth (all vehicles) was insignificant and was estimated to be approximately 0.84 percent, linear. Thus, for analysis, the projected 20-year truck traffic was estimated to be 3,456,486 trucks, which translates into 2,070,000 rigid equivalent single axle loads (ESALs).

Step 2—First Structural Evaluation for Project ERI-6

A detailed and comprehensive structural evaluation was conducted in August 2004, prior to the commencement of 2004 rehabilitation activities. The structural evaluation consisted of only deflection testing using the Dynaflect; no cores were extracted.

Step 3—Pre-Overlay Activities/Repair for Project ERI-6

Following the first structural evaluation, comprehensive pre-overlay repairs were conducted, basically consisting of milling off 1.5 in of the existing HMA.

Step 4—Second Structural Evaluation for Project ERI-6

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement in September 2004. Second structural evaluation consisted of Dynaflect deflection testing only. Deflection testing was done as previously described in chapter 1. Test locations were matched as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project ERI-6

Following the second structural evaluation, a 1.5-in HMA overlay (ODOT Item 446, Type 1 mix, PG 64-22) was placed over the milled pavement structure.

Step 6—Third Structural Evaluation for Project ERI-6

The third and final structural evaluation was done after HMA overlay placement in November 2005. Structural evaluation consisted of field coring, laboratory examination of the cores (to determine their condition and layer thicknesses), and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

Coring and Laboratory Examination

Coring was performed in November 2005. Seven cores were extracted along the entire 1,500-ft length of the project section at intervals ranging from 100 to 300 ft. The extracted cores were visually examined to assess their condition. All seven cores were in poor to good condition. Although there were no signs of moisture damage or stripping, two of the cores were broken into several pieces. Photos of some of the extracted cores are presented in figure 8. Detailed information regarding core thicknesses and condition is as follows:
Mean HMA overlay thickness: 5.8 in (HMA overlay thickness ranged from 3.5 to 9.0 in, the 2004 HMA overlay thickness ranged from 1.25 to 1.5 in, with a mean value of 1.3 in).

Existing HMA prior to the 2004 overlay appears to be a sandy asphalt mix.

Mean total PCC thickness = 6.9 in (PCC thickness ranged from 6.5 to 7.5 in. Note that thickness measurements were not made for damaged/broken cores).

The condition of the HMA overlay at all seven locations was deemed good (i.e., intact material with less than two pieces).

Five of the seven PCC cores were deemed good (i.e., intact core with less than two pieces), and the remaining two cores were in poor condition (two or more pieces of PCC and rubble).

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

*Deflection Testing for Project ERI-6*

Deflection testing was done using a Dynaflect, as described in chapter 1. Testing was done as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.

*Data Analysis for Project ERI-6*

Coring and deflection testing results, along with other relevant information (such as layer type, pavement structure, and layer thicknesses) assembled from ODOT records were entered into a
project database. The data then were analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of the overall pavement system, pavement upper layers, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining the effective pavement thickness and HMA overlay thickness needed to carry future traffic.

The objective of both the preliminary and detailed analysis was to determine a baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically, milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity (specifically, filling with perhaps superior/thicker HMA materials). The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, S1. Figure 9 presents the plot of S1 profiles for project ERI-6 for different stages of rehabilitation in 2004, and it shows the following:

- Milling off the existing 1.5-in HMA did not significantly affect overall pavement system structural capacity (i.e., there was no observable difference in S1 of the original pavement and the original pavement after milling).
- Overall pavement deflection, S1 was highest after HMA overlay placement. This is contrary to expected trends. However, the increase was not statistically significant.
- Variability of S1 along the entire project did not change significantly with the placement of the HMA overlay.

The trends observed in figure 9 are confirmed by the ANOVA results presented in table 7. The AOV results also showed no significant changes in S1 during the rehabilitation process.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 10 presents SPR profiles at different stages of the 2004 rehabilitation, and it shows the following:

- Milling off the existing 1.5-in HMA significantly influenced pavement upper layers structural capacity.
- SPR before milling and after HMA overlay placement was essentially the same.
- SPR variability did not change significantly for the different stages of rehabilitation.

The trends observed in figure 10 are confirmed by the ANOVA results presented in table 8. There were no significant differences in SPR for each stage of rehabilitation.
Figure 9. Plot showing S₁ profiles for ERI-6.

Table 7. Summary of analysis of variance results for maximum deflections (ERI-6).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils*</th>
<th>Duncan's Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>7</td>
<td>0.467 (0.152)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>7</td>
<td>0.453 (0.177)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>7</td>
<td>0.510 (0.175)</td>
<td>Good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 8. Summary of analysis of variance results for SPR (ERI-6).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>7</td>
<td>67 (6.0)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>7</td>
<td>68 (6.8)</td>
<td>Fair</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>7</td>
<td>61 (4.8)</td>
<td>Fair</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Detailed Structural Analysis**

Detailed structural analysis involved computing the deflection basin parameter AREA and $D_{eff}$ for the different stages of rehabilitation. Both area AREA and $D_{eff}$ were computed as described in chapter 1.

By comparing the AREA, $D_{eff}$, and required HMA overlay thickness across the different stages of rehabilitation with the preliminary trends in maximum deflection and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed. Agreement between the trends observed in the preliminary and detailed analysis implies that the current ODOT backcalculation and overlay design procedure is effective.
Results of the detailed structural analysis are presented in tables 9 and 10. Information presented in table 9 shows that although trends observed in computed AREA appear to be reasonable, there is no significant differences in actual AREA values at the different rehabilitation stages. This is in agreement with trends observed in S1 and SPR. The information in table 10 shows $D_{eff}$ increasing after milling and decreasing after HMA overlay placement, a trend which is contrary to theory. However, the changes in $D_{eff}$ were not significant.

Information presented in table 10 indicates a 22 percent increase in backcalculated $E_p$ after milling with a corresponding 17 percent reduction in k-value. Both $E_p$ and k-value dropped to close to their pre rehabilitation values after HMA overlay placement. The before milling, after milling, and after HMA overlay placement $E_p$ and k-values estimates do not provide a clear trend on overall pavement strength.

Table 9. Summary of analysis of variance results for AREA (ERI-6).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>7</td>
<td>24.23 (2.95)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>7</td>
<td>24.81 (3.14)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>7</td>
<td>21.55 (2.26)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 10. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for ERI-6.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{eff}$, in*</th>
<th>Is There a Significant Difference in $D_{eff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>7</td>
<td>811,588 (361,342)</td>
<td>259 (134.2)</td>
<td>6.4 (0.42)</td>
<td>7.9 (1.2)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>7</td>
<td>1960,884 (1,251,005)</td>
<td>215 (73.3)</td>
<td>6.5 (0.22)</td>
<td>8.1 (1.3)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>7</td>
<td>583,322 (348,611)</td>
<td>288 (66.8)</td>
<td>6.3 (0.19)</td>
<td>6.8 (1.4)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Summary

Results of the preliminary and detailed structural analysis show that milling off a relatively small portion (1.5-in HMA) of the HMA layer of a composite pavement and the placement of a thin overlay (1.5-in HMA) did not significantly affect overall pavement structural capacity, as shown by the following trends:

- Overall pavement structural capacity characterized using $S_1$ did not change significantly over the different rehabilitation stages.
- Pavement upper layers structural capacity characterized using SPR did not change significantly over the different rehabilitation stages.
- Pavement foundation strength characterized using the parameter AREA did not change significantly over the different rehabilitation stages.
- Trends in computed $E_p$ and k-value were inconsistent with theory as there was a significant increase in $E_p$ and a significant decrease in k-value after milling.
- Overall pavement structural capacity characterized using $D_{eff}$ did not change significantly over the different rehabilitation stages. Trends in computed $D_{eff}$ were inconsistent with theory.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages although there were significant changes in k-value. This implies that the effect of k-value on determining required HMA overlay thickness is minimal.
CHAPTER 3. PROJECT FAY-71(N)

Overview of Project FAY-71(N)

Project FAY-71(N) is a 5,280-ft-long composite (HMA over PCC) pavement located in the northbound lanes of Interstate 71. The exact project location was between station 726+63 and 779+43 in Fayette County (ODOT District 6). Information available in ODOT records and from field studies indicates that the project was constructed originally as a 9.6-in jointed reinforced concrete pavement (JRCP) over 5.5-in subbase and subgrade. Although the ODOT records reviewed by the project team had no specific information on subgrade material type or properties, information obtained from nearby Long Term Pavement Performance projects (LTPP Project 39_9006 on I-71 in nearby Clinton County) indicate a fine-grained subgrade material classified as AASHTO A-6 to A-7-6.

The original 9.6-in JRCP was overlaid in 1978 with 2.9-in HMA overlay to become a composite pavement. Additional significant rehabilitation was performed in 1992 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project FAY-71(N)

A six-step rehabilitation/structural evaluation program was implemented in 1992, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Projects FAY-71(N)

A comprehensive search of ODOT records netted historical information pertaining to the project FAY-71(N) site, design, construction, M&R, and performance history. Although ODOT records yielded no specific distress information from past visual windshield surveys, there was information available on the historical pavement condition (characterized using PCR), original pavement and subsequent M&R design (original pavement structure and subsequent HMA overlay thicknesses, milling depths, and so on), layer material properties, and historical traffic. The information was assembled, reviewed for quality and consistency, and found to be generally reasonable. A summary of the information obtained from ODOT records is presented in table 11.

The plot in figure 11 shows the pavement condition history for project FAY-71(N). The plot agrees with historical M&R data from ODOT that show a pavement in fair to poor condition (PCR of 65) prior to rehabilitation in 1992. The plot shows that pavement condition improved significantly after 1992, with the PCR rising to approximately 96 (very good condition).

The historical traffic information presented in figure 12 shows an AADT of 27,380 in 1992. Approximately 30.4 percent of the AADT were trucks. Total daily truck traffic in 1992 was thus 8,332. Traffic growth over the 20-year analysis period was approximately 9.17 percent linear. Based on the traffic information obtained from ODOT records, projected 20-year traffic for FAY-71(N) analyzed as a rigid pavement was 56,100,000 million ESALs (122,428,783 trucks).
Table 11. Timeline showing significant historical construction and M &R events for FAY-71(N).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgrade</td>
<td>Placement of a 2.9-in HMA</td>
<td>Stage A (Milling off the existing HMA layer)</td>
</tr>
<tr>
<td>9.6-in JRC</td>
<td>2.9-in HMA</td>
<td>5.5-in HMA (301)</td>
</tr>
<tr>
<td>5.5-in Aggregate Base</td>
<td>9.6-in JRC</td>
<td>9.6-in JRC</td>
</tr>
<tr>
<td></td>
<td>5.5-in Aggregate Base</td>
<td>5.5-in Aggregate Base</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
<tr>
<td></td>
<td>New JRCP</td>
<td>3-in HMA (846)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5-in Aggregate Base</td>
</tr>
</tbody>
</table>

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 1992 rehabilitation and specifically for this study.
Figure 11. Historical pavement performance characterized using PCR for FAY-71(N).

Figure 12. Historical traffic application for FAY-71(N).
Step 2—First Structural Evaluation for Project FAY-71(N)

A comprehensive structural evaluation was conducted prior to rehabilitation in 1992. Structural evaluation consisted of extraction of cores, laboratory examination of the extracted cores, and nondestructive deflection testing. The coring was performed to determine existing pavement layer thicknesses, condition of the layer materials, and so on.

Core Extraction and Laboratory Examination for Project FAY-71(N)

Four cores were extracted from locations that reflected both pavement design and condition. Information on exact coring locations, however, was not available in the ODOT records reviewed. Also, information on the condition of the extracted cores was not available. Layer thickness information obtained from the four cores was as follows:

- Mean HMA thickness: 2.9 in (HMA thickness ranged from 2.75 to 3.0 in).
- Mean PCC thickness: 9.6 in (PCC thickness ranged from 9.0 to 10.0 in).

The measured core thicknesses were deemed reasonable, as they were in agreement with planned thicknesses obtained from ODOT records.

Nondestructive Deflection Testing for Project FAY-71(N)

Deflection testing was done using Dynaflect and FWD equipment. Testing was performed at 100- to 150-ft intervals along both projects.

Step 3—Pre-Overlay Repair for Project FAY-71(N)

Rehabilitation for FAY-71(N) in 1992 began with extensive pre-overlay repairs consisting of milling off the entire 2.9 in of the existing HMA layer.

Step 4—Second Structural Evaluation for Project FAY-71(N)

Limited field testing was done after pre-overlay repairs to characterize pavement structural capacity. Field testing consisted of deflection testing performed after milling the existing HMA overlay (i.e., on the intact JRCP slab). On the intact slab, deflection testing was done at the mid-slab and approach and leave ends of the transverse joint. However, only the mid-slab deflections were used in analysis.

Step 5—Placement of HMA Overlay For Project FAY-71(N)

Following pre-overlay repairs and the second structural evaluation, an 8.5-in HMA overlay was placed. The overlay consisted of a 3.0-in ODOT Item 846 surface layer and a 5.5-in ODOT Item 301 asphalt base layer.
Step 6—Third Structural Evaluation for Project FAY-71(N)

A third and final structural evaluation was done after the placement of the 8.5-in HMA overlay. Structural evaluation consisted of deflection testing only. Testing was done at 100- to 150-ft intervals and was made to match as closely as possible the locations of the previous deflection tests. Deflection testing was done as described in chapter 1.

Data Analysis for Project FAY-71(N)

All relevant information obtained from ODOT records and field testing was assembled into a project database. The data were analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement system and pavement upper layers strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining effective thicknesses and HMA overlay thickness needed to carry future traffic. The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity (specifically, milling and filling, use of superior HMA materials for overlay, use of thicker HMA overlays). The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 13 presents $S_1$ profiles for the different stages of rehabilitation. A review of the $S_1$ profiles shows the following:

- Milling off the existing 2.9-in HMA did not significantly affect overall pavement system structural capacity.
- $S_1$ was significantly lower after the placement of the 8.5-in HMA overlay, which indicates a significant increase in overall pavement system structural capacity after HMA overlay placement.
- Variability in $S_1$ along the entire project was considerably lower with the placement of the HMA overlay.

The trends observed in figure 13 were confirmed by the results of the ANOVA presented in table 12. The ANOVA results also showed that there was a significant decrease in $S_1$ after HMA overlay placement.
Table 12. Summary of analysis of variance results for maximum deflections (FAY-71(N)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Maximum Deflection</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original construction (2.9-in HMA over 9.6-in JRC)</td>
<td>6</td>
<td>0.385 (0.063)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Original construction (with 2.9-in HMA milled off)</td>
<td>6</td>
<td>0.455 (0.060)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Overlaid pavement (8.5-in HMA over 9.6-in fractured JRC)</td>
<td>5</td>
<td>0.222 (0.083)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 14 presents SPR profiles for project FAY-71(N) at different stages of rehabilitation and shows the following:
- Milling off the existing 2.9-in HMA significantly improved pavement upper layers structural capacity. The increased strength was most likely due to the removal of highly deteriorated surface material.
- SPR remained about the same after HMA overlay placement. This observation runs contrary to expectations.

The trends observed in figure 14 were confirmed by the results of the ANOVA presented in table 13. Also, the ANOVA results showed that there were significant differences in SPR for each stage of rehabilitation.

![Figure 14: Plot showing SPR profiles for FAY-71(N).](image)

**Table 13. Summary of analysis of variance results for SPR (FAY-71(N)).**

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from ANOVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original composite pavement (before milling)</td>
<td>6</td>
<td>71 (2.2)</td>
<td>Fair</td>
<td>B</td>
</tr>
<tr>
<td>Original pavement (with 2.9-in HMA milled off and intact PCC)</td>
<td>7</td>
<td>77 (3.0)</td>
<td>Fair</td>
<td>A</td>
</tr>
<tr>
<td>Overlaid pavement (with 8.5-in HMA overlay)</td>
<td>5</td>
<td>76 (1.3)</td>
<td>Fair</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis involved computing the deflection basin parameter AREA and $D_{eff}$ for the different stages of rehabilitation. Both AREA and $D_{eff}$ were computed as described in chapter 1.

By comparing the AREA and $D_{eff}$ across the different stages of rehabilitation with the preliminary trends in maximum deflection and SPR, the effectiveness of the ODOT procedure (programmed in DOITOVER) for backcalculating pavement layer moduli and characterizing pavement structural capacity could be assessed.

Results of the detailed structural analysis are presented in tables 14 and 15. Information presented in table 14 shows that there was a significant increase in AREA after milling. The reduction in AREA after HMA overlay placement was not significant. This was contrary to theory and past observed empirical trends. The information in table 15 shows $D_{eff}$ increasing significantly after HMA overlay placement, a trend which is reasonable and in agreement with theoretical analysis.

Table 14. Summary of analysis of variance results for AREA (FAY-71(N)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>25.81  (0.98)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2.9-in of existing HMA milled off)</td>
<td>5</td>
<td>28.72  (1.37)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>28.45  (0.66)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis show that milling off a considerable portion (2.9-in HMA) of the HMA layer of a composite pavement and the placement of a thick overlay (8.5-in HMA) did have a considerable to significant effect on overall pavement structural capacity, as shown by the following trends:

- Although there was no significant change in $S_1$ after milling off 2.9 in of the existing HMA layer, the placement of an 8.5-in HMA overlay did significantly reduce $S_1$ (increase in overall pavement structural capacity) as expected.
- Milling of 2.9 in of the existing HMA layer did significantly impact pavement upper layers structural capacity characterized using SPR. The placement of the 8.5-in HMA overlay, however, had no significant impact on SPR. This was contrary to expectations and theoretical analysis.
Table 15. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for FAY-71(N).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated $k$-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{eff}$, in</th>
<th>Is There a Significant Difference in $D_{eff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>1,059,808 (194,477)</td>
<td>243 (34.4)</td>
<td>11.4 (0.07)</td>
<td>8.2 (0.49)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2.9-in of existing HMA milled off)</td>
<td>6</td>
<td>3,483,840 (688,474)</td>
<td>130 (41.3)</td>
<td>11.7 (0.12)</td>
<td>8.5 (0.52)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>5</td>
<td>1,026,984 (239,165)</td>
<td>293 (93.5)</td>
<td>11.3 (0.19)</td>
<td>12.4 (1.08)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

- Pavement foundation strength characterized using the parameter AREA did change significantly after milling but was not affected by the HMA overlay placement.
- Trends in computed $E_p$ and $k$-value were inconsistent with theory, as there was a significant increase in $E_p$ and a significant decrease in $k$-value after milling.
- Overall pavement structural capacity characterized using $D_{eff}$ did not change significantly after milling. There was a significant increase in $D_{eff}$ (approximately 46 percent) after the placement of the 8.5-in HMA overlay. The observed trends were reasonable.
- Required HMA overlay thickness (computed based on expected future traffic and $k$-value) did not change significantly over the different rehabilitation stages although there were significant changes in $k$-value. This implies that the effect of $k$-value on determining required HMA overlay thickness is minimal.
CHAPTER 4. PROJECT FAY/MAD-71(S)

Overview of Project FAY/MAD-71(S)

Project FAY/MAD-71(S) is a 5,300-ft-long composite (HMA over PCC) pavement located in the southbound lanes of Interstate 71. The exact project location was between station 35+00 and 88+00 in Fayette and Madison counties (ODOT District 6). Information available in ODOT records and from field studies indicates that the project was constructed originally as a 9.6-in JRCP over 5.5-in subbase and subgrade. Although ODOT records had no specific information on subgrade material type or properties, information obtained from nearby LTPP projects (LTPP Project 39_9006 on Interstate 71 in nearby Clinton County) indicate a fine-grained subgrade material classified as AASHTO A-6 to A-7-6. The original 9.6-in JRCP was overlaid in 1978 with a 2.9-in HMA overlay, transforming it into a composite pavement. Additional significant rehabilitation was performed in 1992 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project FAY/MAD-71(S)

A six-step rehabilitation/structural evaluation program was implemented in 1992, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project FAY/MAD-71(S)

A comprehensive search of ODOT records was done to obtain historical information pertaining to project FAY/MAD-71(S) including site, design, construction, M&R, and performance history. Although records yielded no information pertaining to visual windshield distress survey, there was historical pavement condition (characterized using PCR) information available. Note that PCR was only available for the northbound lanes of Interstate 71. It was assumed that the southbound lanes that are the subject of this investigation were in similar condition. Also available in the ODOT records was information on original pavement and subsequent M&R design, layer thicknesses, M&R events, and traffic. The assembled information was reviewed for quality and consistency and was found to be generally reasonable. A summary of design, material, and M&R history information obtained from ODOT records is presented in table 16.

The historical performance data are presented in figure 15. This information agrees with historical M&R data from ODOT that shows a pavement in fair to poor condition (PCR of 66) prior to rehabilitation in 1992. Pavement condition improved significantly after rehabilitation, with the PCR rising to approximately 92 (very good condition), but deteriorated rather quickly until additional rehabilitation was performed in 2002. The historical traffic information presented in figure 16 shows an AADT of 27,322 in 1992. Approximately 30.4 percent of the AADT were trucks. Total daily truck traffic in 1992 was 8,295. Traffic growth over the 20-year analysis period was approximately 9.01 percent linear. Based on the traffic information obtained from ODOT records, projected 20-year traffic for FAY/MAD-71(S) analyzed as a composite/rigid pavement was 55,900,000 million ESALs (120,867,814 trucks).
Table 16. Timeline showing significant historical construction and M&R events for FAY/MAD-71(S).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stage B (Placement of upper and lower HMA overlays)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-in HMA (846)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5-in HMA (301)</td>
</tr>
<tr>
<td>New JRCP</td>
<td>Placement of a 2.9-in HMA</td>
<td></td>
</tr>
<tr>
<td>9.6-in JRC</td>
<td>Stage A (Milling off the existing HMA layer)</td>
<td></td>
</tr>
<tr>
<td>5.5-in Aggregate Base</td>
<td>9.6-in JRC</td>
<td>9.6-in JRC</td>
</tr>
<tr>
<td>Subgrade</td>
<td>5.5-in Aggregate Base</td>
<td>5.5-in Aggregate Base</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>

The layer thicknesses presented were obtained from data assembled from ODOT historical records and extracted cores.
Figure 15. Historical pavement performance characterized using PCR for FAY/MAD-71(S).

Figure 16. Historical traffic application for FAY/MAD-71(S).
Step 2—First Structural Evaluation for Project FAY/MAD-71(S)

A comprehensive structural evaluation was conducted for both projects prior to rehabilitation in 1992. Structural evaluation consisted of extraction of cores, laboratory examination of the extracted cores, and nondestructive deflection testing.

Core Extraction and Laboratory Examination for Project FAY/MAD-71(S)

Four cores were extracted for FAY/MAD-71(S) (note that cores were extracted from both the northbound and southbound lanes). Information on exact coring locations was not available in the records reviewed, nor was information on the extracted core material condition. Layer thickness information obtained from the four cores was as follows:

- Mean HMA thickness: 2.9 in (HMA thickness ranged from 2.75 to 3.0 in).
- Mean PCC thickness: 9.6 in (PCC thickness ranged from 9.0 to 10.0 in).

The measured core thicknesses were deemed reasonable, as they were in agreement with planned thicknesses obtained from ODOT records.

Nondestructive Deflection Testing for Projects FAY/MAD-71(S)

Deflection testing was done using both Dynaflect and FWD testing equipment. Deflection testing was done at 100- to 150-ft intervals along the entire length of the project.

Step 3—Pre-Overlay Repair for Project FAY/MAD-71(S)

Rehabilitation for FAY/MAD-71(S) in 1992 began with extensive pre-overlay repairs consisting of milling off the entire 2.9 in of the existing HMA layer. Milling was done following typical ODOT construction practices.

Step 4—Second Structural Evaluation for Project FAY/MAD-71(S)

Limited field testing was done after pre-overlay repairs to characterize pavement structural capacity. For FAY/MAD-71(S) deflection testing was done once, after milling the existing HMA overlay (i.e., on the intact JRCP slab). Testing was done at the mid-slab and approach and leave ends of the transverse joint. However, only the mid-slab deflections were used in analysis.

Step 5—Placement of HMA Overlay for Project FAY/MAD-71(S)

Following pre-overlay repairs and the second structural evaluation, an 8.5-in HMA overlay was placed. The overlay consisted of a 3.0-in ODOT Item 846 upper layer and a 5.5-in ODOT Item 301 lower layer.
Step 6—Third Structural Evaluation for Project FAY/MAD-71(S)

A third and final structural evaluation was done after the placement of the 8.5-in HMA overlay. Structural evaluation consisted of deflection testing only. Testing was done at 100- to 150-ft intervals and was made to match as closely as possible the locations of the previous deflection tests.

Data Analysis for Project FAY/MAD-71(S)

For project FAY/MAD-71(S), relevant information obtained from ODOT records and field testing were assembled into a project database. Data analysis was two parts—preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement system and pavement upper layers strength. The trends were specifically reviewed to determine if milling and HMA overlay placement significantly affected pavement structural capacity. Detailed analysis consisted of computing the parameter AREA, backcalculating pavement layer moduli, and determining $D_{eff}$ and HMA overlay thickness needed to carry future traffic. Trends in computed $D_{eff}$ and HMA overlay thickness needed to carry future traffic were analyzed to determine if current ODOT design procedure reflected actual changes in pavement structural capacity as reflected by deflection test results.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 17 presents a plot of $S_1$ profiles for project FAY/MAD-71(S) for different stages of rehabilitation and shows the following:

- Milling off the existing 2.9-in HMA affected overall pavement system structural capacity (i.e., there was an observable difference in $S_1$ of the original composite pavement and the original pavement after milling). However, the effect of milling on $S_1$ was not significant.
- Overall pavement deflection, $S_1$ decreased significantly after the placement of the 8.5-in HMA overlay. This indicates a significant increase in overall pavement system structural capacity after HMA overlay placement.
- There was a significant reduction in the variability of $S_1$ along the entire project after the placement of the 8.5-in HMA overlay. Standard deviation of $S_1$ was reduced by approximate 50 percent (from 0.048 to 0.024 mils) from the original composite pavement after HMA overlay placement.

The trends observed in figure 17 were confirmed by the results of the ANOVA presented in table 17 for project FAY/MAD-71(S).
Figure 17. Plot showing $S_1$ profiles for FAY/MAD-71(S).

Table 17. Summary of analysis of variance results for maximum deflections (FAY/MAD-71(S)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Maximum Deflection</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original construction (2.9-in HMA over 9.6-in JRC)</td>
<td>6</td>
<td>0.337 (0.045)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Original construction (with 2.9-in HMA milled off)</td>
<td>6</td>
<td>0.323 (0.034)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Overlaid pavement (8.5-in HMA over 9.6-in fractured JRC)</td>
<td>6</td>
<td>0.173 (0.027)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Spreadability**

The structural contribution of the pavement upper layers was characterized using SPR. Figure 18 presents SPR profiles for project FAY/MAD-71(S) at different stages of rehabilitation and shows the following:

- Milling off the existing 2.9-in HMA did significantly reduce pavement upper layer structural capacity for FAY/MAD-71(S).
- SPR was significantly higher after the placement of the 8.5-in HMA overlay. This indicates an increase in the structural contribution of the pavement upper layers after the placement of the 8.5-in HMA overlay.
- SPR variability did not change significantly for the different stages of rehabilitation.

The trends observed in figure 18 were confirmed by the results of the ANOVA presented in table 18 for project FAY/MAD-71(S). The ANOVA results showed that there were significant differences in SPR for each stage of rehabilitation.

![Figure 18. Plot showing SPR profiles for FAY/MAD-71(S).](image)

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from ANOVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original composite pavement (before milling)</td>
<td>6</td>
<td>71 (1.4)</td>
<td>Poor/Fair</td>
<td>B</td>
</tr>
<tr>
<td>Original pavement (with 2.9-in HMA milled off and intact PCC)</td>
<td>6</td>
<td>67 (2.3)</td>
<td>Poor</td>
<td>C</td>
</tr>
<tr>
<td>Overlaid pavement (with 8.5-in HMA overlay)</td>
<td>6</td>
<td>77 (2.0)</td>
<td>Fair/Good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis for FAY/MAD-71(S) consisted of determining the parameter AREA, \( E_p \), k-value, \( D_{eff} \), and HMA overlay thickness required to carry future traffic for the different stages of rehabilitation. This was done by analyzing deflection test data along with other pavement information using DOITOVER.

By computing AREA, \( E_p \), k-value, and \( D_{eff} \), the pavement structural capacity at different stages of rehabilitation as characterized by DOITOVER could be ascertained. By comparing these parameters at the different stages of rehabilitation with the preliminary trends observed from analyzing maximum deflection and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli and characterizing pavement structural capacity could be assessed.

Results of the detailed structural analysis (estimates AREA and \( E_p \), k-value, \( D_{eff} \) and required HMA overlay thickness) are presented in tables 19 and 20 for project FAY/MAD-71(S) at the various rehabilitation stages.

Table 19. Summary of analysis of variance results for AREA (FAY/MAD-71(S)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>25.80  (0.62)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.9-in of existing HMA milled off)</td>
<td>6</td>
<td>24.26  (1.05)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>28.90  (0.99)</td>
<td>C</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 20. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for FAY/MAD-71(S).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated ( E_p ), psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>( D_{eff} ), in</th>
<th>Is There a Significant Difference in ( D_{eff} ) (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original pavement (before milling)</td>
<td>6</td>
<td>1,307,054 (146,241)</td>
<td>257 (45.7)</td>
<td>11.4 (0.10)</td>
<td>8.8 (0.33)</td>
<td>B</td>
</tr>
<tr>
<td>Original pavement (with 2.9-in milled off and intact PCC)</td>
<td>6</td>
<td>2,470,244 (204,365)</td>
<td>319 (63.4)</td>
<td>11.3 (0.113)</td>
<td>7.6 (0.20)</td>
<td>C</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>1,334,865 (139,101)</td>
<td>334 (97.5)</td>
<td>11.2 (0.16)</td>
<td>13.6 (0.38)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Information presented in table 19 shows that there was a significant reduction in AREA after milling, followed by a significant increase after HMA overlay placement. This was contrary to theory and past observed empirical trends. The information in table 20 shows $D_{eff}$ decreasing after milling and increasing significantly after HMA overlay placement, a trend which is reasonable and in agreement with theoretical analysis.

Backcalculated $E_p$ and $k$-value before rehabilitation were 1,325,107 psi and 279 psi/in, respectively, while after HMA overlay placement, they were 1,285,896 psi and 386 psi/in, respectively. After milling, $E_p$ and $k$-value were 2,470,244 psi and 319 psi/in, respectively. A review of the estimated $E_p$ and $k$-value shows a slight drop in computed $E_p$ and an increase in $k$-value after HMA overlay placement which is not consistent with theory. Also, the significant increase in $E_p$ after milling is contrary to theoretical analysis. The before and after rehabilitation $E_p$ and $k$-value estimates do not provide a clear trend on overall pavement strength.

Although it is generally assumed that a significant increase in pavement foundation strength should result in a significant reduction in required HMA overlay thickness, the information presented in table 20 showed otherwise. The pavement foundation strength characterized by $k$-value had very little impact on required HMA overlay thickness.

Summary

Results of the preliminary and detailed structural analysis show that milling off a considerable portion (2.9-in HMA) of the HMA layer of a composite pavement and the placement of a thick overlay (8.5-in HMA) did have a considerable to significant effect on overall pavement structural capacity, as shown by the following trends:

- Although there was no significant change in $S_1$ after milling off 2.9 in of the existing HMA layer, the placement of an 8.5-in HMA overlay did significantly reduce $S_1$ (increase in overall pavement structural capacity), as expected.
- Milling of 2.9 in of the existing HMA layer did significantly impact pavement upper layers structural capacity characterized using SPR. The placement of the 8.5-in HMA result in a significant increase in SPR, as expected. This in agreement with theoretical analysis.
- Pavement foundation strength characterized using the parameter AREA did change significantly after milling and after HMA overlay placement. The observed trends were contrary to expectations.
- Trends in computed $E_p$ and $k$-value were inconsistent with theory, as there was a significant increase in $E_p$ and a significant decrease in $k$-value after milling.
- There was a significant decrease in overall pavement structural capacity characterized using $D_{eff}$ after milling, followed by a significant increase in $D_{eff}$ after HMA overlay placement. The observed trends were reasonable.
- Required HMA overlay thickness (computed based on expected future traffic and $k$-value) did not change significantly over the different rehabilitation stages, although there were significant changes in $k$-value. This implies that the effect of $k$-value on determining required HMA overlay thickness is minimal.
CHAPTER 5. PROJECTS GRE-4(N)

Overview of Project GRE-4(N)

Project GRE-4(N) is a 5,499-ft-long composite (HMA over PCC) pavement located in the northbound lanes of State Route 4 (SR-4). The exact project location was between station 105+50 and 160+49 in Greene County (ODOT District 8). Information available in ODOT records and from field studies indicates that that the project was originally constructed as a 9.0-in JRCP over 3.0-in subbase and subgrade. Although the ODOT records reviewed by the project team had no specific information on subgrade material type or properties, information obtained from a nearby LTPP project (LTPP Project 39_4018 on I-675 in Greene County) indicate a coarse-grained subgrade material classified as AASHTO A-1-a. The original 9.0-in JRCP was overlaid in 1973 with 2.5-in HMA overlay. Additional significant rehabilitation was performed on the composite pavements in 1993 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project GRE-4(N)

A six-step rehabilitation/structural evaluation program was implemented in 1993, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project GRE-4(N)

ODOT records were reviewed to obtain historical design, construction, M&R, and performance information. The search yielded historical information on overall pavement condition (characterized using PCR), design details such as layer material types and thicknesses, M&R, and traffic. The information was collected, assembled, and reviewed for quality and consistency. Data quality was found to be generally reasonable. A summary of the gathered information is presented in table 21. The layer thicknesses were obtained from data assembled from ODOT historical records and confirmed through field testing. Presented in figures 19 and 20 are plots of historical PCR and traffic, respectively.

The information presented in figure 19 is in agreement with historical M&R records that indicated that significant rehabilitation occurred in 1993. PCR prior to rehabilitation was 63 (i.e., an existing pavement prior to rehabilitation in fair to poor condition). Figure 19 also shows that the pavement condition improved significantly after rehabilitation in 1993, with PCR rising to approximately 100 (i.e., very good condition).

The historical traffic information presented in figure 20 shows an AADT of 23,007 in 1993. Approximately 9.1 percent of the AADT were trucks. Total daily truck traffic in 1993 was therefore 2,091. Traffic growth over the 20-year analysis period was approximately 0.93 percent linear. Thus, projected cumulative traffic for the 20-year design period of 1993 to 2013 was 17,518,074 trucks (9.2 million ESALs).
Table 21. Timeline showing significant historical construction and M &R events for GRE-4(N).

<table>
<thead>
<tr>
<th>Stage A (Milling off the existing HMA layer)</th>
<th>Placement of a 2.5-in HMA</th>
<th>Stage B (Placement of upper and lower HMA overlays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Construction</td>
<td>Rehabilitation (1973)</td>
<td>Rehabilitation (1993)</td>
</tr>
<tr>
<td>New JRCP</td>
<td>Placement of a 2.5-in HMA</td>
<td>3-in HMA (846)</td>
</tr>
<tr>
<td>9-in JRC</td>
<td>2.5-in HMA</td>
<td>3-in HMA (301)</td>
</tr>
<tr>
<td>3-in Aggregate Base</td>
<td>9-in JRC</td>
<td>9-in JRC</td>
</tr>
<tr>
<td>Subgrade</td>
<td>3-in Aggregate Base</td>
<td>3-in Aggregate Base</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>
Figure 19. Historical pavement performance characterized using PCR for GRE-4(N).

Figure 20. Historical traffic application for GRE-4(N).
Step 2—First Structural Evaluation for Project GRE-4(N)

A comprehensive structural evaluation was conducted prior to rehabilitation in 1993. Structural evaluation consisted of extraction of cores, laboratory examination of the extracted cores, and nondestructive deflection testing.

Core Extraction and Laboratory Examination for Project GRE-4(N)

Three cores were extracted for the entire project. Information on exact coring locations and cores condition was not available in the ODOT records reviewed. Layer thickness information was available for only the subbase and showed subbase thickness ranging from 3.0 to 7.5 in, with a mean of 6.0 in.

Nondestructive Deflection Testing for Project GRE-4(N)

Deflection testing was done using Dynaflect and FWD testing equipment. Deflection testing was done at 100- to 150-ft intervals.

Step 3—Pre-Overlay Repair for Project GRE-4(N)

Rehabilitation in 1993 began with extensive pre-overlay repairs consisting of milling off the entire 2.5 in of the existing HMA layer.

Step 4—Second Structural Evaluation for Project GRE-4(N)

Limited field testing was done after pre-overlay repairs to characterize pavement structural capacity. Field testing consisted of deflection testing done after milling the existing HMA overlay (i.e., on the intact JRCP slab). On the intact slab, deflection testing was done at the mid-slab and approach and leave ends of the transverse joint. However, only the mid-slab deflections were used in analysis. Testing locations were selected to be as close to those of the first structural evaluation as possible. Deflection testing was done, as previously described in chapter 1.

Step 5—Placement of HMA Overlay for Project GRE-4(N)

Following pre-overlay repairs and the second structural evaluation, a 6.0-in HMA overlay was placed.

Step 6—Third Structural Evaluation for Project GRE-4(N)

A third and final structural evaluation was done after the placement of the 6.0-in HMA overlay. Structural evaluation consisted of deflection testing only. Testing was done at 100- to 150-ft intervals and was made to match as closely as possible the locations of the previous deflection tests.
Data Analysis for Project GRE-4(N)

All relevant information obtained from ODOT records and field testing was assembled into a project database for analysis. The data were analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of the overall pavement system and pavement upper layers strength. Detailed analysis consisted of computing the parameter AREA, backcalculating $E_p$ and $k$-value, and determining $D_{ef}$ and HMA overlay thickness needed to carry future traffic. The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity (use of thicker/superior HMA materials). The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 21 presents plots of $S_1$ profiles for project GRE-4(N) for different stages of rehabilitation and shows the following:

- Milling off the existing 2.5-in HMA did significantly weaken the existing pavement, with overall pavement system structural capacity increasing over 100 percent.
- Although, overall pavement system structural capacity $S_1$ was lowest after the placement of the 6.0-in HMA overlay, the observed difference in before rehabilitation pavement strength and post HMA placement pavement strength was not significant.
- Placing the 6.0-in HMA overlay over intact PCC did not change variability of $S_1$ along the entire project, significantly.

The trends observed in figure 21 were confirmed by the results of the ANOVA presented in table 22.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 21 presents SPR profiles at the different stages of rehabilitation. A review of figure 21 shows the following:

- Milling off the existing 2.5-in HMA did significantly lower pavement upper layers structural capacity.
- The placement of the 6.0-in HMA overlay did restore pavement structural capacity to before-rehabilitation levels.
Figure 21. Plot showing $S_1$ profiles for GRE-4(N).

Table 22. Summary of analysis of variance results for maximum deflections (GRE-4(N)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Maximum Deflection</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original construction (2.5-in HMA over 9.6-in JRC)</td>
<td>6</td>
<td>0.332 (0.074)</td>
<td>Excellent</td>
<td>B</td>
</tr>
<tr>
<td>Original construction (with 2.5-in HMA milled off)</td>
<td>6</td>
<td>0.687 (0.231)</td>
<td>Fair</td>
<td>A</td>
</tr>
<tr>
<td>Overlaid pavement (6.0-in HMA over 9.6-in fractured JRC)</td>
<td>6</td>
<td>0.263 (0.077)</td>
<td>Fair</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

The trends observed in figure 22 were confirmed by the results of the ANOVA presented in table 23. Also, the ANOVA results showed that there were significant differences in SPR for each stage of rehabilitation.
Detailed Structural Analysis

Detailed structural analysis for GRE-4(N) consisted of computing AREA, backcalculating $E_p$ and k-value, and determining $D_{\text{eff}}$ and HMA overlay thickness required to carry future traffic for the different stages of rehabilitation. This was done by analyzing deflection test data along with other pavement information using DOITOVER.

By computing AREA, backcalculating $E_p$ and k-value, and determining $D_{\text{eff}}$ and HMA overlay thickness required to carry the same levels of future traffic, the pavement structural capacity at different stages of rehabilitation as characterized by DOITOVER could be ascertained. By
Comparing the $D_{eff}$ at the different stages of rehabilitation with the preliminary trends observed from analyzing maximum deflection data and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli and characterizing pavement structural capacity could be assessed.

Results of the detailed structural analysis are presented in tables 24 and 25. Also presented are the results of an ANOVA performed to determine whether AREA and $D_{eff}$ changed significantly at the various rehabilitation stages.

Information presented in table 24 shows that AREA did not change significantly during the rehabilitation process. This was contrary to theory and past observed empirical trends. The information in table 25 shows $D_{eff}$ decreasing after milling and increasing significantly after HMA overlay placement, which is reasonable and in agreement with theoretical analysis. The pavement strength after HMA overlay placement was not significantly higher than the pavement strength before rehabilitation.

Information presented in table 25 indicates that backcalculated $E_P$ decreased significantly after milling. There was a further significant decrease in $E_P$ after HMA overlay placement.

Pavement foundation strength decreased significantly after milling and increased significantly after HMA overlay placement. The before, during, and after rehabilitation $E_P$ and k-value estimates do not provide a clear trend on overall pavement strength.

Although it is generally assumed that a significant increase in pavement foundation strength should result in a significant reduction in required HMA overlay thickness, the information presented in table 25 showed otherwise. The pavement foundation strength characterized by k-value had very little impact on required HMA overlay thickness.

**Table 24. Summary of analysis of variance results for AREA (GRE-4(N)).**

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>26.48 (2.91)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.5-in of</td>
<td>6</td>
<td>24.50 (2.53)</td>
<td>A</td>
</tr>
<tr>
<td>existing HMA milled off)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>25.08 (3.06)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 25. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for GRE-4(N).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated E_p, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>D_eff, in</th>
<th>Is There a Significant Difference in D_eff (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original composite pavement (before milling)</td>
<td>6</td>
<td>2,121,067 (741,622)</td>
<td>248 (96.9)</td>
<td>8.5 (0.21)</td>
<td>9.3 (1.40)</td>
<td>A</td>
</tr>
<tr>
<td>Original pavement (with 2.5-in HMA milled off and intact PCC)</td>
<td>6</td>
<td>1,712,191 (752,231)</td>
<td>154 (44.6)</td>
<td>8.8 (0.13)</td>
<td>6.2 (1.08)</td>
<td>B</td>
</tr>
<tr>
<td>Overlaid pavement (with 6.0-in HMA overlay)</td>
<td>6</td>
<td>971,175 (312,441)</td>
<td>396 (194.5)</td>
<td>8.2 (0.36)</td>
<td>10.0 (1.38)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis show that milling off a considerable portion (2.5-in HMA) of the HMA layer of a composite pavement and the placement of a thick overlay (6.0-in HMA) did have a considerable to significant effect on overall pavement structural capacity, as shown by the following trends:

- There was a significant change in S_1 after milling off 2.5 in of the existing HMA layer, and the placement of a 6.0-in HMA overlay did significantly reduce S_1 (increase in overall pavement structural capacity), as expected.
- Milling of 2.5 in of the existing HMA layer did significantly impact pavement upper layers structural capacity characterized using SPR. The placement of the 6.0-in HMA result did not significantly increase SPR. This was contrary to the results of theoretical analysis.
- Pavement foundation strength characterized using the AREA parameter did change significantly after milling and after HMA overlay placement.
- Trends in computed E_p and k-value were inconsistent with theory.
- There was a significant decrease in overall pavement structural capacity characterized using D_eff after milling followed by a significant increase in D_eff after HMA overlay placement. The observed trends were reasonable.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages, although there were significant changes in k-value. This implies that the effect of k-value on determining required HMA overlay thickness is minimal.
CHAPTER 6. PROJECT JEF-7

Overview of Project JEF-7

Project JEF-7 is a 1,500-ft-long composite (HMA over PCC) pavement located on State Route 7. The exact project location was between station 336+65 (near mile post 6) and 351+65 in Jefferson County (ODOT District 11). ODOT historical records indicate that the project was originally constructed as a 9.0-in JRCP over a 6.0-in dense graded aggregate base (DGAB) and an A-6 subgrade in 1968. In 1987, the JRCP structure was overlaid with a 4.0-in HMA surface course (average thickness obtained from cores). Significant rehabilitation was performed in 2004/2005 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project JEF-7

A six-step rehabilitation/structural evaluation program was implemented in 2004/2005, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project JEF-7

A windshield survey was conducted to determine the condition of the pavement prior to rehabilitation. Information obtained from the survey was made available to the project team in the form of photo logs. Figures 23 through 26 present photos depicting pavement condition prior to the 2004/2005 rehabilitation. A review of the photos showed moderate damage manifested by the presence of low-, moderate-, and high-severity reflection “transverse” cracking, along with some patching. There were several areas within the project with severe localized distress.

In addition to the windshield survey, a comprehensive search of ODOT records was performed to obtain historical information on project JEF-7 original design and construction, subsequent M&R, and performance history:

- Historical pavement condition characterized using PCR was available for the years 1985 through 2004/2005. Detailed distress information from visual windshield survey was not available.
- Historical traffic.
- Design plans describing layer thicknesses, material types, and so on.
- Historical M&R activities.

The information gathered was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. A timeline showing the original pavement structure and subsequent M&R is presented in Table 26. Figures 27 and 28 are plots of historical pavement performance (PCR) and traffic.
Figure 23. JEF-7 windshield survey (photo 1) showing low-severity “transverse” reflection cracking.

Figure 24. JEF-7 windshield survey (photo 2) showing low-severity “transverse” reflection cracking and significant amounts of patching.
Figure 25. JEF-7 windshield survey (photo 3) showing moderate-severity “transverse” reflection cracking.

Figure 26. JEF-7 windshield survey (photo 4) showing-low severity “longitudinal” reflection cracking (from the JRCP lane to lane joint).
Table 26. Timeline showing significant historical construction and M & R events for JEF-7.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Milling off 3.25-in of existing HMA layer</td>
</tr>
<tr>
<td>B</td>
<td>Placement of upper and lower HMA overlays</td>
</tr>
<tr>
<td>C</td>
<td>Placement of a 4-in HMA</td>
</tr>
</tbody>
</table>

Note that the layer thicknesses presented in table 26 were obtained from data assembled from ODOT historical records and field testing.
Figure 27. Historical pavement performance characterized using PCR for JEF-7.

Figure 28. Historical traffic application for JEF-7.
Figure 27 shows a PCR of approximately 60 prior to the 1987 rehabilitation (placement of 4.0-in HMA overlay), which suggests an existing pavement in fair to poor condition. The 1987 HMA overlay was probably placed to improve both pavement functionality and structural capacity. The PCR value reported in 1988 (a year after HMA overlay placement) was nearly 100. Between 1988 and 2004/2005 there was a steady decline in pavement condition, leading to a PCR of 69 reported in 2004/2005.

The historical traffic information presented in figure 28 shows that traffic levels have changed significantly since the early 1970’s. AADT just prior to the 2004/2005 rehabilitation was estimated to be 14,513. ODOT records indicated that approximately 15.2 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2004/2005 was estimated to be approximately 2,209. Historical traffic (all vehicles) was estimated to be approximately 3.68 percent, linear. Thus for analysis, projected 20-year truck traffic was estimated to be 23,162,955 trucks, which translates into 16,800,000 ESALs.

Step 2—First Structural Evaluation for Project JEF-7

A detailed and comprehensive structural evaluation was conducted prior to pre-overlay repairs and HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores (to determine their condition and layer thicknesses), and deflection testing. A summary of the data collected, along with data analysis, is presented in the following sections.

Coring and Laboratory Examination for Project JEF-7

Coring was performed in May 2005. Six cores were extracted along the entire 1,500-ft-long project section at regular intervals of 300 ft. The extracted cores were visually examined to assess their condition. All six cores examined were in relatively good condition (PCC was intact with no signs of damage or fatigue, HMA was generally intact). The condition for HMA cores at all six locations was deemed good. The HMA layer for each core was de-bonded from the PCC layer but was in sound condition. The condition of the PCC cores at all but one of the six locations was deemed good; one core was fractured. Photos of extracted cores are presented in figure 29. Layer thicknesses derived from the cores are as follows:

- Mean HMA thickness: 3.9 in (HMA overlay thickness ranged from 3.5 to 4.0 in).
- Mean PCC thickness: 9.0 in (PCC thickness ranged from 8.75 to 9.5 in).

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records. The layer thicknesses obtained from the cores were used in detailed analysis.
Deflection Testing for Project JEF-7

Deflection testing was performed for this section using Dynaflect testing equipment. Testing was done at 50-ft intervals. The test data were processed and included in the assembled project database for analysis.

Step 3—Pre-Overlay Activities/Repair for Project JEF-7

After the first structural evaluation, comprehensive pre-overlay repairs were performed as part of rehabilitation. Pre-overlay repairs consisted of milling off approximately 3.25 inches of the existing HMA layer.

Step 4—Second Structural Evaluation for Project JEF-7

The second structural evaluation was done after the completion of pre-overlay repairs but prior to HMA overlay placement. Structural evaluation consisted of only deflection testing. Test locations were as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project JEF-7

Following the second structural evaluation, a 5.0-in (average thickness) HMA overlay (Superpave mix) was placed on the prepared surface.
Step 6—Third Structural Evaluation for Project JEF-7

The third and final structural evaluation was done after HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores (to determine their condition and layer thicknesses), and deflection testing. A summary of the data collected, along with data analysis, is presented in the following sections.

Coring and Laboratory Examination

Coring was performed in November 2005. Six cores were extracted along the entire 1,500-ft-long project section at regular intervals. The extracted cores were visually examined to assess their condition. All six cores were in good condition. Figure 30 shows a photo of three of the six extracted cores. Layer thicknesses derived from the cores are as follows:

- Mean HMA thickness: 6.0-in (HMA overlay thickness ranged from 5.75 to 6.25-in).
- Mean PCC thickness: 9.0-in (all cores reported 9.0-in).

The condition for HMA cores at all six locations was deemed good. The HMA layer for each core was de-bonded from the PCC layer, but was in sound condition. De-bonding may have been caused by the coring action. The PCC cores at all six locations were deemed good with no signs of distress or damage. The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

Figure 30. Picture of cores extracted from JEF-7.
Deflection Testing

Deflection testing was done using Dynaflect. The testing process was as previously described in the first structural evaluation. Test locations were selected to be as close as possible to the locations of previous deflection tests.

Data Analysis for Project JEF-7

Coring and deflection testing results, along with other relevant information (such as layer type, pavement structure, and layer thicknesses) assembled from ODOT records were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of the overall pavement system, pavement upper layers, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically, milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity (specifically, filling with perhaps superior/thicker HMA materials). The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, S1. Figure 31 presents the plot of S1 profiles for project JEF-7 for different stages of rehabilitation in 2004. A review of the plot presented in figure 31 shows the following:

- Milling off the existing 3.25-in HMA had a considerable effect on overall pavement system structural capacity. However, the effect was not very significant.
- S1 was significantly lower after the placement of the 5.0-in HMA overlay on the milled existing pavement. This is indicative of a significant increase in overall pavement system structural capacity after HMA overlay placement.
- Variability of S1 along the entire project was considerably lower with the placement of the HMA overlay.

The trends observed in figure 31 are confirmed by the ANOVA results presented in table 27.
Table 27. Summary of analysis of variance results for maximum deflections (JEF-7).

<table>
<thead>
<tr>
<th>Construction or Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original composite pavement (4.0-in HMA over 9.0-in JRC)</td>
<td>6</td>
<td>0.31 (0.122)</td>
<td>A, B</td>
</tr>
<tr>
<td>Original composite pavement (with 3.25-in HMA milled off)</td>
<td>6</td>
<td>0.38 (0.110)</td>
<td>A</td>
</tr>
<tr>
<td>Overlaid pavement (5.0-in HMA over 9.0-in JRC)</td>
<td>6</td>
<td>0.24 (0.037)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 32 presents SPR profiles for project JEF-7 at different stages of the rehabilitation. A review of the plot shows the following:

- Milling off the existing 3.25-in HMA did significantly affect pavement upper layers structural capacity.
- SPR after milling and after HMA overlay placement were not significantly different.
- SPR variability was lower after HMA overlay placement.
The trends observed in figure 32 are confirmed by the results of the ANOVA presented in table 28.

Figure 32. Plot showing SPR profiles for JEF-7.

Table 28. Summary of analysis of variance results for SPR (JEF-7).

<table>
<thead>
<tr>
<th>Rehabilitation Stage*</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original construction (4.0-in HMA over 9.0-in JRC)</td>
<td>6</td>
<td>76 (5.6)</td>
<td>A</td>
</tr>
<tr>
<td>Original construction (with 3.25-in HMA milled off)</td>
<td>6</td>
<td>64 (3.7)</td>
<td>B</td>
</tr>
<tr>
<td>Original construction (5.0-in HMA over 9.0-in JRC)</td>
<td>6</td>
<td>69 (2.7)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Detailed Structural Analysis

Detailed structural analysis involved computing the deflection basin parameter AREA and $D_{eff}$ for the different stages of rehabilitation. Both AREA and $D_{eff}$ were computed as described in chapter 1.

By comparing the AREA and $D_{eff}$ across the different stages of rehabilitation with observed preliminary trends for maximum deflection and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli and characterizing pavement structural capacity could be assessed.
Results of the detailed structural analysis are presented in tables 29 and 30. Table 29 shows that there was a significant reduction in AREA after milling. There was no significant reduction in AREA after HMA overlay placement. This trend is contrary to theory. Table 30 shows $D_{\text{eff}}$ decreasing significantly after milling and increasing significantly after HMA overlay placement, which is reasonable and in agreement with theoretical analysis. The pavement strength after HMA overlay placement was not significantly higher than the pavement strength before rehabilitation.

Additional information presented in table 30 indicates that backcalculated $E_p$ and k-value before rehabilitation were 2,373,287 psi and 207 psi/in, respectively, while after HMA overlay placement they were 1,061,552 psi and 375 psi/in, respectively. $E_p$ and k-value after milling were 1,687,577 psi and 329 psi/in, respectively. This information does not provide a clear trend on overall pavement strength.

Finally, pavement foundation strength (characterized using k-value) had very little impact on required HMA overlay thickness.

Table 29. Summary of analysis of variance results for AREA (JEF-7).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>28.53 (2.76)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 3.25-in of existing HMA milled off)</td>
<td>6</td>
<td>23.20 (1.71)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>25.62 (1.15)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 30. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for JEF-7.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{\text{eff}}$ in*</th>
<th>Is There a Significant Difference in $D_{\text{eff}}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>2,373,287 (981,368)</td>
<td>207 (77.1)</td>
<td>9.4 (0.20)</td>
<td>10.4 (1.6)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 3.25-in of existing HMA milled off)</td>
<td>6</td>
<td>1,687,577 (485,097)</td>
<td>329 (133.5)</td>
<td>9.2 (0.12)</td>
<td>7.2 (0.68)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>1,061,552 (230,590)</td>
<td>375 (69.1)</td>
<td>9.1 (0.19)</td>
<td>10.4 (0.76)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Summary

Results of the preliminary and detailed structural analysis show that milling off 3.25 in of HMA did reduce pavement structural capacity significantly. The placement of a 5.0-in-thick HMA overlay had a considerable significant effect on overall pavement structural capacity. The most reasonable indications of pavement structural capacity were $S_1$ and $D_{eff}$, as described below:

- There was significant increase in $S_1$ after milling off 2.5 in of the existing HMA layer. Also, $S_1$ after the placement of a 5.0-in HMA decreased significantly.
- Milling of 3.25 in of the existing HMA layer did significantly impact pavement upper layers structural capacity characterized using SPR. Placement of the 5.0-in HMA did not result in a significant increase SPR as expected. This was contrary to the theory.
- Pavement foundation strength characterized using the parameter AREA decrease significantly after milling. There was a subsequent increase in AREA after HMA overlay placement. The observed changes and trends were not consistent with expectations or theory.
- Trends in computed $E_P$ and k-value were not consistent with the theoretical analysis.
- There was a significant decrease in overall pavement structural capacity characterized using $D_{eff}$ after milling followed by a significant increase in $D_{eff}$ after HMA overlay placement. The observed trends were reasonable.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages although there were significant changes in k-value. This implies that the effect of k-value on determining required HMA overlay thickness was minimal.
CHAPTER 7. PROJECT MOT-4(S)

Overview of PROJECT MOT-4(S)

Project MOT-4(S) is a 5,050-ft-long composite (HMA over PCC) pavement located in the southbound lanes of State Route 4 (SR-4). The exact project location is between station 217+00 and 267+50 in Montgomery County (ODOT District 7). Information available in ODOT records and from field studies indicates that the project was constructed originally as a 9.0-in JRCP over 3.0-in subbase and subgrade. Although ODOT did not provide information on subgrade material type, information obtained from nearby LTPP projects (LTPP Project 39_4018 on I-675 in Greene County) indicates a coarse-grained subgrade material.

The original 9.0-in JRCP was overlaid in 1973 with a 2.5-in HMA overlay to become a composite pavement. Additional significant rehabilitation was performed in 1993 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project MOT-4(S)

A six-step rehabilitation/structural evaluation program was implemented in 1993, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project MOT-4(S)

A comprehensive search of ODOT records was performed to obtain historical information pertaining to the project MOT-4(S) site. Data obtained from the search included historical pavement condition (characterized using PCR for the northbound lanes of SR-4), design details, materials properties, and M&R history. The information was reviewed for quality and consistency and was found to be generally reasonable. A summary of the history information is presented in table 31. Figures 33 and 34 are plots of performance and traffic. The condition of the northbound and southbound lanes was assumed to be similar.

The historical traffic information presented in figure 34 shows that this project had an AADT of 33,239 in 1993. Approximately 6.9 percent of the AADT were trucks, and thus, total daily truck traffic in 1993 was 2,300. Traffic growth over the 20-year analysis period was approximately 0.11 percent linear. Based on the traffic information obtained from ODOT records, projected future 20-year traffic for MOT-4(S) analyzed as a composite/rigid pavement was 9,850,000 ESALs (17,823,425 trucks).

Step 2—First Structural Evaluation for Project MOT-4(S)

A detailed and comprehensive structural evaluation was conducted prior to pre-overlay repairs and HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing. A summary of the data collected, along with data analysis, is presented in the following sections.
Table 31. Timeline showing significant historical construction and M &R events for MOT-4(S).

<table>
<thead>
<tr>
<th>Original Construction</th>
<th>Rehabilitation (1973)</th>
<th>Rehabilitation (1993)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subgrade</strong> 3-in Aggregate Base</td>
<td>Placement of a 2.5-in HMA</td>
<td>Stage A (Milling off the existing HMA layer)</td>
</tr>
<tr>
<td><strong>3-in HMA</strong></td>
<td></td>
<td><strong>3-in HMA (301)</strong></td>
</tr>
<tr>
<td><strong>Subgrade</strong> 9-in JRC</td>
<td></td>
<td><strong>3-in HMA (846)</strong></td>
</tr>
<tr>
<td><strong>3-in Aggregate Base</strong></td>
<td></td>
<td><strong>3-in Aggregate Base</strong></td>
</tr>
<tr>
<td><strong>Subgrade</strong></td>
<td></td>
<td><strong>3-in Aggregate Base</strong></td>
</tr>
<tr>
<td><strong>New JRCP</strong></td>
<td></td>
<td><strong>9-in JRC</strong></td>
</tr>
<tr>
<td><strong>9-in JRC</strong></td>
<td></td>
<td><strong>9-in JRC</strong></td>
</tr>
<tr>
<td><strong>3-in Aggregate Base</strong></td>
<td></td>
<td><strong>3-in Aggregate Base</strong></td>
</tr>
<tr>
<td><strong>Subgrade</strong></td>
<td></td>
<td><strong>Subgrade</strong></td>
</tr>
</tbody>
</table>
Figure 33. Historical pavement performance characterized using PCR for MOT-4(S).

Figure 34. Historical traffic application for MOT-4(S).
Coring and Laboratory Examination for Project MOT-4(S)

Three cores were extracted for MOT-4(S), but information on exact coring locations and condition was not available in the ODOT records reviewed. Layer thickness information was available for only the subbase and showed a mean subbase thickness of 3.0 in.

Deflection Testing for Project MOT-4(S)

Deflection testing was performed using both Dynaflect and FWD testing equipment. Testing was performed at 100- to 150-ft intervals along both projects.

Step 3—Pre-Overlay Activities/Repair for Project MOT-4(S)

Rehabilitation for MOT-4(S) began in 1993 with pre-overlay repairs. The pre-overlay repairs consisted of milling off 2.5 inches of the existing HMA layer.

Step 4—Second Structural Evaluation for Project MOT-4(S)

For this project, deflection testing was done after pre-overlay repairs to characterize pavement structural capacity. Testing was done once at the mid-slab and approach and leave ends of the transverse joint. Only the mid-slab deflections were used in analysis. Testing locations were selected to be as close to those of the first structural evaluation as possible.

Step 5—Placement of HMA Overlay for Project MOT-4(S)

Following pre-overlay repairs and the second structural evaluation, a 6.0-in HMA overlay was placed.

Step 6—Third Structural Evaluation for Project MOT-4(S)

A third and final structural evaluation was done after the placement of the 6.0-in HMA overlay. Structural evaluation consisted of deflection testing only. Testing was done at 100- to 150-ft intervals and was made to match as closely as possible the locations of the previous deflection tests. Deflection testing was done as previously described in chapter 1.

Data Analysis for Project MOT-4(S)

The data collected from ODOT records and field testing was assembled into a project database for preliminary and detailed analysis. Preliminary analysis reviewed trends of structural indices that were indicative of the overall pavement system and pavement upper layers Deff and strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining HMA overlay thickness needed to carry future traffic. The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity. The analysis results are presented in the following sections.
Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using Dynaflect. Figure 35 presents plots of $S_1$ profiles for different stages of rehabilitation. A review of the plots presented in figure 35 shows the following:

- Milling off the existing 2.5-in HMA did significantly influence the pavement system structural capacity.
- Overall pavement deflection, $S_1$ decreased significantly lower after the placement of the 6.0-in HMA overlay. However, before and after the rehabilitation, $S_1$ was not significantly different. Thus, there was no significant increase in overall pavement structural capacity after the rehabilitation.
- Variability of $S_1$ along the entire project was considerably lower with the placement of the HMA overlay.

The trends observed in figure 35 were confirmed by the results of the ANOVA presented in table 32.

![Figure 35. Plot showing $S_1$ profiles for MOT-4(S).](image-url)
Table 32. Summary of analysis of variance results for maximum deflections (MOT-4(S)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>5</td>
<td>0.280 (0.087)</td>
<td>Excellent</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2.5-in of existing HMA milled off)</td>
<td>5</td>
<td>0.564 (0.1)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>5</td>
<td>0.268 (0.044)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Spreadability**

The structural contribution of the pavement upper layers was characterized using SPR. Figure 36 presents SPR profiles for project MOT-4(S) at different stages of rehabilitation. A review of the plots presented in figure 36 show the following:

- Milling off the existing 2.5-in HMA did not significantly influence pavement upper layers structural capacity.
- SPR before milling, after milling, and after HMA overlay placement were essentially the same.
- SPR variability did not change significantly for the different stages of rehabilitation.

The trends observed in figure 36 were confirmed by the results of the AOV presented in table 33 for project MOT-4(S).

**Detailed Structural Analysis**

Detailed structural analysis involved computing the deflection basin parameter AREA and $D_{eff}$ for the different stages of rehabilitation. Both the AREA and $D_{eff}$ terms were computed as described in chapter 1.

By comparing the AREA and $D_{eff}$ across the different stages of rehabilitation with the preliminary trends in maximum deflection and SPR, the effectiveness of the ODOT procedure (programmed in DOITOVER) for backcalculating pavement layer moduli and characterizing pavement structural capacity could be assessed.

Results of the detailed structural analysis (estimates of AREA, $E_p$, k-value, $D_{eff}$, and required HMA overlay thickness) for MOT-4(S) are presented in tables 34 and 35. Table 34 shows that there was no significant difference in AREA before milling, after milling, and after the placement of HMA overlay.
Table 33. Summary of analysis of variance results for SPR (MOT-4(S)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>5</td>
<td>69 (3.7)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.5-in of existing HMA milled off)</td>
<td>5</td>
<td>68 (3.7)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>5</td>
<td>68 (5.8)</td>
<td>Good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 35 indicates that backcalculated $E_p$ and $k$-value before rehabilitation were 2,060,323 psi and 344.9 psi/in, respectively, while after rehabilitation (post-HMA overlay placement) $E_p$ and $k$-value before rehabilitation were 923,064 psi and 348.3 psi/in, respectively. However, $E_p$ and $k$-value after milling were 1,920,479 psi and 174.2 psi/in, respectively. A review of the estimated $E_p$ and $k$-value shows that they were not consistent with expected trends and are not good indicators of overall pavement strength.

Completed $D_{eff}$, however, were in agreement with expected trends. There was a significant decrease after milling, followed by a significant increase after the placement of the 6.0-in-thick HMA overlay.
Table 34. Summary of analysis of variance results for AREA (MOT-4(S)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>5</td>
<td>25.23 (0.12)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.5-in of existing HMA milled off)</td>
<td>5</td>
<td>24.67 (0.23)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>5</td>
<td>25.10 (0.10)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 35. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for MOT -4(S).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated E_p, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>D_{eff}, in</th>
<th>Is There a Significant Difference in D_{eff} (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>5</td>
<td>2,060,323 (678,036)</td>
<td>344.9 (111)</td>
<td>8.4 (0.2)</td>
<td>9.3 (1.2)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.5-in of existing HMA milled off)</td>
<td>5</td>
<td>1,920,479 (597,073)</td>
<td>174.2 (24.1)</td>
<td>8.8 (0.1)</td>
<td>6.5 (0.8)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>5</td>
<td>923,064 (348,683)</td>
<td>348.3 (76.8)</td>
<td>8.4 (0.1)</td>
<td>9.8 (1.4)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis show that milling off the existing 2.5-in HMA layer of a composite pavement and the placement of a thick overlay (6.0-in HMA) did have a considerable to significant effect on overall pavement structural capacity, as shown by the following trends:

- There was a significant increase in S_1 after milling off the existing 2.5-in HMA layer, which implies a decrease in pavement structure capacity. S_1 increased significantly after HMA overlay placement (increase pavement structure capacity).
- Milling of 2.5-in of the existing HMA layer did not significantly impact pavement upper layers structural capacity characterized using SPR. The placement of the 6.0-in HMA result did not significantly increase SPR.
- Pavement foundation strength characterized using the parameter AREA did not change significantly before milling, after milling and after HMA overlay placement.
- Trends in computed E_p and k-value were no in agreement with theoretical analysis.
• There was a significant decrease in overall pavement structural capacity characterized using $D_{\text{eff}}$ after milling followed by a significant increase in $D_{\text{eff}}$ after HMA overlay placement. The observed trends were reasonable. Placement of the 6.0-in HMA overlay did not significantly increase pavement structure capacity.

• Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages although there were significant changes in k-value. This implies that the effect of k-value on determining required HMA overlay thickness is minimal.
CHAPTER 8. PROJECT MOT-40 (04)

Overview of Project MOT-40 (04)

Project MOT-40 (04) is an 800-ft composite pavement (HMA/PCC) section located in the westbound lanes of U.S. Route 40 in Montgomery County (ODOT District 7). Historical records obtained from ODOT show that the project was originally constructed as a JPCP in 1947. The original pavement was overlaid with HMA in 1965 and underwent rehabilitation again in 1974. In 1992, a 1.75-in HMA overlay (ODOT Item 448, Type 1, placed in two lifts of 1.25-in and 0.5-in) was placed after milling off 0.5 inches of the existing HMA. Significant rehabilitation was performed in 2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project MOT-40 (04)

A six-step rehabilitation/structural evaluation program was implemented in 2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project MOT-40 (04)

A comprehensive search of ODOT records for project MOT-40 (04) revealed historical information pertaining to original design and construction, subsequent M&R, and performance history. Specific information gathered was as follows:

- Design plans describing layer thicknesses, material types, and so on.
- No visual distress records available for this project.
  Historical pavement condition records characterized using PCR. (Note that no PCR records were available for the westbound lanes of U.S. Route 40 containing the test section MOT-40 (04). However, pavement condition data for the years 1987 through 2004 was available for the adjacent eastbound lanes and was thus used to characterize the pavement condition of the westbound lanes.)
- Historical traffic.

The information was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. A summary of the information assembled from ODOT records and confirmed through coring is presented in table 36.
Table 36. Timeline showing significant historical construction and M&R events for MOT-40 (04).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgrade</td>
<td>New JPCP</td>
<td>Stage A (Milling off 0.5-in of existing HMA layer)</td>
<td>Stage A (Milling off 2-in of existing HMA layer)</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td>2.5-in HMA</td>
<td>2-in HMA</td>
<td>1.75-in HMA</td>
</tr>
<tr>
<td>Subgrade</td>
<td>9-in JPC</td>
<td>2-in HMA</td>
<td>1.75-in HMA (448)</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td>9-in JPC</td>
<td>9-in JPC</td>
<td>9-in JPC</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td>Stage B (Placement HMA overlay)</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td>Subgrade</td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Note that layer type and thickness information were obtained primarily from ODOT plans and cores extracted as part of the 2004 rehabilitation and specifically for this study. A 6-in aggregate subbase was assumed based on typical ODOT construction practices. No plan records were available for the year 1965.
Plots of historical pavement performance and traffic are presented in figures 37 and 38. The plot in figure 37 shows a PCR value of 52 prior to rehabilitation in 1992 (placement of 1.75-in HMA overlay). The PCR value of approximately 52 suggests an existing pavement in relatively poor condition. The PCR value reported immediately after the overlay placement was 97. The 1992 HMA overlay was probably mostly intended to improve the functional serviceability, and the rise in PCR value indicates that the overlay fulfilled this purpose, as the pavement condition was rated as very good. However, the pavement condition deteriorated rapidly in the years following the rehabilitation, and in 2003, a PCR value of 70 was reported (existing pavement in fair condition). In 2004, a 2-in HMA overlay was placed, which helped improve the PCR value to almost 100.

Figure 37. Historical pavement performance characterized using PCR for MOT-40 (04).
The historical traffic information presented in figure 38 indicates a steady growth in traffic of 8.15 percent, linear. Initial two-way AADT prior to rehabilitation in 2004 was estimated to be 7,204. Approximately 3.3 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2004 was estimated to be approximately 235. For analysis, projected future 20-year truck traffic was estimated to be 3,269,314 trucks which translate into 977,000 rigid ESALs.

**Step 2—First Structural Evaluation for Project MOT-40 (04)**

A detailed and comprehensive structural evaluation was conducted in July 2004, prior to the commencement of 2004 rehabilitation activities. The structural evaluation consisted of only deflection testing using the Dynaflect. No cores were extracted.

**Step 3—Pre-Overlay Activities/Repair for Project MOT-40 (04)**

Following the first structural evaluation, was the performance of pre-overlay repairs. Pre-overlay repairs consisted of milling off 2 inches of the existing HMA.

**Step 4—Second Structural Evaluation for Project MOT-40 (04)**

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement in July 2004. This evaluation consisted of Dynaflect deflection testing only. Deflection testing was done as previously described in chapter 1. Test locations were matched as close as possible to those of the first structural evaluation.
Step 5—Placement of HMA Overlay for Project MOT-40 (04)

Following the second structural evaluation, a 2-in (average thickness) HMA overlay (consisting of an upper layer – 12.5 mm Superpave, Type B mix and a lower layer – 9.5 mm Superpave, Type B mix) was placed over the milled pavement structure.

Step 6—Third Structural Evaluation for Project MOT-40 (04)

The third and final structural evaluation was done after HMA overlay placement in July 2004. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

Initial Coring and Laboratory Examination

Coring was first performed in October 2004. Seven cores were extracted along the entire 800-ft length of the project section, at intervals ranging from 25 to 200 ft. Three of the seven cores were excluded from evaluation/analysis due to discrepancies in ODOT field records and core location information. The remaining four cores were visually examined to assess condition. The condition of the cores ranged from poor to good. A detailed description of core condition is as follows:

- There was no sign of moisture damage or stripping in any of the HMA cores. A photo showing all of the extracted cores (including the three excluded cores) is presented in figure 39.
- The condition of the HMA overlay at the four selected core locations was deemed good (i.e., intact material with less than two pieces).
- Three of the four selected PCC cores were deemed good (i.e., intact core with less than two pieces).
- The remaining PCC core was badly damaged and in poor condition (i.e., two or more pieces of PCC and rubble).

Detailed information regarding core thicknesses is as follows:

- Mean total HMA thickness = 3.6 in (total HMA thickness ranged from 3.4 to 4.0 in, the 2004 HMA overlay thickness ranged from 1.75 to 2 in, with a mean value of 2 in).
- Mean total PCC thickness = 8.9 in (PCC thickness ranged from 8 to 11.5 in. Thickness measurements were not made for damaged/broken cores).

Verification Coring and Laboratory Examination

A second round of verification coring was also performed for MOT-40 (04) in August 2006. Six additional cores were extracted along the entire 800-ft length of the project section, at intervals ranging from 25 to 200 ft. Two of the six cores were deteriorated and were not included in the analysis. The remaining cores were visually examined and were found to in good condition. There were no signs of cracking or moisture damage in both HMA and PCC or HMA stripping. A few cores showed HMA de-bonded from the PCC. A photo showing of all the extracted cores
Figure 39. Photos of cores extracted from MOT-40 (04) in 2004.

(including the two excluded cores) is presented in figure 40. Detailed information regarding core thicknesses and condition are as follows:

- The condition of the HMA overlay at the four selected core locations was deemed good (i.e., intact material with less than two pieces).
- The condition of the four selected PCC cores was deemed good (i.e., intact core with less than two pieces).
- Mean total HMA thickness = 3.5 in (total HMA thickness ranged from 3.3 to 4.0 in, the 2004 HMA overlay thickness ranged from 1.75 to 2 in, with a mean value of 2 in).
- Mean total PCC thickness = 9.2 in (PCC thickness ranged from 8.5 to 10.75 in).

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

*Deflection Testing for Project MOT-40 (04)*

Deflection testing was done using Dynaflect as described in chapter 1. Testing was done as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.
Data Analysis for Project MOT-40 (04)

Coring and deflection testing results along with other relevant information obtained from ODOT records were assembled into a project database for analysis. Data analysis was done to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, and pavement upper layer strength. Detailed analysis consisted of estimating the parameter AREA, backcalculating pavement layer moduli and k-value, and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 41 presents $S_1$ profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 2-in HMA did not significantly affect overall pavement structural capacity. However, $S_1$ increased slightly, as expected.
- $S_1$ was significantly lower after placement of the 2-in HMA overlay, which indicates a significant increase in overall pavement structural capacity after HMA overlay placement.
Variability in $S_1$ along the entire project was considerably lower with the placement of the HMA overlay.

The trends observed in figure 41 were confirmed by the results of the ANOVA presented in table 37.

Table 37. Summary of analysis of variance results for maximum deflections (MOT-40 (04))

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>8</td>
<td>1.553 (0.22)</td>
<td>Poor</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2-in of existing HMA milled off)</td>
<td>8</td>
<td>1.628 (0.208)</td>
<td>Poor</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>8</td>
<td>1.128 (0.146)</td>
<td>Poor</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 42 presents SPR profiles at different stages of the 2004 rehabilitation and shows the following:
• Milling off the existing 2-in HMA did not improve pavement upper layers structural capacity.
• SPR improved significantly after HMA overlay placement.
• SPR variability was considerably lower after milling and stayed after HMA overlay placement.

The trends observed in figure 42 were confirmed by the results of the ANOVA presented in tables 38.

![Figure 42. Plot showing SPR profiles for MOT-40 (04).](image)

Table 38. Summary of analysis of variance results for SPR (MOT-40 (04)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan's Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>8</td>
<td>46 (5.6)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2-in of existing HMA milled off)</td>
<td>8</td>
<td>46 (3.8)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>8</td>
<td>56 (3.1)</td>
<td>Poor</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis involved computing AREA, Ep, k-value, $D_{eff}$ and required HMA thickness to carry future traffic for the different stages of rehabilitation.

By comparing the AREA, $D_{eff}$, and required HMA overlay thickness across the different stages of rehabilitation with the preliminary trends in maximum deflection and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analysis are presented in tables 39 and 40. Information presented in table 39 shows that trends observed in computed AREA appear not to be in agreement with expectations. While there is no significant difference in actual AREA values for the before and after milling stages, AREA obtained after overlay placement is significantly higher than that from the previous two rehabilitation stages. The information in table 40 shows $D_{eff}$ decreasing after milling and increasing significantly after HMA overlay placement, a trend which agrees with theory.

Table 39. Summary of analysis of variance results for AREA (MOT-40 (04)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>8</td>
<td>14.81 (2.65)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2-in of existing HMA milled off)</td>
<td>8</td>
<td>14.76 (1.88)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>8</td>
<td>19.78 (1.52)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 40. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for MOT-40 (04).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{eff}$, in*</th>
<th>Is There a Significant Difference in $D_{eff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>8</td>
<td>56,377 (17,838)</td>
<td>175 (30.7)</td>
<td>5.7 (0.11)</td>
<td>3.3 (0.55)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 2-in of existing HMA milled off)</td>
<td>8</td>
<td>95,414 (52,848)</td>
<td>167 (26.8)</td>
<td>5.8 (0.1)</td>
<td>3.1 (0.34)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>8</td>
<td>174,641 (69,559)</td>
<td>147 (28)</td>
<td>5.8 (0.11)</td>
<td>4.6 (0.37)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Information presented in table 5 indicates a 70 percent increase in backcalculated $E_P$ after milling with a corresponding 4.5 percent reduction in k-value. $E_P$ value increased by almost three times, and the k-value dropped by about 16 percent of their pre-rehabilitation values after HMA overlay placement. The before milling, and after HMA overlay placement $E_P$ show a gain in pavement strength after placement of HMA overlay. Even though the k-value estimates decrease with each successive rehabilitation stage.

Summary

Results of the preliminary and detailed structural analysis show that milling off a relatively small portion (2-in HMA) of the HMA layer of a composite pavement and the placement of a thin overlay (2-in HMA) did significantly affect overall pavement structural capacity, as shown by the following trends:

- Overall pavement structural capacity characterized using $S_1$ did not change significantly after milling off 2-in of existing HMA. The placement of the 2-in HMA overlay resulted in a significant decrease in $S_1$, indicating increase in the overall pavement structural capacity.
- Pavement upper layers structural capacity characterized using SPR did not change significantly after the milling operation. A significantly higher SPR value was observed after placing the 2-in HMA overlay indicating improved pavement upper layer strength.
- Trends in pavement foundation strength characterized using the AREA parameter were not found to be reasonable.
- Trends in computed $E_P$ and k-value were not consistent with theory
- Trends in overall pavement structural capacity characterized using $D_{eff}$ were also consistent with theory.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages although there were considerable changes in k-value.
CHAPTER 9. PROJECT ROS-35

Overview of Project ROS-35

ROS-35 is a 1,500-ft-long composite (HMA over PCC) pavement section located in the northbound lanes of U.S. Route 35 in Ross County (ODOT District 9). The exact project location was between station 1214+36 and 1229+36. According to ODOT historical records, the original pavement was constructed in 1963 as 9-in JRCP with a 6.0-in DGAB overlying a 24-in granular fill and an A-1-a subgrade. The original 1963 structure was overlaid with HMA first in 1981 and then again in 1990. Data obtained from cores in 1990 showed a 4.7-in HMA over the existing JRCP. Significant rehabilitation was performed in 2005 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project ROS-35

A six-step rehabilitation/structural evaluation program was implemented in 2005, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project ROS-35

A comprehensive search of ODOT records was done to obtain historical information pertaining to project ROS-35 original design and construction, subsequent M&R, and traffic and performance history. Specific information gathered was as follows:

- Pre-2005 rehabilitation pavement condition (in terms of PCR) and visual windshield survey data.
- Historical traffic.
- Design plans describing layer thicknesses, material types, and so on.

The information gathered was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. The pre-2005 pavement condition was assessed during the 2005 windshield survey and documented in the photos presented as figures 43 through 46. The main type of distress present was reflected “transverse” cracking. The reflection cracks were at various severity levels (i.e., low to high). The pavement was generally in a moderate condition with areas of severe localized distress.

A summary of the information assembled from ODOT records and confirmed through coring is presented in table 41. Presented in figures 47 and 48 are plots of historical pavement performance and traffic.

As shown in figure 47, PCR information was available for only a few years. A PCR of about 74 was reported in 2004, indicating that the pavement was in relatively fair condition prior to rehabilitation.
Figure 43. ROS-35 windshield survey (photo 1) showing moderate-severity reflection “transverse” cracking.

Figure 44. ROS-35 windshield survey (photo 2) showing high-severity reflection “transverse” cracking.
Figure 45. ROS-35 windshield survey (photo 3) showing high-severity reflection “transverse” cracking and patching.

Figure 46. ROS-35 windshield survey (photo 4) showing moderate-severity reflection “transverse” cracking.
Table 41. Timeline showing significant historical construction and M&R events for ROS-35.

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 2004/2005 rehabilitation and specifically for this study.

Figure 47. Historical pavement performance characterized using PCR for ROS-35.
The historical traffic information presented in figure 48 shows significant growth in traffic since the early 1960’s. AADT just prior to the 2005 rehabilitation was estimated to be 17,232. ODOT records indicated that approximately 18.9 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2005 was estimated to be approximately 3,260. Historical traffic growth (all vehicles) was quite significant and was estimated to be approximately 9.48 percent, linear. Thus, for analysis, projected 20-year truck traffic was estimated to be 48,676,429 trucks, which translates into 26,300,000 rigid ESALs.

**Step 2—First Structural Evaluation for Project ROS-35**

A detailed and comprehensive structural evaluation was conducted prior to the commencement of rehabilitation activities. The evaluation consisted of field coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the first structural evaluation is presented in the following sections.

**Coring and Laboratory Examination**

Coring was performed in May 2005. Five cores were extracted along the entire 1,500-ft length of the project section at regular intervals of 300 ft. The extracted cores were visually examined and were generally in poor to good condition. Photos of some of the extracted cores are presented in figure 49. Detailed information regarding core thicknesses and condition is as follows:
Mean total HMA thickness = 4.7 in (total HMA thickness ranged from 4.5 to 4.75 in).
Mean total PCC thickness = 9.8 in (PCC thickness ranged from 9 to 10.5 in. Note that thickness measurements were not made for damaged/broken cores).
The condition of the HMA for four out of the five extracted cores was deemed good (i.e., intact material with less than two pieces). The remaining HMA core was in poor condition.
Four of the five PCC cores were deemed good (i.e., intact core with less than two pieces) while one PCC core was fractured at several locations and considered to be in poor condition.

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

Deflection Testing for Project ROS-35

Deflection testing was done using Dynaflect. The collected data were processed and included in the assembled project database for analysis.

Step 3—Pre-Overlay Activities/Repair for Project ROS-35

Pre-overlay repairs were made following the first structural evaluation, basically consisting of milling off 1.75 inches of the existing HMA.
Step 4—Second Structural Evaluation for Project ROS-35

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement in September 2005. This evaluation consisted of Dynaflect deflection testing only. Test locations were matched as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project ROS-35

Following the second structural evaluation, a 3.25-in HMA overlay (consisting of an upper layer – 12.5 mm Superpave, Type A mix and a lower layer – 19 mm Superpave, Type A mix) was placed.

Step 6—Third Structural Evaluation for Project ROS-35

The third and final structural evaluation was done after HMA overlay placement in November 2005. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

Initial Coring and Laboratory Examination

Initial coring was performed in November 2005. Six cores were extracted along the entire 1,500-ft length of the project section at regular intervals of 300-ft. The extracted cores were visually examined and assessed to determine condition, and they were deemed to be in poor to good condition. Photos of some of the extracted cores are presented in figure 50.

Figure 50. Photos of cores extracted from ROS-35 in 2005.
Detailed information regarding core thicknesses and condition are as follows:

- Mean total HMA thickness = 6.5 in (total HMA thickness ranged from 6 to 7 in, the 2005 HMA overlay thickness ranged from 3.2 to 3.6 in, with a mean value of 3.25 in), HMA overlay thickness was thus 3.25 in.
- Mean total PCC thickness = 10 in (all cores reported PCC thickness of 10 in).
- The condition of the HMA overlay from all the cores was deemed good (i.e., intact material with less than two pieces), though one core showed de-bonding between new and existing HMA.
- The condition of only two of the six PCC cores was deemed good (i.e., intact core with less than two pieces), the remaining four PCC cores were in poor condition (i.e., two or more pieces of PCC and rubble).

**Verification Coring and Laboratory Examination**

A second round of coring was performed in August 2006. Five cores were extracted along the entire 1,500-ft length of the project section at intervals ranging from 150 to 300 ft. The extracted cores were visually examined to assess condition. A photo showing all the five cores is presented in figure 51. Detailed information regarding core thicknesses and condition are as follows:

![Five cores extracted from ROS-35 in 2006.](image)

**Figure 51. Photos of verification cores extracted from ROS-35 in 2006.**

- Mean total HMA thickness = 5.9 in (total HMA thickness ranged from 5.4 to 6.3 in, the 2005 HMA overlay thickness ranged from 3.2 to 3.5 in, with a mean value of 3.25 in). Thus HMA overlay thickness was 3.25 in.
• Mean total PCC thickness = 9.3 in (PCC thickness ranged from 9 to 9.5 in).
• The condition of the HMA overlay for all five cores was deemed good (i.e., intact material with less than two pieces), though one core showed de-bonding between the existing HMA and PCC.
• The condition of all four PCC cores was deemed good (i.e., intact core with less than two pieces), though two of the five core showed some signs of fracture and hairline cracks.

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

Deflection Testing for Project ROS-35

Deflection testing was done using Dynaflect and was performed as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.

Data Analysis for Project ROS-35

Coring and deflection testing results along with other relevant information assembled from ODOT records were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, and pavement upper layers strength. Detailed analysis consisted of computing the parameter AREA and backcalculating pavement layer moduli and k-value along with determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically, milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity. The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 52 presents $S_1$ profiles for the different stages of rehabilitation and shows the following:

• Milling off the existing 1.75-in HMA did not significantly affect overall pavement structural capacity (i.e., increase in $S_1$ was not significant).
• Overall pavement structural capacity increased significantly after placement of the 3.25-in HMA overlay (i.e., $S_1$ decreased significantly).
• Variability in $S_1$ along the entire project was considerably lower with the placement of the HMA overlay.
The trends observed in figure 52 were confirmed by the results of the ANOVA presented in table 42.

![Figure 52. Plot showing $S_1$ profiles for ROS-35.](image)

**Table 42. Summary of analysis of variance results for maximum deflections (ROS-35)**

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>0.287 (0.064)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>11</td>
<td>0.288 (0.083)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>0.211 (0.031)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Spreadability**

The structural contribution of the pavement upper layers was characterized using SPR. Figure 53 presents SPR profiles at different stages of the 2005 rehabilitation and shows the following:

- Milling off the existing 1.75-in HMA did not improve pavement upper layers structural capacity.
- SPR increased significantly after placement of 3.25-in HMA overlay.
- SPR variability changed considerably after HMA overlay placement.

The trends observed in figure 53 were confirmed by the results of the ANOVA presented in table 43.

![Graph showing SPR profiles for ROS-35.](image)

**Figure 53. Plot showing SPR profiles for ROS-35.**

**Table 43. Summary of analysis of variance results for SPR (ROS-35).**

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>69 (2.9)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>11</td>
<td>69 (5.9)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>78 (3.4)</td>
<td>Good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Detailed Structural Analysis**

Detailed structural analysis involved computing the parameters AREA, Ep, k-value, D_{eff}, and required HMA overlay thickness for the different stages of rehabilitation.
By comparing the AREA, $D_{\text{eff}}$, and required HMA overlay thickness across the different stages of rehabilitation with the preliminary trends in maximum deflection and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analysis are presented in tables 44 and 45. Information presented in table 44 shows that trends observed in computed AREA was not reasonable. While there is no significant difference in actual AREA values before and after milling, AREA obtained from after-overlay placement is significantly higher than that from the previous two rehabilitation stages. The information in table 45 shows $D_{\text{eff}}$ decreasing slightly after milling and increasing significantly after HMA overlay placement, a trend which agrees with theory. The $D_{\text{eff}}$ for the before and after milling stages was not significantly different, indicating that the effect of milling was minimal.

Table 44. Summary of analysis of variance results for AREA (ROS-35).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>25.48 (1.34)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>11</td>
<td>25.26 (2.68)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>29.15 (1.46)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 45. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for ROS-35.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_P$, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{\text{eff}}$, in*</th>
<th>Is There a Significant Difference in $D_{\text{eff}}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>1,066,034 (301,686)</td>
<td>318 (75.6)</td>
<td>9.9 (0.14)</td>
<td>9.6 (0.95)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>11</td>
<td>1,700,648 (889,379)</td>
<td>326 (72)</td>
<td>9.9 (0.14)</td>
<td>9.3 (1.63)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>1,727,875 (390,050)</td>
<td>260 (50)</td>
<td>10.0 (0.11)</td>
<td>12.3 (0.84)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Information presented in table 45 indicates a 60 percent increase in backcalculated $E_P$ after milling with a corresponding 2 percent reduction in k-value. $E_P$ value increased slightly while the
k-value decreased by approximately 20 percent after placement of the 3.25-in HMA overlay. The before milling, and after HMA overlay placement $E_p$ show a gain in pavement strength after placement of HMA overlay. This was, however, accompanied by a loss in k-value. There was no clear trend in $E_p$ and k-values across the different rehabilitation stages.

**Summary**

The following is a summary of the observed trends in pavement structure capacity over the different rehabilitation stages:

- Overall pavement structural capacity characterized using $S_1$ did not change significantly after milling off 1.75 in of existing HMA; however, placement of the 3.25-in overlay resulted in a significant decrease in $S_1$, indicating an increase in the overall pavement structural capacity.
- Pavement upper layers structural capacity characterized using SPR did not change significantly after the milling operation. However, SPR increased significantly after placing the 3.25-in HMA overlay, indicating improved upper layer strength.
- Trends in pavement foundation strength characterized using the AREA parameter were not reasonable.
- Trends in computed $E_p$ and k-value were not consistent with theory across the different rehabilitation stages.
- Overall pavement structural capacity characterized using $D_{eff}$ was reasonable, with $D_{eff}$ increasing significantly after HMA overlay placement.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages. The effect of k-value on this parameter was minimal.
Overview of Project WAY-30

WAY-30 is a 1,500-ft-long composite (HMA over PCC) pavement located on the westbound lanes of U.S. Route 30. The exact project location is between station 1271+92 and 1286+92 in Wayne County (ODOT District 3). Information available in ODOT records and from field studies indicates that the project was originally constructed as a 9.5-in JRCP (average thickness from core data) over a 6.0-in DGAB and an A-4 subgrade in 1960. The original structure was overlaid in 1978 with a 2.5-in HMA overlay to become a composite pavement. In 1990, a second overlay (3.5-in HMA) was placed after milling off 1.0 inches of the existing HMA overlay. Additional significant rehabilitation was performed in 2003/2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project WAY-30

A six-step rehabilitation/structural evaluation program was implemented in 2003/2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project WAY-30

A comprehensive search of ODOT records was performed. Although the records review yielded no information pertaining to visual windshield survey, there was information available pertaining to pavement condition (characterized using PCR), design (layer material type and thicknesses), and traffic. The information assembled was reviewed for quality and consistency and was found to be generally reasonable; table 46 provides a summary of the collected historical data.

Several years of pavement condition data were available for the eastbound lanes of U.S. 30 adjacent to project WAY-30. Pavement conditions in the eastbound and westbound directions were assumed to be similar. The available performance data are presented in figure 54. The plot shows a significant increase in PCR to approximately 100 after rehabilitation (i.e., milling off 1.0-in HMA and placement of 3.5-in HMA overlay) was performed in 1990. Following the 1990 rehabilitation, there was a steady decrease in the pavement condition, resulting in an overall PCR of 53 immediately before the 2003/2004 rehabilitation. The PCR value of 53 indicates that the pavement was in poor condition prior to rehabilitation. PCR data after the 2003/2004 rehabilitation were not available.

The historical traffic information presented in figure 55 shows that this project had an initial AADT of 17,123 in 2004. Approximately 27.9 percent of the AADT were trucks. Total daily truck traffic in 2004 was 4,775. Traffic growth over the 20-year analysis period was approximately 6.9 percent (linear). Based on the traffic information obtained from ODOT records, projected 20-year traffic for WAY-30 analyzed as a composite/rigid pavement was 38,600,000 ESALs (61,781,433 trucks).
Table 46. Timeline showing significant historical construction and M&R events for WAY-30*.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>New JRC</td>
<td>Placement of a 2.5-in HMA</td>
<td>Stage A (Milling off 1-in of existing HMA layer)</td>
<td>Stage A (Milling off 1.5-in of existing HMA layer)</td>
</tr>
<tr>
<td>9-in JRC</td>
<td>2.5-in HMA (848)</td>
<td>1.5-in HMA (848)</td>
<td>1.5-in HMA (848)</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td>9-in JRC</td>
<td>9-in JRC</td>
<td>9-in JRC</td>
</tr>
<tr>
<td>Subgrade</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
</tr>
</tbody>
</table>

*Layer thicknesses presented in this table were obtained from data assembled from ODOT historical records and field testing.
Figure 54. Historical pavement performance characterized using PCR for WAY-30.

Figure 55. Historical traffic for WAY-30.
Step 2—First Structural Evaluation for Project WAY-30

A detailed and comprehensive structural evaluation was conducted prior to pre-overlay repairs and HMA overlay placement. This evaluation consisted of only deflection testing. Deflection profiles were obtained from Dynaflect testing as part of the first structural evaluation and assembled in a project database.

Step 3—Pre-Overlay Activities/Repair for Project WAY-30

After the first structural evaluation, comprehensive pre-overlay repairs were conducted as part of rehabilitation. Pre-overlay repairs consisted of milling off 1.5 inches of the existing HMA.

Step 4—Second Structural Evaluation for Project WAY-30

The second structural evaluation was done after the completion of pre-overlay repairs but prior to HMA overlay placement. Structural evaluation consisted of only deflection testing. Test locations were as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project WAY-30

Following the second structural evaluation, a 3.25-in (average thickness) HMA overlay (Superpave mix) was placed on the milled pavement surface.

Step 6—Third Structural Evaluation for Project WAY-30

The third and final structural evaluation was done after HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing. A summary of the data collected, along with data analysis, is presented in the following sections.

Coring and Laboratory Examination for Project WAY-30

Six cores were extracted along the entire 1,500-ft long project section at regular intervals of 300 ft. The extracted cores were visually examined and were deemed to be in good condition. A photo of the extracted cores is shown in figure 56. Detailed information regarding core thickness and condition is as following:

- Mean HMA overlay thickness: 7.5 in (ranged from 6.25 to 8.25 in).
- Mean PCC thickness: 9.5 in (ranged from 9.0 to 10.25 in).
- The condition for both HMA and PCC cores at all six locations was deemed good.

Deflection Testing

Deflection testing was done using Dynaflect. Test locations were selected to be as close as possible to the locations of previous deflection tests.
Data Analysis for Project WAY-30

Coring and deflection testing results, along with other relevant information, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement and pavement upper layers strength. Detailed analysis consisted of backcalculating $E_p$ and k-value and determining effective pavement thickness, computing the pavement AREA, and HMA overlay thickness needed to carry future traffic.

The objective of both the preliminary and detailed analysis was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically, milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity. The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, $S_1$. Figure 57 presents the $S_1$ profile for different stages of rehabilitation. A review of the plots presented in figure 57 shows the following:
• Milling off the existing 1.5-in HMA did not significantly affect overall pavement structural capacity (i.e., there was very little difference in $S_1$ before and after milling).
• Overall pavement deflection, $S_1$ decreased significantly after placement of the 3.25-in HMA overlay. This indicates an increase in overall pavement system structural capacity after rehabilitation.
• There was a considerable reduction in the variability of $S_1$ along the entire project after the placement of the 3.25-in HMA overlay. Standard deviation of $S_1$ was reduced by approximate 30 percent (i.e., from 0.031 to 0.019 mils) from the original composite pavement to after HMA overlay placement.

The trends observed in figure 57 were confirmed by the results of the ANOVA presented in table 47.

**Spreadability**

The structural contribution of the pavement upper layers was characterized using SPR. Figure 58 presents SPR profiles for project WAY-30 at different stages of rehabilitation. A review of the plot shows the following:

• Contrary to expectations, there were no significant differences for SPR before milling, after milling, and after the HMA overlay placement.
• SPR variability did not change significantly after the HMA overlay placement and before the milling.

The trends observed in figure 58 were confirmed by the results of the ANOVA presented in table 48.

![Figure 57. Plot showing $S_1$ profiles for WAY-30.](image-url)
Table 47. Summary of analysis of variance results for maximum deflections (WAY-30).

<table>
<thead>
<tr>
<th>Construction or Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Pavement Structure Condition</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.228 (0.031)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>0.218 (0.033)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.148 (0.019)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Figure 58. Plot showing SPR profiles for WAY-30.

Table 48. Summary of analysis of variance results for SPR (WAY-30).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>80 (3.3)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>75 (7.5)</td>
<td>Fair</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>78 (3.5)</td>
<td>Good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis involved computing AREA, $E_p$, k-value, $D_{eff}$, and required HMA overlay thicknesses for the different stages of rehabilitation. Table 49 shows that there was no significant difference in AREA before milling, after milling, and after the placement of the HMA overlay. This was contrary to theoretical and empirical trends.

Table 50 indicates that backcalculated $E_p$ and k-value before rehabilitation were 2,335,435 psi and 208 psi/in, respectively, while after rehabilitation (post-HMA overlay placement), $E_p$ and k-value before rehabilitation were 2,149,689 psi and 366 psi/in, respectively. $E_p$ and k-value after milling were 2,848,789 psi and 290 psi/in, respectively. A review of the estimated $E_p$ and k-value shows unreasonable trends not consistent with theory. The before and after rehabilitation $E_p$ and k-value estimates do not provide a clear trend on overall pavement strength.

Table 50 shows a significant decrease in $D_{eff}$ after milling, following by a significant increase in $D_{eff}$ after HMA overlay placement. This trend is reasonable and is as expected. Estimates of required mean HMA overlay thickness computed using DOITOVER, using before and after rehabilitation k-values, were 10.8-in and 10.5-in, respectively. ANOVA results showed that there was no significant difference in the required HMA overlay thickness. The pavement foundation strength characterized by k-value had very little impact on required HMA overlay thickness.

Summary

Results of the preliminary and detailed structural analysis are summarized as follows:

- There was no significant increase in $S_1$ after milling off the existing 1.5-in HMA layer. However, overall pavement structural capacity characterized using $S_1$ did significantly increase after the placement of HMA overlay.
- Overall pavement structural capacity characterized using SPR did not change significantly over the different rehabilitation stages. This was contrary to expectations and theoretical analysis.
- Pavement foundation strength characterized using the parameter AREA did change significantly over the different rehabilitation stages. This was contrary to expectations and theoretical analysis.
- There was a significant reduction in overall pavement structural capacity characterized using $D_{eff}$ after milling, followed by a significant increase in $D_{eff}$ after HMA overlay placement. The observed trends were reasonable.
- Required HMA overlay thickness (computed based on expected future traffic and k-value) did not change significantly over the different rehabilitation stages, although there were significant differences in k-value. This implies that the effect of k-value on determining required HMA overlay thickness is minimal.
Table 49. Summary of analysis of variance results for AREA (WAY-30).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>AREA*</th>
<th>Is There a Significant Difference in AREA (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>30.21</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>28.31</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>29.32</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 50. Summary of backcalculated layer moduli, effective thickness and required HMA overlay thickness for WAY-30.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated k-value, psi/in*</th>
<th>Required HMA Overlay Thickness, in*</th>
<th>$D_{eff}$, in</th>
<th>Is There a Significant Difference in $D_{eff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>2,335,435 (952,098)</td>
<td>208 (75.3)</td>
<td>10.8 (0.18)</td>
<td>12.4 (0.72)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>2,848,789 (1,886,366)</td>
<td>290 (131.7)</td>
<td>10.6 (0.24)</td>
<td>11.0 (1.52)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>2,149,689 (751,494)</td>
<td>366 (127.2)</td>
<td>10.5 (0.21)</td>
<td>13.3 (0.7)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
CHAPTER 11. PROJECT CLA-68

Overview of Project CLA-68

CLA-68 is a 1,550-ft-long flexible (HMA over HMA) pavement section located in the southbound lane of U.S. Route 68 in Clark County (ODOT District 7). Extensive review of ODOT records yielded information that was used to develop a timeline of significant construction and rehabilitation activities involving CLA-68 (ODOT, 1989):

- 1923 – original pavement was constructed (9-in JRCP over a granular base [tapered across the lane width] with an A-6 subgrade).
- 1968 - restoration work was performed (no plans available).
- 1984 - resurfacing was performed (no plans available).
- 1994 - 1.75-in-thick HMA overlay consisting of 1.25-in ODOT Item 404 HMA upper layer over a 0.5-in ODOT Item 403 HMA lower layer.

Additional significant rehabilitation was performed in 2005 and is the subject of this structural evaluation. Detailed site investigations performed just prior to this rehabilitation indicated that the southbound lane consisted of two types of structures, 1) HMA over PCC and 2) full-depth HMA. The full-depth HMA extended 4 ft into the southbound lane from the pavement edge. This section was treated as flexible pavement. Although the exact timing of the construction of the full-depth HMA is unknown, it is assumed that the outer 4 ft of the southbound lane was sawed and removed, and replaced by a full-depth HMA layer as part of the 1968-1994 restoration work. Figure 59 illustrates the cross-section of CLA-68 prior to rehabilitation in 2005.

Rehabilitation and Structural Evaluation Activities for Project CLA-68

A six-step rehabilitation/structural evaluation program was implemented in 2005, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project CLA-68

A comprehensive search of ODOT records provided historical information pertaining to project CLA-68 original design and construction, subsequent M&R, traffic, and performance history. Specific information gathered was as follows:

- Historical pavement condition characterized using PCR. PCR data were available for the years 1985 through 2004, but only for the northbound lanes of U.S. 68 adjacent to project CLA-68. The condition of the northbound and southbound lanes was assumed to be similar.
- Historical traffic (mid 1960’s to 2005).
- Design plans detailing layer thicknesses, material types, and so on.
Figure 59. Cross-section of the southbound lane for CLA-68.
The information was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. A summary of the design and M&R information is presented in table 51. Presented in figures 60 and 61 are plots of historical pavement performance and traffic.

The plot in figure 60 shows a PCR value of 97 in 1985, immediately after the 1984 rehabilitation, suggesting a pavement in very good condition. From 1984 to 1993, there was a steady decrease in PCR. In 1993, just prior to rehabilitation, the PCR was 67 (pavement in fair condition). After the 1994 rehabilitation, the PCR was approximately 100 (pavement in very good condition). Following a steady decline in PCR, the value in 2004 was 74 (pavement in fair condition). The rapid steady decline after both the 1985 and 1994 rehabilitations indicates that the pavement structure was quite weak and that the HMA overlay placement simply restored pavement functionality.

The historical traffic information presented in figure 61 shows a steady growth in traffic since the mid-1960’s. AADT just prior to the 2005 rehabilitation was estimated to be 9,164. ODOT records indicated that approximately 5.8 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2005 was estimated to be approximately 532. Historical traffic growth (all vehicles) was estimated to be approximately 1.17 percent, linear. Thus, for this analysis, projected 20-year truck traffic was estimated to be 4,554,880 trucks, which translates into 2,840,000 flexible ESALs.

Table 51. Timeline showing significant historical construction and M & R events for CLA-68.

<table>
<thead>
<tr>
<th>Rehabilitation (2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement before rehabilitation</td>
</tr>
<tr>
<td>13.35-in HMA</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
<tr>
<td>Stage A (Milling off 1.5-in of existing HMA layer)</td>
</tr>
<tr>
<td>11.9-in HMA</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
<tr>
<td>Stage B (Placement HMA overlay)</td>
</tr>
<tr>
<td>1.8-in HMA</td>
</tr>
<tr>
<td>11.9-in HMA</td>
</tr>
<tr>
<td>11.9-in HMA</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 2005 rehabilitation and specifically for this study. No plan records were available for the original construction year, and years 1968, and 1984.
Figure 60. Historical pavement performance characterized using PCR for CLA-68.

Figure 61. Historical traffic for CLA-68.
Step 2—First Structural Evaluation for Project CLA-68

A detailed and comprehensive structural evaluation was conducted in April 2005, prior to the commencement of 2005 rehabilitation activities. The structural evaluation consisted of deflection testing using the Dynaflect.

Step 3—Pre-Overlay Activities/Repair for Project CLA-68

Following the first structural evaluation, comprehensive pre-overlay repairs were performed, consisting of milling off 1.5-in of the existing HMA.

Step 4—Second Structural Evaluation for Project CLA-68

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement in June 2005. This evaluation consisted of Dynaflect deflection testing only. Test locations were matched as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project CLA-68

Following the second structural evaluation, a 1.8-in HMA overlay (ODOT 12.5 mm Superpave, Type B mix) was placed.

Step 6—Third Structural Evaluation for Project CLA-68

The third and final structural evaluation was done after HMA overlay placement in September 2005. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

Coring and Laboratory Examination

Coring was performed in August 2006. Six cores were extracted along the entire 1,550-ft length of the project section at regular intervals of 300 ft. The extracted cores were visually examined and found to be in good condition. Although there were no signs of moisture damage or stripping, one HMA core was broken at the bottom (due to the coring action) and another showed de-bonding between the new and existing HMA layers. HMA from both cores was reported to be in sound condition. Some of the extracted cores are shown in figure 62. Detailed information regarding core thickness and condition is as follows:

- Mean total HMA thickness = 13.7 in (total HMA thickness ranged from 13 to 15 in; the 2005 mean HMA overlay thickness ranged from 1.5 to 2 in, with a mean value of 1.8 in).
- The condition of the HMA overlay at all six core locations was deemed good (i.e., intact material with less than two pieces).

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.
Deflection Testing for Project CLA-68

Deflection testing was done using Dynaflect, as described in chapter 1. Testing was done as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.

![Figure 62. Photos of cores extracted from CLA-68 in 2006.](image)

Data Analysis for Project CLA-68

Coring and deflection testing results, along with layer type and layer thicknesses obtained from ODOT records, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layer, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli using the ODOT DOITOVER software and determining the effective pavement thickness and HMA overlay thickness needed to carry future traffic.

Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, $S_1$. Figure 63 presents $S_1$ profiles for the different stages of rehabilitation. A review of these profiles shows the following:
• Milling off the existing 1.5-in HMA did not significantly affect overall pavement system structural capacity.
• Even though there was a slight decrease in the $S_1$ after placement of the 1.8-in HMA overlay, it is not significantly different from the $S_1$ values after milling. Thus, milling and placement of the overlay did not impact the pavement structural capacity significantly.
• Variability in $S_1$ along the entire project was the lowest after the placement of the HMA overlay.

The trends observed in figure 63 were confirmed by the results of the ANOVA presented in table 52.

Table 52. Summary of analysis of variance results for maximum deflections (CLA-68).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.475 (0.087)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>0.477 (0.106)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.425 (0.073)</td>
<td>Excellent</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 64 presents SPR profiles at different stages of the 2005 rehabilitation. A review of the plots shows the following:

- Milling off the existing 1.5-in HMA made an observable improvement in the pavement upper layers structural capacity; however, the change was not significant.
- SPR decreased significantly after HMA overlay placement. This trend is contrary to theory.
- SPR variability was significantly lower after HMA overlay placement, as compared to the before and after milling stages.

The trends observed in figure 64 were confirmed by the results of the ANOVA presented in table 53.

![Figure 64. Plot showing SPR profiles for CLA-68.](image-url)
Table 53. Summary of analysis of variance results for SPR (CLA-68).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>66 (5.8)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>71 (5.7)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>54 (2.2)</td>
<td>Fair</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Subgrade Strength (characterized using $S_5$)

Information presented in table 54 shows that the overall trend in $S_5$ across the entire rehabilitation process is not quite as expected, although the trends observed before milling and after overlay placement appear to be reasonable. While there is no significant difference in $S_5$ values for the before milling and after overlay stages, $S_5$ from the after milling stage is significantly higher than that from the other two rehabilitation stages. This increase is not agreement with theory — $S_5$ should not show significant change—and may indicate the stress-sensitive nature of the A-6 subgrade soil.

Table 54. Summary of analysis of variance results for $S_5$ deflections (CLA-68).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $S_5$ Deflections, mils*</th>
<th>Is There a Significant Difference in $S_5$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.12 (0.042)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>0.217 (0.052)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.072 (0.015)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Detailed Structural Analysis

Detailed structural analysis involved backcalculating pavement moduli, $E_p$ and $M_r$, followed by estimating the $S_{Neff}$ and $S_{Nreq}$ for the different stages of rehabilitation. Backcalculation was done as described in chapter 1.

By comparing the $S_{Neff}$ and $S_{Nreq}$ across the different stages of rehabilitation with the preliminary trends in maximum deflection, SPR, and $S_5$ the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.
Results of the detailed structural analysis are presented in table 55. $\text{SN}_{\text{eff}}$ increased significantly after milling and decreased significantly after HMA overlay placement, a trend which does not agree with theory. The $\text{SN}_{\text{eff}}$ values before milling and after placement of the overlay were not statistically different.

Information presented in table 55 indicates a significant increase by almost five times in backcalculated $E_P$ after milling, with a corresponding 47 percent reduction in $M_r$. This is followed by a significant decrease in $E_P$ value and a corresponding increase in $M_r$ after HMA overlay placement. The before milling, after milling, and after HMA overlay placement $E_P$ and $M_r$ estimates do not provide a clear trend on overall pavement strength. The information in table 55 also shows that $\text{SN}_{\text{eff}}$ increased significantly after milling and decreased significantly after HMA overlay placement. This trend is contrary to trends developed through theoretical analysis. $\text{SN}_{\text{req}}$ changes with the rehabilitation stages due to significant variations in computed $M_r$. Although the trends presented in table 55 are not consistent with theory, the changes in $M_r$ indicate that the procedure for estimating $\text{SN}_{\text{req}}$ is sensitive to $M_r$.

Table 55. Summary of backcalculated layer moduli and effective structural number for CLA-68.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_P, \text{ psi}^*$</th>
<th>Backcalculated $M_r, \text{ psi}^*$</th>
<th>$\text{SN}_{\text{req}}^*$</th>
<th>$\text{SN}_{\text{eff}}^*$</th>
<th>Is There a Significant Difference in $\text{SN}_{\text{eff}}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>99,615 (49,467)</td>
<td>44,356 (12,686)</td>
<td>2.7 (0.3)</td>
<td>4.0 (0.8)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>535,893 (290,411)</td>
<td>23,980 (6,955)</td>
<td>3.3 (0.3)</td>
<td>6.4 (1.4)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>69,691 (30,783)</td>
<td>71,029 (16,157)</td>
<td>2.2 (0.2)</td>
<td>3.6 (0.6)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis show:

- Although overall pavement structural capacity characterized using $S_1$ did not change significantly over the three rehabilitation stages, trends in $S_1$ were generally reasonable.
- Pavement upper layers structural capacity characterized using SPR did not change significantly after HMA overlay placement. The change, however, was contrary to theory.
- There were significant changes in pavement foundation strength characterized using $S_5$ over the three rehabilitation stages. This is contrary to theory.
• Trends in computed $E_p$ and $M_r$ were inconsistent with theory.
• Overall pavement structural capacity characterized using $SN_{eff}$ increased significantly from the before milling to the after milling stage and then decreased significantly after overlay placement. Trends in computed $D_{eff}$ were inconsistent with theory.
• The procedure for computing $SN_{req}$ was sensitive to $M_r$. However, computed $SN_{req}$ was inconsistent due to the inconsistent estimates of $M_r$ for the different rehabilitation stages.
Overview of Project GAL-35

GAL-35 is a 1,500-ft-long pavement section located on U.S. 35. The exact project location is between station 158+29 and 173+29 in Gallia County (ODOT District 10). The pavement was constructed in 1955 as a JRCP over a 6.0-in DGAB and subgrade. Subgrade type information was not available. ODOT records indicate that the existing JRCP was rubblized and overlaid with a 14.2-in HMA layer in 1990.

In 1999, 1.5 inches of the existing HMA surface course (placed in 1990) was milled off and replaced with a 1.5-in HMA overlay. The pavement outer lane was also widened from the existing 12 ft to 13 ft. Additional significant rehabilitation was performed in 2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project GAL-35

A six-step rehabilitation/structural evaluation program was implemented in 2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project GAL-35

A windshield survey was conducted to determine the condition of the HMA/rubblized PCC pavement prior to rehabilitation in 2004. Information obtained from the survey was available in ODOT records in the form of photos (see figures 65 through 68). The pavement showed considerable moderate to high-severity transverse and longitudinal cracking. It was therefore concluded that overall pavement conditions was moderate to poor.

In addition to the windshield survey, a comprehensive search of ODOT records elicited historical information pertaining to project, design, construction, M&R, traffic, and performance. A summary of the information obtained from ODOT records is presented in table 56. Historical PCR and traffic data available in ODOT records are presented in figures 69 and 70.

Several years of pavement condition data were available for the eastbound lanes of U.S. 35 adjacent to project GAL-35. Pavement conditions in the eastbound and westbound directions were assumed to be similar. The plot in figure 69 shows PCR value of 100 in 1990 (after the placement of HMA overlay). Following the 1990 rehabilitation, there was a rapid decrease in the pavement condition, resulting in an overall PCR of 71 immediately before the 1999 rehabilitation. This rehabilitation increased the PCR to 84 in 2000. Subsequently, the pavement condition decreased rapidly down to 77, before the 2004 rehabilitation. The PCR value indicates that the pavement was at the lower limit of good condition before the 2004 rehabilitation. After that, there was a significant increase in PCR, to approximately 100 in 2006.

The historical traffic information presented in figure 70 shows that this project had an AADT of 11,514 in 2005. Approximately 32.8 percent of the AADT were trucks, and thus, total daily truck traffic in 2005 was 3,780. Traffic growth over the 20-year analysis period was approximately
Figure 65. GAL-35 windshield survey (photo 1) showing moderate-severity cracking (longitudinal, transverse, and alligator).

Figure 66. GAL-35 windshield survey (photo 2) showing high-severity cracking (longitudinal, transverse (reflection), and alligator).
Figure 67. GAL-35 windshield survey (photo 3) showing high-severity alligator cracking.

Figure 68. GAL-35 windshield survey (photo 4) showing moderate-severity reflection “transverse” cracking.
Table 56. Timeline showing significant historical construction and M&R events for GAL-35.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2-in HMA layer</td>
<td>2.7-in HMA layer</td>
<td>1.5-in HMA layer</td>
<td>1.5-in HMA layer</td>
<td></td>
</tr>
<tr>
<td>10.0-in HMA Base</td>
<td>2.7-in HMA layer</td>
<td>2.7-in HMA layer</td>
<td>2.7-in HMA layer</td>
<td></td>
</tr>
<tr>
<td>(ODOT 301 layer)</td>
<td>10.0-in HMA Base</td>
<td>10.0-in HMA Base</td>
<td>10.0-in HMA Base</td>
<td></td>
</tr>
<tr>
<td>(Fractured)</td>
<td>(ODOT 301 layer)</td>
<td>(ODOT 301 layer)</td>
<td>(ODOT 301 layer)</td>
<td></td>
</tr>
<tr>
<td>6.0-in DGAB</td>
<td>9.0-in JRC Slab</td>
<td>9.0-in JRC Slab</td>
<td>10.0-in HMA Base</td>
<td></td>
</tr>
<tr>
<td>(Fractured)</td>
<td>(Fractured)</td>
<td>(Fractured)</td>
<td>(ODOT 301 layer)</td>
<td></td>
</tr>
<tr>
<td>Subgrade</td>
<td>6.0-in DGAB</td>
<td>6.0-in DGAB</td>
<td>9.0-in JRC Slab</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subgrade</td>
<td>Subgrade</td>
<td>(Fractured)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0-in DGAB</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subgrade</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

136
Figure 69. Historical pavement performance characterized using PCR for GAL-35.

Figure 70. Historical traffic application for GAL-35.
10.31 percent linear. Based on the traffic information obtained from ODOT records, projected 20-year traffic for GAL-35 analyzed as a flexible pavement was 20,100,000 ESALs (58,845,585 trucks).

Step 2—First Structural Evaluation for Project GAL-35

A detailed and comprehensive structural evaluation consisting of laboratory examination of the cores, and deflection testing was conducted prior to rehabilitation in 2004.

Coring and Laboratory Examination for Project GAL-35

Six cores were extracted at 300-ft intervals along the entire 1,500-ft-long project. The extracted cores were visually examined to assess their condition, and all were determined to be in relatively good condition (i.e., intact HMA material). The underlying PCC at all six locations was rubble (which confirmed that the JRCP had previously been rubblized). A photo of extracted cores is presented in figure 71. Layer thicknesses from cores were as follows:

- Mean HMA and HMA aggregate base thickness: 12.8 in (ranged from 12.5 to 13.0 in).
- Mean PCC thickness: 9.0-in rubblized and rolled JRCP slab.

The measured core thicknesses were in reasonable agreement with ODOT plan thicknesses.

Figure 71. Cores extracted from GAL-35 in 2004.
Deflection Testing for Project GAL-35

Deflection testing was performed at 50-ft intervals using Dynaflect testing equipment.

Step 3—Pre-Overlay Activities/Repair for Project GAL-35

After the first structural evaluation, comprehensive pre-overlay repairs were conducted as part of rehabilitation. Pre-overlay repairs basically consisted of milling off 1.5-in of the existing HMA overlay.

Step 4—Second Structural Evaluation for Project GAL-35

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement. This evaluation consisted of only deflection testing. Test locations were as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project GAL-35

Following the second structural evaluation, a 1.5-in (average thickness) HMA overlay (Superpave) was placed.

Step 6—Third Structural Evaluation for Project GAL-35

The third and final structural evaluation was done after HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing.

Coring and Laboratory Examination for Project GAL-35

Twelve cores were extracted along the entire 1,500-ft-long project (at 150-ft intervals, on average) in 2005 and 2006. Coring locations for six of the cores were selected to match as close as possible to the six cores extracted during the first structural evaluation. All cores were visually examined to assess their condition. The HMA portions of the cores were determined to be in good condition (i.e., intact core with less than two pieces). The PCC portions were rubble, as expected for an HMA/rubblized PCC pavement.

A photo of six of the extracted cores (2005) is presented in figure 72. Layer thicknesses derived from the cores are as follows:

- Mean HMA thickness: 13.0 in (all the cores reported a HMA thickness of 13.0 in).
- Mean PCC thickness: 9.0 in (rubblized and rolled JRCP material).

Layer thicknesses derived from cores extracted in 2006 are as follows:

- Mean HMA: 15.7 in (ranges from 11.5 to 24.0 in).
- Mean PCC thickness: 9.0 in (rubblized and rolled JRCP material).
Although the measured mean core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records, the range of HMA layer thicknesses was exceedingly large. The reason for such a large range in core thickness was unclear.

Deflection Testing for Project GAL-35

Deflection testing was done using Dynaflect. The testing process was as previously described in the first structural evaluation, and the test locations were selected to be as close as possible to the locations of previous deflection tests.

Data Analysis for Project GAL-35

Coring and deflection testing results, along with information such as layer type and layer thicknesses obtained from ODOT records, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layer, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli using DOITOVER and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.
Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, $S_1$. Figure 73 presents $S_1$ profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 1.5-in HMA did significantly affect overall pavement structural capacity. There was a 36 percent increase in measured $S_1$.
- Overall pavement deflection, $S_1$ decreased significantly after the placement of the 1.5-in HMA overlay.
- There was no significant difference for $S_1$ after the rehabilitation, implying that the use of new materials did not significantly impact pavement structure capacity.
- Variability in $S_1$ along the project did not change during rehabilitation.

The trends observed in figure 73 were confirmed by the results of the ANOVA presented in table 57.

![Figure 73. Plot showing $S_1$ profiles for GAL-35.](image)
Table 57. Summary of analysis of variance results for maximum deflections (GAL-35).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>0.212 (0.057)</td>
<td>Excellent</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>0.290 (0.064)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>0.186 (0.054)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 74 presents SPR profiles at different stages of rehabilitation and shows the following:

- Milling off the existing 1.5-in HMA resulted in a significant reduction in the pavement upper layers structural capacity.
- SPR increased significantly after HMA overlay placement.
- There was no significant difference in before and after rehabilitation. SPR structural properties of HMA overlay material was similar to early (before rehabilitation) HMA material.
- SPR variability decreased significantly after milling and overlay placement.

The trends observed in figure 74 were confirmed by the results of the ANOVA presented in table 58.

Subgrade Strength, $S_5$

Information presented in table 59 shows there were no significant differences $S_5$ before milling, after milling, and after the HMA overlay placement. The fact of unchanging $S_5$ is in agreement with theory.
Figure 74. Plot showing SPR profiles for GAL-35.

Table 58. Summary of analysis of variance results for SPR (GAL-35).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>72 (8.0)</td>
<td>Good to Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>66 (3.2)</td>
<td>Good</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>74 (4.0)</td>
<td>Excellent</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 59. Summary of analysis of variance results for S₅ deflections (GAL-35).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean S₅ Deflections, mils*</th>
<th>Is There a Significant Difference in S₅ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>12</td>
<td>0.08 (0.051)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>12</td>
<td>0.103 (0.048)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>12</td>
<td>0.08 (0.038)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis involved 1) backcalculating pavement layer moduli, \( E_p \) and \( M_r \), 2) estimating \( SN_{eff} \), and 3) estimating \( SN_{eff} \) for all the three stages of rehabilitation. Analysis was done using the ODOT DOTIOVER software.

Results of the detailed structural analysis are presented in table 60. The results indicate reasonable trends for all the computed parameters. The ANOVA results also indicate that there was a significant increase in \( SN_{eff} \) after the HMA overlay placement.

Table 60. Summary of backcalculated layer moduli and effective structural number for GAL-35.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated ( E_p, \text{ psi}^* )</th>
<th>Backcalculated ( M_r, \text{ psi}^* )</th>
<th>Required ( SN_{eff}^* )</th>
<th>( SN_{eff}^* )</th>
<th>Is There a Significant Difference in ( SN_{eff} ) (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>12</td>
<td>326,022 (111,769)</td>
<td>65,529 (34,225)</td>
<td>3.3 (0.61)</td>
<td>8.8 (1.14)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>12</td>
<td>284,507 (83,636)</td>
<td>48,100 (15,359)</td>
<td>3.5 (0.40)</td>
<td>8.1 (0.74)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>12</td>
<td>438,663 (132,686)</td>
<td>65,139 (27,905)</td>
<td>3.2 (0.44)</td>
<td>9.9 (0.97)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

A summary of preliminary and detailed structural evaluation results is as follows:

- Overall pavement structural capacity characterized using \( S_1 \) did change significantly during the rehabilitation process. Before rehabilitation pavement structure capacity and after rehabilitation pavement structure capacity were, however, the same.
- Pavement upper layers structural capacity characterized using SPR followed the same trend as \( S_1 \).
- Pavement foundation strength characterized using \( S_5 \) did not significantly change during the rehabilitation process. This is consistent with theory.
- Trends observed for \( E_p \) and \( M_r \) during the rehabilitation process were reasonable.
- Trends in overall pavement structural capacity characterized using \( SN_{eff} \) were reasonable. \( SN_{eff} \) decreased by 8 percent after milling and increased significantly (by 22 percent) after HMA overlay placement.
CHAPTER 13. PROJECT GRE-72

Overview of Project GRE-72

GRE-72 is a 1,500-ft-long flexible (HMA over HMA) pavement located in the northbound lanes of U.S. Route 72 in Greene County (ODOT District 8). The project begins approximately 200 ft north of milepost 1.0. The original pavement was constructed in 1938 as a flexible pavement. It was subsequently rehabilitated in 1952, 1966, 1982, 1994, and then again in 2005. The 2005 rehabilitation is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project GRE-72

A six-step rehabilitation/structural evaluation program was implemented in 2005, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project GRE-72

A comprehensive search of ODOT records provided:

- Historical pavement condition data (PCR data for the years 1985 through 2004).
- Detailed distress information from visual windshield survey just prior to the 2005 rehabilitation.
- Historical traffic (1985 through 2004).
- Design plans describing layer thicknesses, material types, and so on.

The information was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. The photos in figures 75 through 78 show a highly damaged pavement with significant amount of moderate to high-severity transverse, longitudinal, and alligator cracking. Also present was some patching resulting from full-depth repairs. The pavement was generally in moderate to poor condition.

A summary of the design, construction, and M&R information assembled is presented in table 61. Presented in figures 79 and 80 are plots of historical pavement performance and traffic. The PCR data plotted in figure 79 suggest an existing pavement in poor to fair condition, prior to the 1994 rehabilitation. That rehabilitation resulted in significant improvements to pavement condition (PCR of approximately 86, suggesting an existing pavement in good condition). In the years following 1994, the PCR value showed a steady decline leading to a PCR of 68 in 2002. Some minor M&R work performed in this year did raise the PCR to approximately 80. A PCR value of 76 was reported in 2004, suggesting that the existing pavement was in fair to good condition.

Figure 80 shows a steady increase in traffic from the mid-1960’s to 2004. AADT just prior to the 2005 rehabilitation was estimated to be 2,300. ODOT records indicated that approximately 8 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2005 was estimated to be approximately 183. Historical traffic growth was approximately 4.19
Figure 75. GRE-72 windshield survey (photo 1) showing moderate to high-severity longitudinal, transverse, and alligator cracking.

Figure 76. GRE-72 windshield survey (photo 2) showing high-severity alligator cracking.
Figure 77. GRE-72 windshield survey (photo 3) showing patching.

Figure 78. GRE-72 windshield survey (photo 1) showing high-severity alligator cracking.
Table 61. Timeline showing significant historical construction and M&R events for GRE-72.

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 2005 rehabilitation and specifically for this study. No plan records were available for the original construction year, and years 1952, 1966, 1982 and 1994.

Figure 79. Historical pavement performance characterized using PCR for GRE-72.
percent, linear. Thus, for analysis, projected 20-year truck traffic was estimated to be 1,990,424 which translated into 722,000 flexible ESALs.

**Step 2—First Structural Evaluation for Project GRE-72**

A detailed and comprehensive structural evaluation was conducted in April/May 2005, prior to the commencement of rehabilitation activities. Structural evaluation consisted of coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the first structural evaluation is presented in the following sections.

**Coring and Laboratory Examination**

Six cores were extracted along the entire 1,500-ft length of the project section at regular intervals of 300 ft. The extracted cores were visually examined to assess their condition. Although there were no signs of moisture damage or stripping, all six HMA cores were in poor condition, with the base HMA layer in pieces. The upper HMA layers were in comparatively better condition. A photo of some of the extracted cores is presented in figure 81. Mean total HMA thickness was 9.3 in, with total HMA thickness ranging from 8 to 11 in.

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.
Deflection Testing for Project GRE-72

Deflection testing was done using Dynaflect as described in chapter 1.

Step 3—Pre-Overlay Activities/Repair for Project GRE-72

Following the first structural evaluation, comprehensive pre-overlay repairs were conducted. Pre-overlay repairs consisted of milling off 1.5 inches of the existing HMA.

Step 4—Second Structural Evaluation for Project GRE-72

The second structural evaluation was done after the pre-overlay repairs but prior to HMA overlay placement in June 2005. This evaluation consisted of only Dynaflect deflection testing. Test locations were matched as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project GRE-72

Following the second structural evaluation, a 1.5-in HMA overlay (ODOT 12.5 mm Superpave, Type B mix) was placed over the milled pavement structure.
Step 6—Third Structural Evaluation for Project GRE-72

The third and final structural evaluation was done after HMA overlay placement in September 2005. Structural evaluation consisted of coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

Initial Coring and Laboratory Examination

Initial coring was performed in November 2005. Eight cores were extracted along the entire 1,500-ft length of the project section at regular intervals of 300 ft (note that two extra cores were extracted at two of the six locations). The extracted cores were visually examined to assess condition. A photo of some of the extracted cores is presented in figure 82. Results of laboratory examination of the cores are presented as follows:

- All six cores examined were in poor condition (i.e., two or more pieces of HMA), and most showed de-bonding between the HMA layers.
- Mean total HMA thickness was 10 in. Total HMA thickness ranged from 8 to 12 in. The mean 2005 HMA overlay thickness was 1.5 in.

Figure 82. Cores extracted from GRE-72 in 2005.
Verification Coring and Laboratory Examination

Additional coring and laboratory examination was performed in August 2006 to verify the information obtained during the November 2005 field testing. For the August 2006 field examination, five cores were extracted along the entire 1,500-ft length of the project section at intervals of 150 and 300 ft. The extracted cores were visually examined to assess their condition. A photo of some of the extracted cores is presented in figure 83. Detailed information regarding core thicknesses and condition is as follows:

![Figure 83. Cores extracted from GRE-72 in 2006.](image)

- Mean total HMA thickness = 10.7 in. Total HMA thickness ranged from 9.5 to 12 in. The mean 2005 HMA overlay thickness was 1.5 in (ranged from 1.38 to 1.75 in).
- All five cores were in poor condition (i.e., two or more pieces of HMA). Some cores showed separation between the different HMA lifts and severe fractures.

The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

Deflection Testing for Project GRE-72

Deflection testing was done using Dynaflect. Testing was done as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.
Data Analysis for Project GRE-72

Coring and deflection testing results, along with pavement layer type and layer thicknesses, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layers, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

The analysis results are presented in the following sections.

Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, S1. Figure 84 presents S1 profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 1.5-in HMA significantly decreased the overall pavement structural capacity (as can be seen by the significant increase in S1 after milling).
- Pavement structural capacity increased significantly after the placement of the HMA overlay.
- Variability in S1 decreased with HMA overlay placement.

The trends observed in figure 84 were confirmed by the results of the ANOVA presented in table 62.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 85 presents SPR profiles at different stages of the 2005 rehabilitation and shows the following:

- Milling off the existing 1.5-in HMA resulted in a decrease in the SPR. Even though this change was not very significant, the trend agrees with theory.
- After placement of the 1.5-in HMA overlay, the pavement upper layer pavement strength increased significantly. Before rehabilitation SPR and after HMA overlay placement SPR were not significantly different.
- SPR variability was decreased significantly after overlay.

The trends observed in figure 85 were confirmed by the results of the ANOVA presented in tables 63.
Figure 84. Plot showing S1 profiles for GRE-72.

Table 62. Summary of analysis of variance results for maximum deflections (GRE-72).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan's Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>0.996 (0.261)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>1.362 (0.302)</td>
<td>Poor</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>0.762 (0.203)</td>
<td>Fair</td>
<td>C</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 63. Summary of analysis of variance results for SPR (GRE-72).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>57 (5.8)</td>
<td>Fair</td>
<td>B, A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>52 (5.7)</td>
<td>Poor to Fair</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>58 (2.2)</td>
<td>Fair</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Subgrade Strength (characterized by $S_5$)

Table 64 presents information showing that $S_5$ values from the three rehabilitation stages are statistically not different. This trend agrees very well with theory.
Table 64. Summary of analysis of variance results for $S_5$ deflections (GRE-72).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $S_5$ Deflections, mils*</th>
<th>Is There a Significant Difference in $S_5$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>0.195 (0.088)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>0.221 (0.136)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>0.196 (0.102)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Detailed Structural Analysis

Detailed structural analysis was performed by backcalculating pavement moduli, $E_p$, and $M_r$, followed by estimation of $S_{neff}$ and $S_{nreq}$ for each stage of rehabilitation.

By comparing the $S_{neff}$ and $S_{nreq}$ across the different stages of rehabilitation with the preliminary trends in maximum deflection, $S_5$, and SPR, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analysis are presented in table 65. Changes in $E_p$ and $M_r$ were consistent with theory. $S_{nreq}$ was basically the same throughout the rehabilitation stages, as expected. $S_{neff}$ decreased significantly after milling and then increased significantly after HMA overlay placement. The $S_{neff}$ trends presented are reasonable.

Table 65. Summary of backcalculated layer moduli and effective structural number for GRE-72.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_p$, psi*</th>
<th>Backcalculated $M_r$, psi*</th>
<th>$S_{nreq}$ *</th>
<th>$S_{neff}$ *</th>
<th>Is There a Significant Difference in $S_{neff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>11</td>
<td>41,142 (20,332)</td>
<td>32,091 (20,332)</td>
<td>2.5 (0.5)</td>
<td>2.5 (0.6)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>11</td>
<td>26,975 (25,023)</td>
<td>36,212 (33,147)</td>
<td>2.6 (0.6)</td>
<td>1.9 (0.6)</td>
<td>C</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>11</td>
<td>94,548 (63,700)</td>
<td>32,740 (17,612)</td>
<td>2.5 (0.5)</td>
<td>3.2 (0.8)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Summary

A summary of the data analysis results is presented as follows:

- Trends in overall pavement structural capacity characterized using $S_1$ were reasonable, since the $S_1$ increased significantly after milling and decreased $S_1$ significantly after placement of the 1.5-in HMA overlay.
- Trends in pavement upper layers structural capacity characterized using SPR were also reasonable.
- There were no appreciable differences in $S_5$ across the different rehabilitation stages as expected.
- Trends in backcalculate $E_p$ and Mr were reasonable and as expected.
- Overall pavement structural capacity characterized using $SN_{eff}$ decreased significantly after milling and then increased significantly after overlay placement. This trend was reasonable.
- Trends in $SN_{req}$ were as expected, and there were no significant changes across rehabilitation stages.
CHAPTER 14. PROJECT JAC-32

Overview of Project JAC-32

JAC-32 is a 1,500-ft-long pavement section located on State Route 32. The exact project location is between station 1171+46 and 1186+46 in Jackson County (ODOT District 9). The original pavement was constructed in 1968 and consisted of a 2.5-in HMA upper layer over an underlying 7.0-in bituminous aggregate base course (ODOT material type – 301) placed over a 6-in dense-graded aggregate subbase and an A-4 subgrade.

A 2.0-in HMA overlay was placed on the existing pavement in 1985. Although there was no specific information in ODOT records of any significant M&R in 1991, a review of the pavement condition indicates a significant increasing in PCR, signaling possible M&R at that time. Pavement layer thickness information also indicates that a 4.5-in HMA overlay was placed in 1991. Additional significant rehabilitation was performed in 2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project JAC-32

A six-step rehabilitation/structural evaluation program was implemented in 2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project JAC-32

A windshield survey was conducted to determine the condition of the pavement prior to the 2004 rehabilitation. Photos showing general distress condition during the survey were made available to the project team as part of records review (see figures 86 through 89). A review of the photos showed high-severity transverse and alligator cracking. The pavement was generally in poor condition.

Other information obtained from ODOT included original construction, subsequent M&R, design and construction plans, historical traffic information, and performance data. Historical pavement condition was characterized using PCR. The information retrieved from ODOT records was reviewed for quality and consistency and was found to be generally reasonable. A summary of the original design and subsequent M&R information assembled is presented in table 66.

Figure 90 presents historical pavement PCR information. This pavement had a PCR of approximately 100 in 1986, immediately after the placement of HMA overlay. Following that rehabilitation, there was a steady decrease in the pavement condition resulting in an overall PCR of 71 in 1991. PCR increased to 97 in 1992 following the placement of an HMA overlay. After 1992, the PCR decreased steadily to 76 in 2004. The PCR value indicates that the pavement was in good condition before the rehabilitation performed in 2004.

The historical traffic information presented in figure 91 shows high compounded growth in traffic, with an AADT of 4,483 in 2005. ODOT records indicate that approximately 30.3 percent
Figure 86. JAC-32 windshield survey (photo 1) showing high-severity transverse cracking.

Figure 87. JAC-32 windshield survey (photo 2) showing high-severity transverse cracking.
Figure 88. JAC-32 windshield survey (photo 3) showing longitudinal and transverse cracking.

Figure 89. JAC-32 windshield survey (photo 4) showing high-severity transverse cracking.
Table 66. Timeline showing significant historical construction and M&R events for JAC-32.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-in HMA layer</td>
<td>2.0-in HMA layer</td>
<td>4.5-in HMA layer</td>
<td>Stage A (Milling off 1.5-in of existing HMA layer)</td>
</tr>
<tr>
<td>7.0-in HMA Agg. Base</td>
<td>2.5-in HMA layer</td>
<td>3.0-in HMA layer</td>
<td>1.5-in HMA layer</td>
</tr>
<tr>
<td>6.0-in DGAB</td>
<td>7.0-in HMA Agg. Base</td>
<td>2.0-in HMA layer</td>
<td>3.0-in HMA layer</td>
</tr>
<tr>
<td>Subgrade</td>
<td>6.0-in DGAB</td>
<td>2.0-in HMA layer</td>
<td>2.0-in HMA layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5-in HMA layer</td>
<td>2.0-in HMA layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.0-in HMA Agg. Base</td>
<td>2.5-in HMA layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0-in DGAB</td>
<td>7.0-in HMA Agg. Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subgrade</td>
<td>6.0-in DGAB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Stage B (Placement of 1.5-in HMA overlay)
Figure 90. Historical pavement performance characterized using PCR for JAC-32.

Figure 91. Historical traffic application for JAC-32.
of the AADT were trucks, and thus, total daily truck traffic in 2005 was 910. Projected 20-year traffic for GAL-35 analyzed as a flexible pavement was 7,720,000 flexible ESALs.

**Step 2—First Structural Evaluation for Project JAC-32**

Prior to rehabilitation in 2004, a detailed and comprehensive structural evaluation was conducted that consisted of field coring, laboratory examination of the cores, and deflection testing.

*Coring and Laboratory Examination for Project JAC-32*

Six cores were extracted along the entire 1,500-ft-long project section at regular intervals of 300 ft. The extracted cores were visually examined to assess their condition. All six cores were determined to be deemed good condition (i.e., intact core with less than two pieces). A photo of extracted cores is presented in figure 92. The mean HMA thickness from cores was 15.9 in (ranged from 14.0 to 17.0 in).

![Cores extracted from JAC-32.](image)

The measured core thicknesses were about 4.5 inches thicker than the plan thicknesses obtained from ODOT records. The discrepancy was attributed to the 4.5-in HMA overlay that was placed in 1991 but missing from ODOT records.

*Deflection Testing for Project JAC-32*

Deflection testing was performed for this section using Dynaflect and FWD testing equipment.
Step 3—Pre-Overlay Activities/Repair for Project JAC-32

After the first structural evaluation, pre-overlay repairs were conducted as part of rehabilitation. Pre-overlay repairs basically consisted of milling off approximately 1.5 inches of the existing HMA layer.

Step 4—Second Structural Evaluation for Project JAC-32

The second structural evaluation was done after the completion of pre-overlay repairs but prior to HMA overlay placement. Structural evaluation consisted of deflection testing using both Dynaflect and FWD equipment. Test locations were as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project JAC-32

Following the second structural evaluation, a 1.5-in (average thickness) HMA overlay was placed on the milled pavement surface.

Step 6—Third Structural Evaluation for Project JAC-32

The third and final structural evaluation was done after HMA overlay placement. This evaluation consisted of field coring, laboratory examination of the cores, and deflection testing. A summary of the data collected, along with data analysis, is presented in the following sections.

Coring and Laboratory Examination for Project JAC-32

In 2005, six cores were extracted along the entire 1,500-ft-long project section at regular intervals of 300 ft. Coring locations were selected to match as close as possible to the locations where cores were extracted during the first structural evaluation. A photo of cores extracted in 2005 is presented in figure 93. All four HMA cores extracted from the first 900 ft of the project were deemed good (i.e., intact core with less than two pieces), while the two cores from the remaining 600 ft were deemed as being in poor condition. The mean HMA layer thickness derived from the extracted cores was 16.0 in (all cores reported 16.0 in thickness).

The measured core thicknesses were about 4.5 inches thicker than plan thicknesses obtained from ODOT records. Possible reasons for this have already been explained.

Deflection Testing for Project JAC-32

Deflection testing was performed, as previously described in the first structural evaluation, after the HMA overlay placement. Deflections were measured using both Dynaflect and FWD equipment. Test locations during this phase of evaluation were as close as possible to those performed during the first and second structural evaluations.
Data Analysis for Project JAC-32

Coring and deflection testing results, along with other relevant information, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layers, and subgrade structure capacity. Detailed analysis consisted of backcalculating pavement layer moduli and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, $S_1$. Figure 94 presents $S_1$ profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 1.5-in HMA did not significantly affect overall pavement system structural capacity, although there was an increase in $S_1$ as expected.
- Overall pavement deflection, $S_1$ decreased significantly after the placement of the 1.5-in HMA overlay, indicating a significant increase in overall pavement structural capacity after the HMA overlay placement.
- Variability in $S_1$ value decreased significantly changing after HMA overlay placement.
The trends observed in figure 94 were confirmed by the results of the ANOVA presented in table 67.

![Graph showing S1 profiles for JAC-32.]

Table 67. Summary of analysis of variance results for maximum deflections (JAC-32).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils*</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.643 (0.117)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>0.663 (0.060)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.473 (0.038)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

**Spreadability**

The structural contribution of the pavement upper layers was characterized using SPR. Figure 95 presents SPR profiles at different stages of the 2004 rehabilitation and shows the following:
• Milling off the existing 1.5-in HMA resulted in a significant increase in the pavement upper layers structural capacity. This was contrary to expected trends.
• SPR further increase significantly after HMA overlay placement. An increase in SPR after HMA overlay placement is reasonable.
• SPR variability remained as the same through the rehabilitation process.

The trends observed in figure 95 were confirmed by the results of the ANOVA presented in table 68.

![Figure 95. Plot showing SPR profiles for JAC-32.](image)

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>41 (0.3)</td>
<td>Poor</td>
<td>C</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>51 (4.2)</td>
<td>Poor to Fair</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>59 (4.2)</td>
<td>Fair</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Subgrade Strength (characterized using S₅)

Information in table 69 shows there was a significant increase for S₅ after milling, which does not agree with theory (S₅ should not show significant change). This finding may indicate the stress-sensitive nature of the subgrade soil.

Table 69. Summary of analysis of variance results for S₅ deflections (GAL-35).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean S₅ Deflections, mils*</th>
<th>Is There a Significant Difference in S₅ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.050 (0.015)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>0.108 (0.048)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.141 (0.043)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Detailed Structural Analysis

Detailed structural analysis involved backcalculating pavement moduli (Eₚ and Mᵣ) and estimating SNₑff and SNₑᵣₑ using ODOT’s DOITIVER software for the different stages of rehabilitation. By comparing computed Eₚ, Mᵣ and SNₑᵣₑ across the different stages of rehabilitation, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analysis are presented in table 70. Backcalculated Eₚ and corresponding decrease in Mᵣ during the rehabilitation process. Neither computed Eₚ nor Mᵣ was reasonable (Mᵣ = 100,019 psi). Neither Eₚ nor Mᵣ provides a clear trend in overall pavement strength.

SNₑff increased after milling, although this increase was not significant. However, after HMA overlay placement, there was a significant 72 percent increase in SNₑff. Computed SNₑff value did not provide a clear trend.
Table 70. Summary of backcalculated layer moduli, and effective structural number GAL-35.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated $E_r$, psi*</th>
<th>Backcalculated $M_r$, psi*</th>
<th>Required $S_{Neff}$*</th>
<th>$S_{Neff}$*</th>
<th>Is There a Significant Difference in $S_{Neff}$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>22,557 (4,534)</td>
<td>104,019 (24,167)</td>
<td>2.3 (0.24)</td>
<td>2.6 (1.14)</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>6</td>
<td>45,854 (23,177)</td>
<td>53,906 (25,990)</td>
<td>3.0 (0.49)</td>
<td>2.9 (0.74)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>128,162 (34,417)</td>
<td>37,104 (10,439)</td>
<td>3.3 (0.35)</td>
<td>5.0 (0.97)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis are summarized as follows:

- Overall pavement structural capacity characterized using $S_1$ did increase significantly after the HMA overlay placement.
- Pavement upper layers structural capacity characterized using SPR did increase significantly both after milling and after HMA overlay placement.
- Trends in pavement foundation strength characterized using $S_5$ were not reasonable.
- Trends in computed $E_r$ and $M_r$ were not reasonable.
- Overall pavement structural capacity characterized using $S_{Neff}$ provided very reasonable trends.
- Trends in $S_{N_{req}}$ were not consistent with expectations.
CHAPTER 15. PROJECT LIC-70

Overview of Project LIC-70

LIC-70 is a 1,500-ft-long flexible (HMA over rubblized PCC) pavement section located in Licking County (ODOT District 5). The exact project location is between stations 1137+51 and 1152+51 in the eastbound lanes of Interstate 70. ODOT historical records indicate that the original pavement was constructed in 1957 as a 9.0-in JRCP over a 6.0-in DGAB (ODOT Item 310) with an AASHTO A-4 subgrade. In 1993 the existing 9.0-in JRCP slab was rubblized and rolled, and a 16-in HMA layer (consisting of an ODOT Item 446 Type 1 upper HMA layer over an ODOT Item 446 Type 2 lower HMA layer, with an underlying ODOT Item 301 bituminous aggregate base course) was placed over the rubblized JRCP. In 2000, 1.5 inches of the existing HMA surface course was milled off and replaced with a 1.5-in (ODOT Item 446 Type 1) HMA overlay. Additional significant rehabilitation was performed in 2004 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project LIC-70

A six-step rehabilitation/structural evaluation program was implemented in 2004, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project LIC-70

A comprehensive search of ODOT records elicited the following information:

- Design plans describing original pavement layer thicknesses, material types, and subsequent M&R.
- Historical pavement condition characterized using PCR (for the years 1985 through 2004). Note that detailed distress information from visual windshield survey was not available.
- Historical traffic.

The information gathered was assembled and reviewed for quality and consistency. Data quality was found to be generally reasonable. A summary of pavement design, construction, and M&R activities assembled from ODOT records is presented in table 71. Presented in figures 96 and 97 are plots of historical pavement performance and traffic, respectively.

PCR data plotted in figure 96 show significant M&R in the mid-1980’s, mid-1990’s, and in 2004. A PCR value of approximately 70 (fair condition) was reported in 1993 prior to major rehabilitation. At the end of this rehabilitation in 1995, the PCR value increased to 97 (indicating a pavement in very good condition). Pavement condition decreased steadily to somewhere around the low to mid-80’s prior to rehabilitation in 2004. At the end of the 2004 rehabilitation, the PCR of the newly overlaid pavement was approximately 100.

Information presented in figure 97 shows a steady increase in traffic since the mid-1960’s. AADT just prior to the 2004 rehabilitation was estimated to be 36,170. ODOT records indicated
Table 71. Timeline showing original construction and significant M&R events for LIC-70.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>New JRCP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-in JRC</td>
<td>Rubblizing &amp; rolling the existing JRCP and HMA overlay placement</td>
<td>14.5-in HMA</td>
<td>14.25-in HMA</td>
</tr>
<tr>
<td>6-in Aggregate Base</td>
<td></td>
<td>9-in JRC (rubblized &amp; rolled)</td>
<td>9-in JRC (rubblized &amp; rolled)</td>
</tr>
<tr>
<td>Subgrade</td>
<td></td>
<td>6-in Aggregate Base</td>
<td>6-in Aggregate Base</td>
</tr>
</tbody>
</table>

Note that layer type and thicknesses information were obtained primarily from ODOT plans and cores extracted as part of the 2004 rehabilitation and specifically for this study.
Figure 96. Historical pavement performance characterized using PCR for LIC-70.

Figure 97. Historical traffic application for LIC-70.
that approximately 33.9 percent of the AADT were trucks or heavy commercial vehicles. Thus, daily truck traffic in 2004 was estimated to be approximately 12,249. Historical traffic growth (all vehicles) was approximately 7.9 percent, linear. Thus, for analysis, projected 20-year truck traffic was estimated to be 167,872,790 trucks, which translates into 45,000,000 flexible ESALs.

**Step 2—First Structural Evaluation for Project LIC-70**

A detailed and comprehensive structural evaluation was conducted in June 2004, prior to the commencement of rehabilitation activities. Structural evaluation consisted of only deflection testing using Dynaflect; no cores were extracted.

**Step 3—Pre-Overlay Activities/Repair for Project LIC-70**

Following the first structural evaluation, comprehensive pre-overlay repairs were conducted. Pre-overlay repairs basically consisted of milling off 1.75 inches of the existing HMA.

**Step 4—Second Structural Evaluation for Project LIC-70**

The second structural evaluation was done in June 2004, after the pre-overlay repairs but prior to HMA overlay placement (also in June 2004). This evaluation consisted of only Dynaflect deflection testing. Test locations were matched as close as possible to those of the first structural evaluation.

**Step 5—Placement of HMA Overlay for Project LIC-70**

Following the second structural evaluation, a 1.75-in HMA overlay (ODOT Item 442, 12.5 mm Superpave, Type A mix) was placed over the milled pavement structure.

**Step 6—Third Structural Evaluation for Project LIC-70**

The third and final structural evaluation was done after HMA overlay placement in August 2004. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing using Dynaflect. Information gathered as part of the third structural evaluation is presented in the following sections.

**Coring and Laboratory Examination**

Coring was performed in November 2005. Six cores were extracted along the entire 1,500-ft length of the project at regular intervals of 300 ft. The extracted cores were visually examined to assess condition. A photo of some of the extracted cores is presented in figure 98. Detailed information regarding core thicknesses and condition is as follows:

- All six HMA cores were in good condition (i.e., two or more pieces of HMA), though most of the cores showed delamination between the HMA layers.
- Mean total HMA thickness was 16 in (total HMA thickness ranged from 13 to 18 in. The 2004 mean HMA overlay thickness reported from all the cores was 1.75 in).
The measured core thicknesses were reasonable when compared to plan thicknesses obtained from ODOT records.

**Deflection Testing for Project LIC-70**

Deflection testing was done using Dynaflect. Testing was done as close as possible to the locations of previous deflection tests conducted as part of the first and second structural evaluations.

**Data Analysis for Project LIC-70**

Coring and deflection testing results, along with information such as layer thicknesses, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement system, pavement upper layers, and subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli (Ep and Mr) and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.
Preliminary Analysis

Maximum Deflection

Overall pavement system structural capacity was characterized using maximum deflection, S1. Figure 99 presents S1 profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 1.75-in HMA did not significantly change S1.
- Although there was a 22 percent decrease in S1 after HMA overlay placement, this decrease was not considered significant. However, the decrease in S1 indicates an increase in pavement structural capacity after HMA overlay placement.
- Variability in S1 along the project increased after the placement of the HMA overlay. This is contrary to expectations.

The trends observed in figure 99 were confirmed by the results of the ANOVA presented in table 72.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 100 presents SPR profiles at different stages of the 2005 rehabilitation. A review of the plots shows the following:

- Milling off the existing 1.75-in HMA made resulted in a considerable increase in the SPR. However, the change in SPR was not significant.
- Even though the SPR after placement of the 1.75-in HMA overlay was significantly lower than the after milling SPR value, this is not consistent with theory.
- Variability in SPR decreased significantly after overlay placement.

The trends observed in figure 100 were confirmed by the results of the ANOVA presented in tables 73.

Subgrade Strength (characterized by S5)

Table 74 shows that there is a statistical difference between the S5 values from the after milling and after placement of HMA overlay with the former report higher S5 values. However, the S5 values from before milling and after milling are statistically similar. The overall trend is not as expected in theory.

Detailed Structural Analysis

Detailed structural analysis involved backcalculating pavement layer moduli – Ep and Mr, and computing SN_eff and SN_req followed by analyzing trends in the backcalculated moduli, SN_eff and SN_req.
By comparing the Ep, Mr, SN_{eff}, and SN_{req} across the different stages of rehabilitation work the effectiveness of the ODOT procedure for backcalculating pavement layer moduli characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed. Results of the detailed structural analysis are presented in table 75.

Figure 99. Plot showing S_{1} profiles for LIC-70.

Table 72. Summary of analysis of variance results for maximum deflections (LIC-70).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.307 (0.058)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>6</td>
<td>0.295 (0.061)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.23 (0.093)</td>
<td>Excellent</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 73. Summary of analysis of variance results for SPR (LIC-70).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>70 (5.8)</td>
<td>Good</td>
<td>A, B</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>6</td>
<td>76 (5.7)</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>66 (2.2)</td>
<td>Good</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 74. Summary of analysis of variance results for $S_5$ deflections (LIC-70).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $S_5$ Deflections, mils*</th>
<th>Is There a Significant Difference in $S_5$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.138 (0.044)</td>
<td>A, B</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>6</td>
<td>0.147 (0.041)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.088 (0.041)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
The information in table 75 shows Ep increasing significantly after milling and remaining about the same as the after milling value after HMA overlay placement. Mr increased significantly after HMA overlay placement. These trends are not consistent with expectations. There was no statistical difference in SN\textsubscript{eff} for the three rehabilitation stages, although there is a considerable increase in SN\textsubscript{eff} after placement of the HMA overlay, as expected. The SN\textsubscript{req} value decreases significantly after placement of the HMA overlay due to significant increase in Mr. This is contrary to expectations.

Table 75. Summary of backcalculated layer moduli and effective structural number for LIC-70.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated EP, psi*</th>
<th>Backcalculated Mr, psi*</th>
<th>SN\textsubscript{req}</th>
<th>SN\textsubscript{eff}</th>
<th>Is There a Significant Difference in SN\textsubscript{eff} (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>216,819 (58,237)</td>
<td>38,730 (13,274)</td>
<td>4.3 (0.5)</td>
<td>8.1 (0.6)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.75-in of existing HMA milled off)</td>
<td>6</td>
<td>304,819 (107,158)</td>
<td>35,855 (10,733)</td>
<td>4.4 (0.4)</td>
<td>8.5 (1.5)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>308,521 (152,243)</td>
<td>68,078 (34,913)</td>
<td>3.7 (0.6)</td>
<td>9.1 (2.1)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

Results of the preliminary and detailed structural analysis are summarized as follows:

- There is no significant change in S\textsubscript{1} over the entire rehabilitation process and, hence, no significant change in the overall pavement structural capacity. The observed trends in S\textsubscript{1} value are reasonable.
- Trends in SPR, which characterizes pavement upper layers structural capacity, do not seem to agree with theory.
- Trends in S\textsubscript{5}, which characterizes pavement foundation strength, are not consistent with theory.
- Overall pavement structural capacity characterized using SN\textsubscript{eff} increased slightly after milling and then considerably after overlay placement. Though these changes were not significant, the observed trends were considered reasonable.
- Trends in backcalculated Ep and Mr were not considered reasonable or consistent with theory.
CHAPTER 16. PROJECT MOT-40 (05)

Overview of Project MOT-40 (05)

MOT-40 (05) is an 800-ft-long pavement section located on U.S. 40 in Montgomery County (ODOT District 7). The pavement was constructed in 1949 as a JRCP. The original pavement was widened and overlaid with HMA sometime before 1992. The widened section was constructed as an HMA pavement. In 1992, 0.5 in of the existing HMA layer was milled off and replaced by a 1.75-in HMA overlay. Information available from field testing conducted after 1992 shows that the original section of MOT-40 (05) consisted of a 9.5-in HMA over a highly deteriorated JRCP. The widened section consisted entirely of HMA over a granular base and subgrade. Significant rehabilitation was performed on the composite pavement in 2005 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project MOT-40(05)

A six-step rehabilitation/structural evaluation program was implemented in 2005, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project MOT-40(05)

A comprehensive search of ODOT records was done to obtain historical information pertaining to project, design, construction, M&R, traffic, and performance. A summary is presented in table 76.

Photos of general pavement condition taken as part of the windshield survey of section MOT-40 (05) are presented in figures 101 through 104. A review of the distresses present in the photos showed considerable pavement deterioration manifested in the form of moderate to high-severity transverse reflection cracking and fatigue alligator cracking. Some potholes had also developed in heavily deteriorated areas. The pavement generally was considered to be in a moderate to poor condition, with several areas experiencing severe localized distress.

Information presented in figure 105 shows that the pavement was mostly in fair condition through the period for which PCR data were available (1985 to 2005). Significant changes in pavement condition during this period occurred immediately before the 1992 rehabilitation, when PCR had dropped to approximately 55 (fair to poor condition), and just after 1992, when PCR was approximately 83. The PCR decreased to approximately 74 just before 1998, when it increased to approximately 87. Subsequently, the PCR value dropped steadily and reached approximately 77 (fair condition) prior to the 2005 rehabilitation. There are no visual distress records available for this project.

Figure 106 shows that this project had an AADT of 17,037 in 2005. Approximately 2.0 percent of the AADT were trucks, and thus, total daily truck traffic in 2005 was 338. Traffic growth over the 20-year analysis period was approximately 4.66 percent linear. Based on the traffic information obtained from ODOT records, projected 20-year traffic for MOT-40 (05) analyzed as a flexible pavement was 748,000 ESALs (3,798,069 trucks).
Table 76. Cross-section of Eastbound lane of MOT-40 (05) in 2005 before major rehabilitation.
Figure 101. MOT-40 (05) windshield survey (photo 1) showing patched longitudinal cracking.

Figure 102. MOT-40 (05) windshield survey (photo 2) showing moderate levels of alligator cracking.
Figure 103. MOT-40 (05) windshield survey (photo 3) showing high-severity alligator cracking.

Figure 104. MOT-40 (05) windshield survey (photo 1) showing moderate-severity transverse cracking.
Figure 105. Historical pavement performance characterized using PCR for MOT-40 (05).

Figure 106. Historical traffic application for MOT-40 (05).
Step 2—First Structural Evaluation for Project MOT-40 (05)

Structural evaluation was conducted prior to pre-overlay repairs. The evaluation consisted of only Dynaflect deflection testing as no cores were extracted.

Step 3—Pre-Overlay Activities/Repair for Project MOT-40 (05)

Pre-overlay repairs, done as part of rehabilitation, consisted of milling off 1.0 in of the existing HMA layer only.

Step 4—Second Structural Evaluation for Project MOT-40 (05)

The second structural evaluation was done after the completion of pre-overlay repairs but prior to HMA overlay placement. Deflection test locations were as close as possible to those of the first structural evaluation.

Step 5—Placement of HMA Overlay for Project MOT-40 (05)

Following the second structural evaluation, a 2.0-in (average thickness) HMA overlay (Superpave mix) was placed on the milled pavement surface.

Step 6—Third Structural Evaluation for Project MOT-40 (05)

The third and final structural evaluation was done after HMA overlay placement. Structural evaluation consisted of field coring, laboratory examination of the cores, and deflection testing.

Coring and Laboratory Examination for Project MOT-40 (05)

In 2005, a total of five cores were extracted along the entire 800-ft-long project at intervals of 200 ft. An additional four cores were extracted in 2006 to verify information obtained from the 2005 cores. These four cores also were extracted along the entire 800-ft-long project section, at intervals of 100 and 200 ft. Extracted cores were visually examined for signs of distress (structural and durability related). All five HMA cores extracted in 2005 were deemed good (i.e., intact core with less than two pieces; see figure 107). All four HMA cores extracted in 2006 were deemed good (i.e., intact core with less than two pieces, see figure 108). For both the 2005 and 2006 cores, the PCC material underlying the HMA layer was rubble. Layer thicknesses measured from the 2005 and 2006 cores are summarized as follow:

Core thicknesses (2005):
- Mean HMA thickness: 9.1 in (ranges from 7.0 to 12.5 in).
- Mean PCC thickness could not be determined as the JRCP material had been reduced to rubble.

Core thicknesses (2006):
- Mean HMA thickness: 11.9 in (ranges from 11.5 to 12.0 in).
- Mean PCC thickness could not be determined as the JRCP had been reduced to rubble.
Figure 107. Cores extracted from MOT-40 (05) in 2005.

Figure 108. Cores extracted from MOT-40 (05) in 2006.
Deflection Testing for Project MOT-40 (05)

Deflection testing was done using Dynaflect. Test locations were selected to be as close as possible to the locations of previous deflection tests.

Data Analysis for Project MOT-40 (05)

Coring and deflection testing results, along with other relevant information, were assembled into a project database. The data were then analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Analysis was done in two phases, preliminary and detailed. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layers, and subgrade structure capacity. Detailed analysis consisted of backcalculating pavement layer moduli and determining effective pavement thickness and HMA overlay thickness needed to carry future traffic.

Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, $S_1$. Figure 109 presents $S_1$ profiles for the different stages of rehabilitation and shows the following:

- Milling off the existing 1.0-in HMA did significantly reduce overall pavement system structural capacity.
- Overall pavement deflection, $S_1$ decreased significantly after the placement of the 2.0-in HMA overlay, indicating a significant increase in overall pavement structural capacity after the HMA overlay placement.
- There was no significant difference for $S_1$ after the rehabilitation, implying that the use of new materials did not significantly impact pavement structure capacity.
- Variability in $S_1$ value decreased significantly changing after HMA overlay placement.

The trends observed in figure 109 were confirmed by the results of the ANOVA presented in table 77.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figure 110 presents SPR profiles at different stages of rehabilitation. A review of the plots shows the following:

- Milling off the existing 1.0-in HMA resulted in a significant reduction in the pavement upper layers structural capacity.
- SPR increased significantly after HMA overlay placement.
- There was a significant reduction in before and after rehabilitation. This trend does not agree with the empirical expectation.
- SPR variability decreased significantly after milling and overlay placement.
Figure 109. Plot showing $S_1$ profiles for MOT-40 (05).

Table 77. Summary of analysis of variance results for maximum deflections (MOT-40 (05)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils*</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>9</td>
<td>0.448 (0.742)</td>
<td>Good to Excellent</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>9</td>
<td>0.992 (0.206)</td>
<td>Poor</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>0.404 (0.072)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

The trends observed in figure 110 were confirmed by the results of the ANOVA presented in table 78.

Subgrade Strength (characterized using $S_5$)

Table 79 shows an observable decrease for $S_5$ after milling and after the HMA overlay placement. This trend does not agree with theory ($S_5$ should not show significant change). It may indicate the stress sensitive nature of the subgrade soil.
Figure 110. Plot showing SPR profiles for MOT-40 (05).

Table 78. Summary of analysis of variance results for SPR (MOT-40 (05)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>9</td>
<td>66 (3.2)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>9</td>
<td>48 (7.7)</td>
<td>Poor</td>
<td>C</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>57 (3.0)</td>
<td>Fair</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 79. Summary of analysis of variance results for $S_5$ deflections (MOT-40 (05)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $S_5$ Deflections, mils*</th>
<th>Is There a Significant Difference in $S_5$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>9</td>
<td>0.120 (0.039)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>9</td>
<td>0.104 (0.039)</td>
<td>A, B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>0.073 (0.027)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Detailed Structural Analysis

Detailed structural analysis involved backcalculating pavement moduli (Ep and Mr) and estimating SN_{eff} and SN_{req} using ODOT’s DOITOVER software for the different stages of rehabilitation.

By comparing computed E_p, M_r and SN_{req} across the different stages of rehabilitation, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analysis are presented in table 80. There was a decrease in backcalculated E_p but an increase in M_r after the milling. The increasing trend for M_r does not agree with theory. After the HMA overlay placement, both E_p and M_r significantly increased with a reasonable trend. There is no clear trend for E_p and M_r during the rehabilitation process.

SN_{eff} significantly decreased after milling, and increased after the HMA overlay placement. The increase SN_{eff} after HMA overlay placement was, however, significantly lower that the before milling SN_{eff} value.

Table 80. Summary of backcalculated layer moduli and effective structural number for MOT-40 (05).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated E_p, psi*</th>
<th>Backcalculated M_r, psi*</th>
<th>SN_{eff}*</th>
<th>SN_{req}*</th>
<th>Is There a Significant Difference in SN_{eff} (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>9</td>
<td>174,923 (70,173)</td>
<td>44,595 (13,541)</td>
<td>3.8</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.5-in of existing HMA milled off)</td>
<td>9</td>
<td>21,649 (30,077)</td>
<td>52,681 (18,499)</td>
<td>1.6</td>
<td>2.5</td>
<td>C</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>73,127 (27,879)</td>
<td>76,666 (31,021)</td>
<td>3.0</td>
<td>2.2</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Summary

A summary of preliminary and detailed structural evaluation results is as follows:

- Overall pavement structural capacity characterized using S_1 did change significantly during the rehabilitation process. The pavement structural capacity before and after rehabilitation were, however, the same.
- There was a significant reduction for overall pavement structural capacity characterized using SPR before and after the rehabilitation. This does not agree with theory.
• Pavement foundation strength characterized using $S_5$ did significantly change during the rehabilitation process. This is not consistent with theory.
• There is no clear trend for $E_p$ and $M_r$ during the rehabilitation process.
• Overall pavement structural capacity characterized using $SN_{eff}$ did decrease significantly before and after the rehabilitation. This does not agree with theory. However, the significant decrease in $SN_{eff}$ after milling was as expected.
CHAPTER 17. PROJECT ROS-35 (MM 9.15) AND ROS-35 (MM 10.0)

Overview of Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

Projects ROS-35 (MM 9.15) and ROS-35 (MM 10.0) are 750 and 1,500 ft long, respectively. Both are flexible (HMA over existing HMA) pavement sections located in the northbound lanes of U.S. Route 35 (between station 231+00 and 539+00, near Concord Township in Ross County [ODOT District 9]). ROS-35 (MM 9.15) is located near mile marker 9.15, while ROS-35 (MM 10.0) is located at mile marker 10.0. Information available in ODOT records indicates that both projects ROS-35 originally were constructed in 1972 as flexible pavements consisting of a 2.5-in HMA surface course (1.25-in ODOT Item 404 HMA surface course over a 1.25-in ODOT Item 402 HMA surface course layer) over a 9.0-in bituminous aggregate base (ODOT Item 301), a 4.0-in aggregate base (ODOT Item 301), and an A-6a subgrade.

The first significant rehabilitation for both projects occurred in 1990. The 1990 rehabilitation consisted of milling off the 2.5-in HMA surface course and replacing it with a 3.5-in HMA (consisting of a 1.0-in HMA surface course [ODOT Item 446, binder type: AC-20] over a 2.5-in intermediate course [binder type: AC-20]). Additional significant rehabilitation was performed in 2006 and is the subject of this structural evaluation.

Rehabilitation and Structural Evaluation Activities for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

A six-step rehabilitation/structural evaluation program was implemented in 2006, as described in the following sections.

Step 1—Windshield Visual Survey and Records Review for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

A comprehensive search of ODOT records yielded information pertaining to original design and construction, subsequent M&R, traffic, and so on. Although there was some detailed distress data available (from a windshield survey conducted prior to the 2006 rehabilitation), historical performance data were not available. The information assembled was reviewed for quality and consistency and was found to be generally reasonable. A summary of the information gathered through the records review is presented in tables 81 and 82.

Distress information collected through windshield survey is presented in figure 111 through 114. These figures show the presence of moderate to high-severity transverse and alligator cracking. Overall, the projects were in fair to poor condition with pockets of severe localized distress and patching.
Table 81. Timeline showing significant historical construction and M&R events for ROS-35 (MM 9.15).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25-in HMA (404)</td>
<td>Stage A (Milling off 2.5-in of existing HMA layer)</td>
<td>Stage A (Milling off 1.9-in of existing HMA layer)</td>
</tr>
<tr>
<td>1.25-in HMA (402)</td>
<td>9-in HMA (301)</td>
<td>3.8-in HMA</td>
</tr>
<tr>
<td>9-in HMA (301)</td>
<td>9-in HMA (301)</td>
<td>1.9-in HMA</td>
</tr>
<tr>
<td>4-in Aggregate Base</td>
<td>4-in Aggregate Base</td>
<td>4-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>

Table 82. Timeline showing significant historical construction and M&R events for ROS-35 (MM 10.0).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25-in HMA (404)</td>
<td>Stage A (Milling off 2.5-in of existing HMA layer)</td>
<td>Stage A (Milling off 3.1-in of existing HMA layer)</td>
</tr>
<tr>
<td>1.25-in HMA (402)</td>
<td>9-in HMA (301)</td>
<td>2.2-in HMA</td>
</tr>
<tr>
<td>9-in HMA (301)</td>
<td>9-in HMA (301)</td>
<td>3.1-in HMA (442)</td>
</tr>
<tr>
<td>4-in Aggregate Base</td>
<td>4-in Aggregate Base</td>
<td>4-in Aggregate Base</td>
</tr>
<tr>
<td>Subgrade</td>
<td>Subgrade</td>
<td>Subgrade</td>
</tr>
</tbody>
</table>
Figure 111. ROS-35 (4.38) windshield survey (photo 1) showing high-severity alligator and medium-severity transverse cracking.

Figure 112. ROS-35 (4.38) windshield survey (photo 2) showing high-severity transverse/reflection cracking.
Figure 113. ROS-35 (4.38) windshield survey (photo 3) showing low-severity cracking.

Figure 114. ROS-35 (4.38) windshield survey (photo 4) showing low-severity alligator cracking.
Figure 115 shows that the pavement was in fair condition in 1989 with a PCR of 69. 1990, rehabilitation work was performed on the pavement which improved the PCR to approximately 100 and the pavement condition to very good. Between 1990 and 2004, the PCR reported a steady decline and in 2004 (2 years prior to the 2006 rehabilitation) a PCR value of 73 was reported. A PCR of 73 indicated that the pavement prior to the 2006 rehabilitation was in fair condition.

The historical traffic information presented in figure 116 shows that both projects had an AADT of 8,712 in 2006. ODOT records indicate that approximately 22.5 percent of the AADT were trucks. Total daily truck traffic in 2005 was 1,956. Based on the traffic information obtained from ODOT records, projected 20-year traffic for both projects was 12,200,000 ESALs.

Step 2—First Structural Evaluation for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

A comprehensive structural evaluation was conducted for both projects prior to rehabilitation in 2006. This evaluation consisted of extraction of cores, laboratory examination of the extracted cores, and nondestructive deflection testing.

Coring and Laboratory Examination for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

Cores were extracted from both projects in August 2006. For ROS-35 (MM 9.15), five cores were extracted at intervals of 175-and 200-ft, while six cores were extracted along the project length for ROS-35 (MM 10.0), at regular intervals of 300-ft. Data gathered from the extracted cores for both projects is summarized as follows:

For ROS-35 (MM 9.15):

- Mean total HMA thickness: 13.2 in (HMA thickness ranged from 12.5 to 14.0 in; ODOT plans indicate a total HMA thickness of 12.5 in).
- All cores were in good condition.

For project ROS-35 (MM 10.0):

- Mean HMA thickness: 12.88 in (HMA thickness ranged from 12.0 to 13.5 in; ODOT plans indicate a total HMA thickness of 12.5 in).
- All cores were in good condition.

The measured core thicknesses were deemed reasonable, as they were in agreement with planned thicknesses obtained from ODOT records.
Figure 115. Historical pavement performance characterized using PCR for ROS-35 (MM 9.15) and ROS-35 (MM 10.0).

Figure 116. Historical traffic application for ROS-35 (MM 9.15) and ROS-35 (MM 10.0).
Deflection Testing for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

For both projects, deflection testing was performed in June 2006, using both Dynaflect and FWD equipment. Deflection testing was done at 25-ft intervals for ROS-35 (MM 9.15) and at 50-ft intervals for ROS-35 (MM 10.0) along the respective projects’ lengths.

Step 3—Pre-Overlay Activities/Repair for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

For both ROS-35 (MM 9.15) and ROS-35 (MM 10.0), pre-overlay repairs consisted of milling off 2.75 and 2.0 in of the existing HMA layer, respectively. The actual milling depths of 2.75 and 2.0 in were different from the milling depth of 1.74 in available in ODOT design plans.

Step 4—Second Structural Evaluation for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

For both projects, limited field testing was conducted after pre-overlay repairs in August 2006. Field testing comprised of nondestructive deflection testing using both Dynaflect and FWD testing equipment. No cores were extracted.

Step 5—Placement of HMA Overlay for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

For both ROS-35 (MM 9.15) and ROS-35 (MM 10.0), following pre-overlay repairs and the second structural evaluation, a 3.25-in HMA overlay (consisting of a 1.5-in Superpave HMA layer [ODOT Item 442, 12.5-mm, Type A] over a 1.75-in Superpave HMA layer [ODOT Item 442, 19.0-mm, Type A]) was placed (according to ODOT records).

Step 6—Third Structural Evaluation for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

For both projects, a third and final structural evaluation was performed after the placement of the 3.25-in HMA overlay. Structural evaluation consisted of extraction of cores, laboratory examination of the extracted cores, and nondestructive deflection testing.

Coring and Laboratory Examination for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)

Coring was extracted in November 2006 for both projects. A total of 10 cores were extracted from ROS-35 (MM 9.15). Layer thickness and condition information is as follows:

- Mean total HMA thickness = 14.3 in (HMA thickness ranged from 12.9 to 15.3 in; ODOT plans indicate a total HMA thickness of 14.0 in).
- All cores were in good condition (see figure 117).
- Mean HMA overlay thickness = 3.1 in (ranged from 2.9 to 3.5 in; ODOT plans show an overlay thickness of 3.3 in).

For project ROS-35 (MM 10.0), a total of six cores were extracted at regular intervals of 300-ft along the project length. Layer thickness and condition information is as follows:
• Mean HMA thickness = 14.1 in (HMA thickness ranged from 13.3 to 15.0 in).
• All cores were in good condition (see figure 118).
• Mean HMA overlay thickness = 3.2 in (ranges from 3.0 to 3.3 in; ODOT plans show an overlay thickness of 3.3 in).

The measured core thicknesses were deemed reasonable, as they were in agreement with planned thicknesses obtained from ODOT records.

**Deflection Testing for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)**

Deflection testing was performed in November 2006 for both projects, using Dynaflect and FWD equipment. Deflection testing was done at 25-ft intervals for ROS-35 (MM 9.15) and at 50-ft intervals for ROS-35 (MM 10.0) and was made to match as closely as possible to the locations of the previous deflection tests.

**Data Analysis for Project ROS-35 (MM 9.15) and ROS-35 (MM 10.0)**

For both ROS-35 (MM 9.15) and ROS-35 (MM 10.0), relevant information (layer type, material type, layer thickness, deflections, etc.) obtained from ODOT records and field testing was assembled into a project database. The data were analyzed to determine pavement structural condition/capacity before, during, and after rehabilitation. Preliminary analysis reviewed trends of structural indices that were indicative of overall pavement, pavement upper layers as subgrade strength. Detailed analysis consisted of backcalculating pavement layer moduli and determining SN_{eff} and SN_{req}. The objective of both analyses was to determine baseline (i.e., original pavement) structural capacity, the effect of subsequent pre-overlay repairs on structural capacity (specifically, milling off all or portions of the existing HMA), and the effect of the HMA overlay on structural capacity. The analysis results are presented in the following sections.
Preliminary Analysis

Maximum Deflection

Overall pavement structural capacity was characterized using maximum deflection, $S_1$. Figures 119 and 120 present $S_1$ profiles at the different stages of rehabilitation, and they reveal the following:

- Milling off the existing HMA (2.8-in HMA for ROS-35[MM9.15] and 1.9-in HMA for ROS-35[MM10.0]) did significantly reduce overall pavement system structural capacity.
- For both projects, $S_1$ reduced significantly after the placement of the HMA overlay (3.1 in for ROS-35[MM9.15] and 3.2 in for ROS-35[MM10.0]). However, compared to values before rehabilitation, $S_1$ decreased significantly for ROS-35(MM9.15) but did not show a significant difference for ROS-35 (MM10.0). This trend does not agree with theory and empirical trends.
- For ROS-35 (MM10.0), there was a significant reduction in the variability of $S_1$. Standard deviation of $S_1$ was reduced by approximate 50 percent from the original pavement to after HMA overlay placement. However, there was a significant increase in the variability of $S_1$ for ROS-30 (MM9.15). Compared to before the milling, variability of $S_1$ increased about 1.5 times after the HMA overlay placement. This does not agree with the empirical expectation.

The trends observed in figures 119 and 120 were confirmed by the results of the ANOVA presented in tables 83 and 84.
Figure 119. $S_1$ profile for ROS-35 (MM 9.15).

Figure 120. $S_1$ profile for ROS-35 (MM 10.0).
Table 83. Summary of analysis of variance results for maximum deflections (ROS-35 (MM9.15)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>10</td>
<td>0.232 (0.022)</td>
<td>Excellent</td>
<td>C</td>
</tr>
<tr>
<td>Existing pavement (with 1.9-in of existing HMA milled off)</td>
<td>10</td>
<td>0.483 (0.123)</td>
<td>Good to Excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>0.318 (0.055)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 84. Summary of analysis of variance results for maximum deflections (ROS-35 (MM10.0)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean Maximum Deflection, mils*</th>
<th>Structural Condition Assessed Based on Max. Deflection, mils</th>
<th>Duncan’s Grouping (Obtained from Analysis of Variance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.303 (0.117)</td>
<td>Excellent</td>
<td>B</td>
</tr>
<tr>
<td>Existing pavement (with 1.9-in of existing HMA milled off)</td>
<td>6</td>
<td>0.434 (0.071)</td>
<td>Good to excellent</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.306 (0.064)</td>
<td>Excellent</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Spreadability

The structural contribution of the pavement upper layers was characterized using SPR. Figures 121 and 122 present SPR profiles at different stages of rehabilitation for these projects. A review of the plots shows the following:

- For both projects, milling off the existing HMA (2.8-in HMA for ROS-35[MM9.15] and 1.9-in HMA for ROS-35[MM10.0]) did significant reduce the pavement upper layers structural capacity characterized by SPR for both projects.
- SPR increased significantly after HMA overlay placement for both projects.
- There were no significant differences before and after rehabilitation for both projects. This trend does not agree with the empirical expectation.
- SPR variability decreased significantly after overlay placement for project ROS-35 (MM10.0), while there was no significant difference for ROS-35 (MM 9.15).

The trends observed in the figures were confirmed by the results of the ANOVA presented in tables 45 and 86 respectively.
Figure 121. SPR profile for ROS-35 (MM 9.15).

Figure 122. SPR profile for ROS-35 (MM 10.0).
Table 85. Summary of analysis of variance results for SPR (ROS-35 (MM9.15)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>10</td>
<td>65 (3.7)</td>
<td>Good</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.8-in of existing HMA milled off)</td>
<td>10</td>
<td>50 (6.7)</td>
<td>Poor to fair</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>63 (3.2)</td>
<td>Fair to good</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Table 86. Summary of analysis of variance results for SPR (ROS-35 (MM10.0)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>SPR, percent*</th>
<th>Structural Condition Assessed Based on SPR</th>
<th>Duncan’s Grouping (Obtained from AOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>57 (10.1)</td>
<td>Fair</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.8-in of existing HMA milled off)</td>
<td>6</td>
<td>48 (2.6)</td>
<td>Poor</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>57 (2.1)</td>
<td>Fair</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Subgrade Strength (characterized using $S_5$)

Tables 87 and 88 show there were no significant differences for $S_5$ at the three rehabilitation stages, except that there was an observable reduction for $S_5$ after the HMA overlay placement for project ROS-35 (MM10.0). Overall, this trend does agree with theory. The only exception indicates the stress sensitive nature of the subgrade soil.

Table 87. Summary of analysis of variance results for $S_5$ deflections (ROS-35 (MM9.15)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $S_5$ Deflections, mils*</th>
<th>Is There a Significant Difference in $S_5$ (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>10</td>
<td>0.077 (0.027)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.9-in of existing HMA milled off)</td>
<td>10</td>
<td>0.073 (0.017)</td>
<td>A</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>0.071 (0.014)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 88. Summary of analysis of variance results for S5 deflections (ROS-35 (MM10.0)).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean S5 Deflections, mils*</th>
<th>Is There a Significant Difference in S5 (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>0.067 (0.010)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.8-in of existing HMA milled off)</td>
<td>6</td>
<td>0.057 (0.010)</td>
<td>A, B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>0.048 (0.017)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

Detailed Structural Analysis

Detailed structural analysis involved backcalculating pavement moduli (E_p and M_r) and estimating S\textsubscript{neff} and S\textsubscript{req} using DOITOVER. By comparing computed E_p, M_r and S\textsubscript{req} across the different stages of rehabilitation, the effectiveness of the ODOT procedure for backcalculating pavement layer moduli, characterizing pavement structural capacity, and determined required HMA overlay thickness was assessed.

Results of the detailed structural analyses are presented in tables 89 and 90. For both projects, there was a decrease in backcalculated E_p after milling and an increase after HMA overlay placement. The tables also show there were no significant differences for M_r during the rehabilitation process for project ROS-35 (MM9.15), while there was a significant reduction for M_r after milling for project ROS-35 (MM10.0). Thus, there is no clear trend for E_p and M_r during the rehabilitation process.

Table 89. Summary of backcalculated layer moduli and effective structural number for ROS-35 (MM9.15).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated E_p, psi*</th>
<th>Backcalculated M_r, psi*</th>
<th>Required S\textsubscript{neff}*</th>
<th>S\textsubscript{neff}*</th>
<th>Is There a Significant Difference in S\textsubscript{neff} (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>10</td>
<td>458,213 (292,587)</td>
<td>73,289 (30,903)</td>
<td>2.8 (0.40)</td>
<td>6.0 (1.17)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 1.9-in of existing HMA milled off)</td>
<td>10</td>
<td>73,677 (49,685)</td>
<td>71,424 (21,080)</td>
<td>2.8 (0.26)</td>
<td>2.7 (0.88)</td>
<td>C</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>9</td>
<td>149,018 (47,469)</td>
<td>71,525 (15,011)</td>
<td>2.8 (0.21)</td>
<td>4.3 (0.57)</td>
<td>B</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.
Table 90. Summary of backcalculated layer moduli and effective structural number for ROS-35 (MM10.0).

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Backcalculated (E_p), psi*</th>
<th>Backcalculated (M_r), psi*</th>
<th>Required (SN_{eff})*</th>
<th>(SN_{eff})*</th>
<th>Is There a Significant Difference in (SN_{eff}) (Duncan’s Grouping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>6</td>
<td>261,414 (219,514)</td>
<td>74,784 (10,532)</td>
<td>2.7 (0.15)</td>
<td>4.5 (1.45)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (with 2.8-in of existing HMA milled off)</td>
<td>6</td>
<td>45,297 (28,820)</td>
<td>89,158 (18,556)</td>
<td>2.6 (0.19)</td>
<td>2.3 (0.54)</td>
<td>B</td>
</tr>
<tr>
<td>HMA overlaid pavement</td>
<td>6</td>
<td>87,362 (33,886)</td>
<td>110,817 (34,071)</td>
<td>2.4 (0.30)</td>
<td>3.6 (0.49)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets.

\(SN_{eff}\) significantly decreased after milling and increased after the HMA overlay placement for both projects, but there was a significant reduction for \(SN_{eff}\) before and after the rehabilitation for project ROS-35 (MM9.15), and there was no significant difference for project ROS-35 (MM10.0). The computed \(SN_{eff}\) value did not provide a clear trend.

**Summary**

A summary of preliminary and detailed structural evaluation results for these two projects is as follows:

- Overall pavement structural capacity characterized using \(S_1\) did change significantly during the rehabilitation process for both projects. Pavement structural capacity before and after rehabilitation increased significantly for project ROS-35 (MM9.15), while it did show any significant difference for ROS-35 (MM10.0).
- There was no significant difference for overall pavement structural capacity characterized using \(SPR\) before and after the rehabilitation. This does not agree with theory.
- Pavement foundation strength characterized using \(S_5\) did not significantly change during the rehabilitation process, except that there was an observable reduction in \(S_5\) after the HMA overlay placement for project ROS-35 (MM10.0). This is basically consistent with theory.
- There is no clear trend for \(E_p\) and \(M_r\) during the rehabilitation process.
- Overall pavement structural capacity characterized using \(SN_{eff}\) decreased significantly for project ROS-35 (MM9.15) and did not show any significant difference for project ROS-35 (MM10.0). This does not agree with theory.
CHAPTER 18. FWD DATA ANALYSIS

As presented in chapters 2 through 16, the $E_p$, $M_r$, and $SN_{eff}$ calculated through the DOITOVER process using the Dynaflect deflection data from the before milling, after milling, and after overlay stages of the rehabilitation process did not always follow logical trends. In many cases, the null hypotheses that $E_p$ and $M_r$ do not change and $SN_{eff}$ does change through the various rehabilitation stages were rejected. In some cases, rather large fluctuations of these parameter values were observed from one rehabilitation stage to the other. To investigate the causes behind the apparent instability in these calculated parameters an alternate process to estimating them was adopted. Three of the HMA/HMA pavement sections—ROS-35 MM9.15, ROS-35 MM10, and JAC-32—were tested by ODOT using the Falling Weight Deflectometer (FWD) at the same locations where the Dynaflect testing was performed. The FWD data were used in conjunction with the AASHTOWare DARWin software (version 3.1)\(^1\) to estimate $E_p$, $M_r$, and $SN_{eff}$ at each of the three stages of rehabilitation for each project. The results from this analysis were compared with the corresponding values from DOITOVER. The findings from this comparison are reported in the following sections.

ROS-35 (MM9.15)

Figures 123 and 124 compare the backcalculated $E_p$ and $M_r$ obtained from DARWin using the FWD data with those obtained from DOITOVER using Dynaflect data (presented in Chapter 17) for the three stages of rehabilitation on the ROS-35 MM9.15 project. Figure 125 compares the $SN_{eff}$ from DARWin/FWD with DOITOVER/Dynaflect. An ANOVA was also performed on the outputs from DARWin and is presented in table 91. Recall that this pavement had an approximately 14 in original asphalt layer which was milled approximately 2.8 in and overlaid with a 3.1 in thick HMA layer. The following conclusions can be drawn from the information presented.

- The DARWin/FWD estimation process of $E_p$, $M_r$, and $SN_{eff}$ gives more logical outputs when compared to the DOITOVER/Dynaflect combination, i.e., the mean values of $E_p$, $M_r$, and $SN_{eff}$ (figures 123, 124, and 125) appear to have the reasonable magnitudes and trends when compared to the corresponding Dynaflect data.
- The before milling computed $SN_{eff}$ values are similar from both the DARWin/FWD and DOITOVER/Dynaflect approaches. However, the after milling and after overlay, the $SN_{eff}$ values vary significantly between the two approaches.
- An ANOVA performed on the DARWin/FWD outputs showed that the differences in $E_p$ and $M_r$ are statistically insignificant between the various rehabilitation stages as expected. However, the post-milling $SN_{eff}$ is statistically significant when compared to the before milling and after overlay $SN_{eff}$ with the latter two being in the same Duncan group. This suggests that $SN_{eff}$ is largely affected by the reduction in thickness alone and also that superior overlay material did not have a big impact on the computed $SN_{eff}$.

---

\(^{1}\) The DARWin software implements the AASHTO 1993 Pavement Design Guide (AASHTO 1993) approach for overlay design. The ODOT overlay design procedure is based on this methodology.
Figure 123. Comparison of backcalculated $E_p$ from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15.

![Graph showing backcalculated $E_p$](image)

<table>
<thead>
<tr>
<th></th>
<th>FWD/DARWin</th>
<th>Dynaflect/DOITOVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Mill</td>
<td>500649</td>
<td>548900</td>
</tr>
<tr>
<td>After Mill</td>
<td>351036</td>
<td>72066</td>
</tr>
<tr>
<td>After Overlay</td>
<td>492305</td>
<td>158395</td>
</tr>
</tbody>
</table>

Figure 124. Comparison of backcalculated $M_r$ from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15.

![Graph showing backcalculated $M_r$](image)

<table>
<thead>
<tr>
<th></th>
<th>FWD/DARWin</th>
<th>Dynaflect/DOITOVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Mill</td>
<td>12600</td>
<td>64179</td>
</tr>
<tr>
<td>After Mill</td>
<td>11150</td>
<td>75445</td>
</tr>
<tr>
<td>After Overlay</td>
<td>13077</td>
<td>82749</td>
</tr>
</tbody>
</table>
Figure 125. Comparison of backcalculated SNeff from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM9.15.

Table 91. ANOVA results for Ep, Mr, and SNeff for ROS-35 MM9.15 project.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Ep Results</th>
<th>Mr Results</th>
<th>SNeff Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean, psi</td>
<td>Std. Dev., psi</td>
<td>Duncan Group</td>
</tr>
<tr>
<td>Before mill</td>
<td>500,649</td>
<td>198,399</td>
<td>A</td>
</tr>
<tr>
<td>After mill</td>
<td>351,036</td>
<td>124,126</td>
<td>A</td>
</tr>
<tr>
<td>After overlay</td>
<td>492,305</td>
<td>112,923</td>
<td>A</td>
</tr>
</tbody>
</table>

Note: The number of data points for each case was 5.

ROS-35 (MM10)

Figure 126 and 127 compare the backcalculated $E_p$ and $M_r$ obtained from DARWin using the FWD data with those obtained from DOITOVER using Dynaflect data (presented in Chapter 17) for the three stages of rehabilitation on the ROS-35 MM10 project. Figure 128 compares the SNeff from DARWin/FWD with DOITOVER/Dynaflect. An ANOVA was also performed on the outputs from DARWin and is presented in table 92. Recall that that this pavement had an approximately 12.9 in original asphalt layer which was milled approximately 1.9 in and overlaid with a 3.2 in thick HMA layer.

All the observations noted for ROS-35 MM9.15 apply here as well and will not be repeated for brevity. Overall, the DARWin/FWD process appears to model the various stages of rehabilitation correctly.
Figure 126. Comparison of backcalculated $E_p$ from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM10.

<table>
<thead>
<tr>
<th></th>
<th>FWD/DARWin</th>
<th>Dynaflect/DOITOVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Mill</td>
<td>390048</td>
<td>261415</td>
</tr>
<tr>
<td>After Mill</td>
<td>288257</td>
<td>45297</td>
</tr>
<tr>
<td>After Overlay</td>
<td>324997</td>
<td>87362</td>
</tr>
</tbody>
</table>

Figure 127. Comparison of backcalculated $M_r$ from DOITOVER/Dynaflect versus DARWin/FWD for ROS-35 MM10.

<table>
<thead>
<tr>
<th></th>
<th>FWD/DARWin</th>
<th>Dynaflect/DOITOVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Mill</td>
<td>13591</td>
<td>74785</td>
</tr>
<tr>
<td>After Mill</td>
<td>11847</td>
<td>89159</td>
</tr>
<tr>
<td>After Overlay</td>
<td>13689</td>
<td>110817</td>
</tr>
</tbody>
</table>
Table 92. ANOVA results for Ep, Mr, and SNeff for ROS-35 MM10 project.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Ep Results</th>
<th>Mr Results</th>
<th>SNeff Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean, psi</td>
<td>Std. Dev., psi</td>
<td>Duncan Group</td>
</tr>
<tr>
<td>Before mill</td>
<td>390,048</td>
<td>150,791</td>
<td>A</td>
</tr>
<tr>
<td>After mill</td>
<td>288,257</td>
<td>120,222</td>
<td>A</td>
</tr>
<tr>
<td>After overlay</td>
<td>924,997</td>
<td>141,218</td>
<td>A</td>
</tr>
</tbody>
</table>

Note: The number of data points for each case was 6.

JAC-32

Figure 129 and 130 compare the backcalculated Ep and Mr obtained from DARWin using the FWD data with those obtained from DOITOVER using Dynaflect data (presented in Chapter 14) for the three stages of rehabilitation on the JAC-32 project. Figure 131 compares the SN_eff from DARWin/FWD with DOITOVER/Dynaflect. An ANOVA was also performed on the outputs from DARWin and is presented in table 93. Recall that this pavement had an approximately 14 in original asphalt layer which was milled approximately 1.5 in and overlaid with a 3.25 in thick HMA layer. The following conclusions can be drawn from the information presented.

- The DARWin/FWD estimation process of Ep, Mr, and SN_eff gives more logical outputs when compared to the DOITOVER/Dynaflect combination. The mean values of Ep, Mr, and SN_eff (figures 129, 130, and 131) appear to have the reasonable magnitudes and trends when compared to the corresponding Dynaflect data.
Figure 129. Comparison of backcalculated Ep from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32.

Figure 130. Comparison of backcalculated Mr from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32.
Figure 131. Comparison of backcalculated SNeff from DOITOVER/Dynaflect versus DARWin/FWD for JAC-32.

Table 93. ANOVA results for Ep, Mr, and SNeff for JAC-32 project.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Ep Results</th>
<th>Mr Results</th>
<th>SNeff Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean, psi</td>
<td>Std. Dev., psi</td>
<td>Duncan Group</td>
</tr>
<tr>
<td>Before mill</td>
<td>169,398</td>
<td>14,939</td>
<td>A</td>
</tr>
<tr>
<td>After mill</td>
<td>172,473</td>
<td>33,643</td>
<td>A</td>
</tr>
<tr>
<td>After overlay</td>
<td>170,367</td>
<td>20,538</td>
<td>A</td>
</tr>
</tbody>
</table>

Note: The number of data points for each case was 8.

- ANOVA on the DARWin/FWD outputs shows that the differences in Ep are statistically insignificant between the various rehabilitation stages as expected. However, the Mr seems to be different for the after milling stage when compared to before milling and after rehabilitation stages. Also, the SNeff is statistically different for all the three stages of rehabilitation. This can be construed as a largely thickness effect since thickness varies significantly between all the three stages of rehabilitation.

One of the consistent observations from comparing the DARWin/FWD and DOITOVER/Dynaflect outputs is that the Ep and Mr appeared to fluctuate a lot from one rehabilitation stage to the other for the latter. To investigate the causes for this apparent instability in the backcalculated values from these two approaches, the last sensor deflections from the FWD and Dynaflect (S5 for Dynaflect and w7 for FWD) were compared for each of these three projects as a first step. The S5 deflection from the Dynaflect is used to compute the Mr in the DOITOVER process (equation 16) which in turn is used to estimate Ep. Therefore, any
instability in the $S_5$ value will have a corresponding effect throughout the backcalculation process and in the determination of $S_{N,eff}$.

$$M_r = \frac{0.24 \cdot P}{d_r \cdot r} \quad \text{Eq. 16}$$

where

- $M_r$ = elastic modulus of subgrade, psi
- $P$ = load, lbs
- $d_r$ = deflection at distance $r$ from the applied load, inches (equivalent to $S_5$ deflection from the Dynaflect)
- $r$ = radial distance from load, in

Table 94 presents the mean, standard deviation, and coefficient of variation (COV) of last sensor deflections from the Dynaflect and FWD for the three projects of interest. Note that the FWD deflections have been normalized to a 9000 lb average load. A number of observations can be drawn from this table including the following:

<table>
<thead>
<tr>
<th>Project</th>
<th>Rehab Stage</th>
<th>Dynaflect Last Sensor Deflection ($S_5$)</th>
<th>FWD Last Sensor Deflection ($w_7$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (mils)</td>
<td>Std. Dev. (mils)</td>
<td>COV</td>
</tr>
<tr>
<td>ROS-35 MM10</td>
<td>Before Milling</td>
<td>0.067</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>After Milling</td>
<td>0.057</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>After Overlay</td>
<td>0.048</td>
<td>0.017</td>
</tr>
<tr>
<td>ROS-35 MM9.15</td>
<td>Before Milling</td>
<td>0.079</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>After Milling</td>
<td>0.073</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>After Overlay</td>
<td>0.067</td>
<td>0.014</td>
</tr>
<tr>
<td>ROS-35 MM10</td>
<td>Before Milling</td>
<td>0.050</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>After Milling</td>
<td>0.108</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>After Overlay</td>
<td>0.142</td>
<td>0.043</td>
</tr>
</tbody>
</table>

- The FWD deflections are, on average, 10 times higher than the Dynaflect deflections. This is not surprising considering the higher load levels imparted by the FWD to the pavement during deflection testing.
- On average, the average deflection seems to vary a lot more for the Dynaflect when compared to the FWD between the various stages of rehabilitation. The same is true for the standard deviation of deflection and consequently the COV.

The significance of the first observation is better explained by plotting $S_5$ versus $M_r$ as used in the ODOT design method (equation 16). Figure 132 presents this relationship. It can be noted that as the deflections get smaller the relationship between the measured deflection and $M_r$ becomes exponential. The median $S_5$ deflection from the Dynaflect is 0.06 mils and the mean deflection is 0.076 mils. Deflections below this range will be in the nonlinear range of the $M_r$-$S_5$ relationship and are the primary cause for the erratic backcalculation of $M_r$, $E_p$, and $S_{N,eff}$ computations.
Another area of concern is that the $M_r$-$S_5$ relationship depicted in figure 132 may not be applicable for Dynaflect deflections in the range noted in table 94. It was necessary to revisit this relationship in light of the magnitudes of deflections noted on this project for thicker asphalt pavements (with 12 inches or higher HMA layer thickness). A recalibration exercise using more FWD data and FWD derived estimates of laboratory resilient moduli was done as follows:

![Graph showing ODOT relationship between subgrade resilient modulus versus Dynaflect’s and FWD’s last sensor deflections.](image)

Figure 132. ODOT relationship between subgrade resilient modulus versus Dynaflect’s and FWD’s last sensor deflections.

- Compute subgrade elastic modulus using FWD deflection data obtained from all the flexible pavement projects considered using the model below:

$$
M_r = \frac{0.24 * P}{d_r * r}
$$

Eq. 17

where

- $M_r$ = elastic modulus of subgrade, psi
- $P$ = 9000 lbs
- $d_r$ = deflection at distance $r$ from the applied load ($w_7$ deflection from FWD)
- $r$ = radial distance from load = 60 in (radial distance from $w_7$)

To be consistent with the laboratory-measured $M_r$ values used for the AASHO Road Test soil in the development of the flexible pavement design equation, a correction factor of $C = 0.33$ recommended by AASHTO was applied to the FWD computed subgrade elastic modulus.
• Compute subgrade elastic modulus using Dynaflect deflection data obtained from all the flexible pavement projects considered using the model below:

\[ M_r = \frac{0.24 \cdot P}{d_r \cdot r} \]  

**Eq. 17**

where
- \( M_r \) = elastic modulus of subgrade, psi
- \( P \) = 1000 lbs
- \( d_r \) = deflection at distance \( r \) from the applied load (\( S_5 \) deflection from Dynaflect)
- \( r \) = radial distance from load = 49.03 in (radial distance from \( S_5 \))

Develop a correction factor of \( C_{DYNA} \) to be applied to the Dynaflect computed subgrade elastic modulus to be consistent with FWD measured estimates of laboratory-measured \( M_r \) values (consistent with AASHO Road Test soil used in the development of the flexible pavement design equation) as follows:

\[ M_r (\text{lab measured}) = 0.33 \cdot M_r (\text{FWD}) = C_{DYNA} \cdot M_r (\text{Dynaflect}) \]  

**Eq. 18**

\( C_{DYNA} \) was estimated using regression analysis and had a value of 0.225. Figure 133 presents a plot of FWD estimated \( M_r \) and lab corrected Dynaflect estimated \( M_r \).

![Figure 133. Plot of FWD estimated Mr and lab corrected Dynaflect estimated Mr.](image-url)
CHAPTER 19. FLEXIBLE PAVEMENT ANALYSIS AND FINDINGS

Introduction

Data from the eight HMA/HMA pavements underwent a rigorous analysis to determine the adequacy of the ODOT overlay design process with respect to the following issues:

- Issue #1: Temperature adjustment of surface deflections.
- Issue #2: Impact of milling on SN_{eff}.
- Issue #3: Impact of new HMA materials on a_{OL}.

Rigorous evaluation of projects provided insights for (1) thoroughly investigating the issues listed above (2) identifying possible deficiencies in the current ODOT HMA overlay design procedure and (3) developing solutions to identified deficiencies.

Summary and Observations

The HMA/HMA pavement structural evaluation consisted of characterizing pavement structural capacity before, during, and after rehabilitation using the following:

- Overall pavement structural capacity (maximum deflection, S_1).
- Spreadability (SPR).
- Subgrade support (fifth sensor deflection, S_5).
- Composite elastic modulus, E_p (for all layers above the subgrade).
- Subgrade resilient modulus, M_r.
- Effective structural number, SN_{eff}.

Figures 134 through 139 present information gathered from the structural evaluation of the 8 selected projects. Observed trends, identified deficiencies, and suggested solutions are presented as follows:

![Figure 134. Summary of observed trends in maximum deflections for HMA-overlaid flexible pavements.](image-url)
Figure 135. Summary of observed trends in SPR for HMA-overlaid flexible pavements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Before Milling</th>
<th>After Milling</th>
<th>After Overlay</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA-68</td>
<td>66</td>
<td>71</td>
<td>54</td>
</tr>
<tr>
<td>GAL-35</td>
<td>73</td>
<td>66</td>
<td>74</td>
</tr>
<tr>
<td>GRE-72</td>
<td>57</td>
<td>52</td>
<td>58</td>
</tr>
<tr>
<td>JAC-32</td>
<td>41</td>
<td>51</td>
<td>60</td>
</tr>
<tr>
<td>LIC-70</td>
<td>70</td>
<td>76</td>
<td>66</td>
</tr>
<tr>
<td>MOT40 (05)</td>
<td>66</td>
<td>48</td>
<td>57</td>
</tr>
<tr>
<td>ROS-35 (MM10)</td>
<td>57</td>
<td>48</td>
<td>63</td>
</tr>
<tr>
<td>ROS-35 (MM9.15)</td>
<td>65</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

Figure 136. Summary of observed trends in S5 for HMA-overlaid flexible pavements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Before Milling</th>
<th>After Milling</th>
<th>After Overlay</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA-68</td>
<td>0.120</td>
<td>0.217</td>
<td>0.072</td>
</tr>
<tr>
<td>GAL-35</td>
<td>0.083</td>
<td>0.103</td>
<td>0.078</td>
</tr>
<tr>
<td>GRE-72</td>
<td>0.195</td>
<td>0.221</td>
<td>0.196</td>
</tr>
<tr>
<td>JAC-32</td>
<td>0.050</td>
<td>0.108</td>
<td>0.142</td>
</tr>
<tr>
<td>LIC-70</td>
<td>0.138</td>
<td>0.147</td>
<td>0.088</td>
</tr>
<tr>
<td>MOT40 (05)</td>
<td>0.120</td>
<td>0.104</td>
<td>0.073</td>
</tr>
<tr>
<td>ROS-35 (MM10)</td>
<td>0.067</td>
<td>0.057</td>
<td>0.048</td>
</tr>
<tr>
<td>ROS-35 (MM9.15)</td>
<td>0.077</td>
<td>0.073</td>
<td>0.071</td>
</tr>
</tbody>
</table>
Figure 137. Summary of observed trends in $E_p$ for HMA-overlaid flexible pavements.

Figure 138. Summary of observed trends in $M_r$ for HMA-overlaid flexible pavements.
Figure 139. Summary of observed trends in SN_{eff} for HMA-overlaid flexible pavements.

- **Maximum Deflection, S_{1}**: In general, the maximum deflection measured using the Dynaflect was a reliable predictor of overall pavement structural capacity. For the before milling to after milling rehabilitation stage, 5 of the 8 projects experienced a significant change in S_{1}. For all cases where there was a significant change in S_{1}, trends observed were reasonable and as expected (i.e., S_{1} increased after HMA overlay placement). For the after milling to after HMA overlay placement rehabilitation stage, 6 of the 8 projects experienced a significant change in S_{1}. For all these cases also the changes observed for S_{1} were reasonable and as expected (i.e., S_{1} decreased after HMA overlay placement).

- **Spreadability (SPR)**: SPR was a very good predictor of pavement upper layer structural capacity. For the before milling to after milling rehabilitation stage, 5 of the 8 projects experienced a significant change in SPR. For all of these cases, the trends observed were as expected (i.e., SPR decreased after milling). For the after milling to after HMA overlay placement rehabilitation stage, SPR changed significantly for 7 of the 8 projects evaluated. This trend was as expected (i.e., SPR increased after HMA overlay placement).

- **Fifth sensor deflection (S_{5} and M_{r})**: S_{5} was not a good predictor of pavement subgrade strength. This is because of the higher variability (characterized by the coefficient of variation) observed in measured S_{5} values as compared to the S_{1} values. The high variability exhibited, adversely affected estimates of M_{r}. Thus, although statistically, for both the before milling to after milling rehabilitation stage and after milling to after HMA overlay placement rehabilitation stage, seven of the eight projects evaluated experienced no significant change in S_{5}, the estimates of S_{5} and by extension M_{r} produced through Dynaflect deflection testing were highly variable and erratic and could not be used in any meaningful manner to characterize pavement structural capacity.

- **Backcalculated E_{P} and M_{r}**: The observed changes in E_{P} and M_{r} for both stages of rehabilitation were not consistent with expectations. This was mostly due to high variability observed in S_{5} values (the key input used for estimating M_{r}). The high
variability in $M_r$ was transferred to $E_p$ as the parameters tended to compensate for each other (an increase in $M_r$ results in a corresponding decrease in $E_p$).

- **Effective structural number ($SN_{eff}$):** $SN_{eff}$ was a moderately good predictor of overall pavement structural capacity. For the before milling to after milling rehabilitation stage, $SN_{eff}$ changed significantly for 4 of the 8 projects evaluated. For three of those four projects, the trends observed in the change in $SN_{eff}$ was as expected (i.e., $SN_{eff}$ decreased after milling). For the after milling to after HMA overlay placement rehabilitation stage, 6 of the 8 projects evaluated experienced a significant change in the value $SN_{eff}$. For 5 of those projects, the trend observed in the change in $SN_{eff}$ was as expected (i.e., $SN_{eff}$ increased after HMA overlay placement).

Based on the trends observed in $S_1$, SPR, and $SN_{eff}$ across the various rehabilitation stages, it was concluded that 4 of the 8 projects evaluated (50 percent) showed a significant decrease in structural capacity after milling, while 6 of the 8 projects (75 percent) showed a significant increase in structural capacity after HMA overlay placement.

**Implications of Observations**

The following conclusions were drawn from the results summarized in the preceding sections:

- **Issue #1: Temperature Adjustment of Surface Deflections:** For the ODOT HMA overlay of existing flexible pavement design procedure, only the first sensor deflections ($S_1$) is temperature corrected. As stated in the preceding sections, for the projects evaluated, the trends observed in $S_1$ were reasonable and consistent with expectations. This shows that the current temperature adjustment procedure utilized by ODOT is effective and the temperature corrected $S_1$ is sensitive and accurate enough to detect changes in pavement structural capacity due to temperature.

- **Issue #2: Impact of Milling on $SN_{eff}$:** The information presented shows that for approximately half of the projects evaluated, milling off 1.5 to 3 inches of existing HMA does significantly affect $SN_{eff}$, a key factor used in determining the HMA overlay thickness required. On average, there was a 17.4 percent decrease in $SN_{eff}$ due to milling (based on typical ODOT milling depth, existing pavement condition, etc). There is, therefore, a need to correct $SN_{eff}$ to account for the effect of milling. A correction procedure developed as part of this research is presented later in this chapter.

- **Issue #3: Impact of New HMA Materials on $a_{OL}$:** The data analysis shows that there was a significant increase in pavement structural capacity after HMA overlay placement. The increased pavement structural capacity may be due to either the use of new superior HMA materials or the removal of deteriorated existing HMA materials, or both. An investigation of the structural contribution of the new materials is therefore warranted and will be presented later in this chapter.
Adjustment of SN_{eff} to Account for the Effect of Milling

Effectiveness of Current Procedure

The current ODOT HMA overlay design procedure computes effective SN as follows:

\[ SN_{eff} = 0.0045 \times h_p \times (E_p)^{0.33} \]  
Eq. 17

where \( h_p \) is the pavement thickness (all layers above the subgrade) and \( E_p \) is the composite modulus of all layers above the subgrade.

For the design of HMA overlays of milled existing pavements (typical mill depth ranges from 1- to 5-in), effective structural number is computed as follows:

\[ SN_{eff} = 0.0045 \times h_{p-m} \times (E_p)^{0.33} \]  
Eq. 18

where \( h_{p-m} \) is the after milling pavement thickness and all other variables are as already defined.

The current ODOT procedure for determining after milling effective structural number is based on the hypothesis that using the after milling pavement thickness and the before milling \( E_p \) in equation 17 is sufficient to accurately characterize after milling \( SN_{eff} \). The validity of this hypothesis was tested by estimating after milling \( SN_{eff} \) using the following two methods:

- Method 1: Current ODOT procedure (applying equation 17 using before milling \( E_p \) and after milling pavement thickness).
- Method 2: Applying equation 18 (with after milling \( E_p \) and after milling pavement thickness).

The estimates of \( SN_{eff} \) computed using methods 1 and 2 was compared using ANOVA. The comparison (ANOVA) results are presented in table 95. The results of the comparison indicate that there was a significant difference in \( SN_{eff} \) computed using methods 1 and 2 in all 8 projects evaluated. Thus, a new approach to estimating \( SN_{eff} \) that considers the effect of milling more rigorously is warranted. The framework for the new correction procedure is presented in the following section.

Framework for Estimating After Milling \( SN_{eff} \)

The framework for a more accurate and reliable procedure for estimating after milling \( SN_{eff} \) is as follows:

- Estimate \( SN_{eff} \) using a more objective and reliable overall pavement structural capacity indicator (e.g., maximum deflection \( S_1 \)).
  - Develop a new relationship for estimating \( SN_{eff} \).
Table 95. ANOVA results for comparison of methods 1 and 2.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Computing Method</th>
<th>Number of Data Points</th>
<th>Mean SN_{eff}</th>
<th>Duncan’s Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA-68</td>
<td>Method 1</td>
<td>6</td>
<td>6.38</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>3.66</td>
<td>B</td>
</tr>
<tr>
<td>GAL-32</td>
<td>Method 1</td>
<td>12</td>
<td>8.08</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>12</td>
<td>5.70</td>
<td>B</td>
</tr>
<tr>
<td>GRE-72</td>
<td>Method 1</td>
<td>11</td>
<td>1.85</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>11</td>
<td>2.22</td>
<td>B</td>
</tr>
<tr>
<td>JAC-32</td>
<td>Method 1</td>
<td>6</td>
<td>2.92</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>4.36</td>
<td>B</td>
</tr>
<tr>
<td>LIC-70</td>
<td>Method 1</td>
<td>6</td>
<td>8.53</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>5.42</td>
<td>B</td>
</tr>
<tr>
<td>MOT-40(05)</td>
<td>Method 1</td>
<td>9</td>
<td>3.53</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>9</td>
<td>1.57</td>
<td>B</td>
</tr>
<tr>
<td>ROS-35mm (10)</td>
<td>Method 1</td>
<td>6</td>
<td>2.32</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>4.54</td>
<td>B</td>
</tr>
<tr>
<td>ROS-35mm (9.15)</td>
<td>Method 1</td>
<td>10</td>
<td>2.69</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>10</td>
<td>5.74</td>
<td>B</td>
</tr>
</tbody>
</table>

*Method 1: use measured after milling $E_P$ and $h_P$ to estimate $SN_{eff}$, method 2: use measure before milling $E_P$ and after milling $h_P$ to estimate $SN_{eff}$.

- Use correction factors as appropriate to adjust before milling $S_1$ to after milling $S_1$.
  - Develop correction factors that can be used to adjust measured before milling $S_1$ to after milling $S_1$. Correction factors will based on factors such as:
    - The depth of milling.
    - Percent change in pavement thickness (before to after milling).
    - Existing pavement condition (particularly condition of the portions of existing HMA milled off as this affects $E_P$).
- Use the $SN_{eff}$ prediction model and after milling $S_1$ (i.e., adjusted before milling $S_1$) to estimate after milling $SN_{eff}$.

The key components of the proposed framework were developed as part of this project and are presented in the following sections.

Model Developed for Estimating $SN_{eff}$

A thorough search of literature was done as part of this study to determine the best approach for estimating $SN_{eff}$. Although the literature presents various feasible solutions, the most appropriate and practical methodology identified that would fit into the current ODOT HMA overlay design procedure was to relate $SN_{eff}$ directly with maximum deflection (an objective measure of pavement structural capacity) obtained through Dynaflect deflection testing. This approach for estimating $SN_{eff}$ has been successfully developed in the past (Romanoschi and Metcalf 1999; Hall and Elliott 1992)

A review of the ODOT data assembled showed that temperature-adjusted $S_1$ was highly correlated to $SN_{eff}$. Thus, a mathematical relationship between $S_1$ and $SN_{eff}$ was developed. The model developed is presented as follows:
\[ SN_{\text{eff}} = 2.3418S_1^{-0.733} \]  
\text{Eq. 19}

Model statistics
\[ R^2 = 0.64 \]
\[ N = 195 \]
\[ \text{SEE} = 1.6 \text{ (SN)} \]

A plot of measured and predicted \( SN_{\text{eff}} \) using equation 19 is presented in figure 140. Figure 141 shows a plot of predicted \( SN_{\text{eff}} \) and actual measured data.

![Figure 140. Plot showing predicted versus measured \( SN_{\text{eff}} \).](image)

R\(^2\) = 0.63
SEE = 1.6 SN
N = 193
Estimating After-Milling Maximum Deflection ($S_1$)

Using current ODOT HMA overlay design procedure, after-milling maximum deflection $S_1$ is computed as follows:

$$S_1 = qa \left( F(0) - F(h) + \frac{F(h_e)}{M_r} \right)$$

Eq. 20

where

- $S_1 =$ maximum deflection, mils
- $q =$ 31.25 psi
- $a =$ 2.257 in
- $h =$ after milling pavement thickness (all layers above subgrade)
- $F(z) =$ is a function used for estimating deflection at depth $z$ (see ODOT Design Manual), $F(0) = 0.4025$
- $h_e =$ equivalent pavement thickness = $h \left( \frac{E_p}{M_r} \right)^{0.333}$
- $E_p =$ before milling composite modulus of all layers above the subgrade
- $M_r =$ before milling subgrade resilient modulus
As demonstrated in the preceding sections, the use of equation 20 with before milling \( E_P \) and \( M_r \) will produce unreasonable estimates of \( S_1 \) and by extension \( S_{\text{eff}} \). There is the need to correct the inputs \( E_P \) and \( M_r \) to reflect after milling conditions or replace equation 20 altogether.

Figure 142 shows the relationship between before and after milling \( S_1 \). The information presented show that on average after milling \( S_1 \) is 1.336 times higher than before milling \( S_1 \). The high correlation between before and after milling \( S_1 \) shows that the development of an adjustment factor based on known factors such as milling depth, percent change in pavement thickness, existing pavement condition is feasible.

![Figure 142. Relationship between before and after milling \( S_1 \).](image)

A correction factor, \( \alpha \), was developed for use in adjusting before milling \( S_1 \) to after milling \( S_1 \). The correction factor is as follows:

\[
S_{1,AM} = \left( 2.6322 \times \text{FRACMILL} + \frac{76.1152}{\text{PCR}} \right) \times S_{1,BM}^{0.8891} \tag{21}
\]

where

\[
\begin{align*}
S_{1,AM} & = \text{predicted after milling maximum deflection} \\
\text{FRACMILL} & = \frac{\text{fraction of pavement thickness milled off}}{BMTHK - AMTHK} \frac{BMTHK}{BMTHK}
\end{align*}
\]
Note that due to the limitations in the dataset used to develop equation 21, it is valid only under the following conditions:

\[ 0 < \text{FRACMILL} < 0.25 \]
\[ 75 < \text{PCR} < 100 \]

These bounds on the FRACMILL and PCR parameters are not expected to significantly hinder minor flexible pavement rehabilitation design with HMA overlays since ODOT’s typical current practice is covered by the dataset used. However, for more significant milling operations, where the FRACMILL and PCR values are expected to be outside the bounds noted, it is recommended that ODOT perform deflection testing after milling and use the \( S_1 \) from those tests to compute the adjusted \( SN_{eff} \) from equation 19.

Figure 143 shows a plot of measured and predicted after milling \( S_1 \). Sensitivity analysis results showing the effect of percent milling, PCR, and existing HMA pavement thicknesses on the adjusted \( SN_{eff} \) are presented in figures 144 through 146. The plots show reasonable trends.

![Figure 143. Plot of measured and predicted after milling \( S_1 \).](image-url)
Figure 144. Plot showing the effect of milling depth and PCR on adjusted $SN_{eff}$ for a 9-in-thick existing pavement.

Figure 145. Plot showing the effect of milling depth and PCR on adjusted $SN_{eff}$ for a 12-in-thick existing pavement.
Impact of New HMA Materials on a_{OL}

The impact of the use of “superior” materials for HMA overlays was also investigated. This was done by comparing structural numbers for projects where milling thickness and HMA overlay thickness were the same and the existing pavement was in relatively good condition (5 of the 8 flexible pavement projects fit this criterion). Using only projects where milling thickness and HMA overlay thickness were practically the same and pavement condition relatively good for analysis ensured that any significant improvements in SN\text{eff} could reasonably be attributed to the enhanced structural properties of the new “superior” HMA material only. The selected projects are presented in table 96.

ANOVA was used to determine if there was a significant difference in SN\text{eff} before rehabilitation and after HMA overlay placement. The results are presented in table 97. The information presented in table 97 shows that although there was some improvement in SN\text{eff}, the change was not significant. Therefore there was no basis or need to revise the current ODOT structural layer coefficients.
Table 96. Selected projects for comparison of $SN_{eff}$ before rehabilitation and after HMA overlay placement.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Number of Data Points</th>
<th>Average Milling Depth, in</th>
<th>Average HMA Overlay Thickness, in</th>
<th>Average PCR Prior to Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA-68</td>
<td>6</td>
<td>1.5</td>
<td>1.8</td>
<td>74</td>
</tr>
<tr>
<td>GAL-35</td>
<td>12</td>
<td>1.5</td>
<td>1.5</td>
<td>77</td>
</tr>
<tr>
<td>GRE-72</td>
<td>11</td>
<td>1.5</td>
<td>1.5</td>
<td>76</td>
</tr>
<tr>
<td>LIC-70</td>
<td>6</td>
<td>1.75</td>
<td>1.75</td>
<td>84</td>
</tr>
<tr>
<td>ROS-35 (MM 9.15)</td>
<td>10</td>
<td>2.8</td>
<td>3.1</td>
<td>73</td>
</tr>
</tbody>
</table>

Table 97. Summary of ANOVA results for comparison of $SN_{eff}$ before rehabilitation and after HMA overlay placement.

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Number of Data Points</th>
<th>Mean $SN_{eff}$*</th>
<th>Duncan’s Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing pavement (before milling)</td>
<td>45</td>
<td>5.9 (2.7)</td>
<td>A</td>
</tr>
<tr>
<td>Existing pavement (after overlay placement)</td>
<td>45</td>
<td>7.0 (6.8)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Standard deviation in brackets
CHAPTER 20. COMPOSITE PAVEMENT ANALYSIS AND FINDINGS

Introduction

A major effort was expended to analyze data from the 9 composite pavements evaluated to determine the effectiveness of the following aspects of ODOT HMA overlay design:

- Issue #1: Backcalculation of $E_p$
- Issue #2: Impact of Milling on $D_{eff}$

Evaluation of these projects provided the project team with valuable insights for (1) thoroughly investigating the issues listed above (2) identifying possible deficiencies in the current ODOT HMA overlay design procedure and (3) developing solutions to identified deficiencies.

Summary and Observations

Composite pavement structural evaluation consisted of characterizing pavement structural capacity before, during, and after rehabilitation using the following:

- Overall pavement structural capacity (maximum deflection, $S_1$).
- Spreadability (SPR).
- Deflection parameter AREA used for estimating radius of relative stiffness, $E_p$ and $k$-value.
- Composite elastic modulus, $E_p$ (for all layers above the subgrade).
- Modulus of subgrade reaction, $k$-value.
- Effective pavement thickness, $D_{eff}$.

Figures 147 through 152 present information gathered from the structural evaluation of nine composite pavements. Observed trends, identified deficiencies, and suggested solutions are presented as follows:

Figure 147. Summary of observed trends in maximum deflections for HMA-overlaid composite pavements.
Figure 148. Summary of observed trends in SPR for HMA-overlaid composite pavements.

Figure 149. Summary of observed trends in AREA for HMA-overlaid composite pavements.
<table>
<thead>
<tr>
<th>Modulus of subgrade reaction, k-value (pci)</th>
<th>Before Milling</th>
<th>After Milling</th>
<th>After Overlay</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERI-6</td>
<td>259</td>
<td>215</td>
<td>288</td>
</tr>
<tr>
<td>FAY71 (NB)</td>
<td>243</td>
<td>130</td>
<td>293</td>
</tr>
<tr>
<td>FAYMAD71 (SB)</td>
<td>257</td>
<td>319</td>
<td>334</td>
</tr>
<tr>
<td>GRE4 (NB)</td>
<td>248</td>
<td>154</td>
<td>396</td>
</tr>
<tr>
<td>JEF-7</td>
<td>207</td>
<td>329</td>
<td>375</td>
</tr>
<tr>
<td>MOT4 (04)</td>
<td>175</td>
<td>167</td>
<td>147</td>
</tr>
<tr>
<td>MOT4 (SB)</td>
<td>345</td>
<td>174</td>
<td>348</td>
</tr>
<tr>
<td>ROS-35</td>
<td>318</td>
<td>326</td>
<td>260</td>
</tr>
<tr>
<td>WAY-30</td>
<td>208</td>
<td>290</td>
<td>366</td>
</tr>
</tbody>
</table>

Figure 150. Summary of observed trends in $E_p$ for HMA-overlaid composite pavements.

<table>
<thead>
<tr>
<th>Modulus of subgrade reaction, k-value (pci)</th>
<th>ERI-6</th>
<th>FAY71 (NB)</th>
<th>FAYMAD71 (SB)</th>
<th>GRE4 (NB)</th>
<th>JEF-7</th>
<th>MOT4 (04)</th>
<th>MOT4 (SB)</th>
<th>ROS-35</th>
<th>WAY-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ (psi)</td>
<td>2,335,435</td>
<td>1,059,808</td>
<td>1,307,054</td>
<td>2,121,067</td>
<td>2,373,287</td>
<td>56,377</td>
<td>2,060,323</td>
<td>1,066,034</td>
<td>2,335,435</td>
</tr>
<tr>
<td>$E_p$ (psi) After Milling</td>
<td>2,848,789</td>
<td>3,483,840</td>
<td>2,470,244</td>
<td>1,712,191</td>
<td>1,687,577</td>
<td>95,414</td>
<td>1,920,479</td>
<td>1,700,648</td>
<td>2,848,789</td>
</tr>
<tr>
<td>$E_p$ (psi) After Overlay</td>
<td>2,149,689</td>
<td>1,026,984</td>
<td>1,334,865</td>
<td>971,175</td>
<td>1,061,552</td>
<td>174,641</td>
<td>923,064</td>
<td>1,727,875</td>
<td>2,149,689</td>
</tr>
</tbody>
</table>

Figure 151. Summary of observed trends in k-value for HMA-overlaid composite pavements.
Figure 152. Summary of observed trends in $D_{eff}$ for HMA-overlaid composite pavements.

- **Maximum Deflection, $S_1$**: In general, the maximum deflection as measured by the Dynaflect was a very good predictor of a composite pavement’s overall structural capacity. For the before milling to after milling rehabilitation stage, 2 of the 9 projects evaluated experienced a statistically significant change in $S_1$. For all cases where there was a significant change in $S_1$, trends observed were reasonable and as expected (i.e., $S_1$ increased after milling). For the remaining projects, although the change in $S_1$ was not statistically significant, an increase in $S_1$ was observed (i.e., for all 7 cases). For the after milling to after HMA overlay placement rehabilitation stage, all 9 projects experienced a significant change in $S_1$. The trends observed were reasonable and as expected (i.e., $S_1$ decreased after HMA overlay placement).

- **Spreadability (SPR)**: SPR was a very good predictor of pavement upper layer structural capacity. For the before milling to after milling rehabilitation stage, 2 of the 9 projects evaluated experienced a significant change in SPR. For both these cases, the trends observed was as expected (i.e., SPR decreased after milling). 6 of the 7 cases with no statistically significant change in SPR also registered an increase in SPR. For the after milling to after HMA overlay placement rehabilitation stage, SPR changed significantly for 3 of the 9 projects and in all 3 cases, the trend observed in SPR was as expected (i.e., SPR increased after HMA overlay placement). For the remaining 6 projects, an increase in SPR was observed.

- **AREA**: AREA was not a very good predictor of pavement subgrade strength. For both the before milling to after milling rehabilitation stage and milling to after HMA overlay placement rehabilitation stage, there was no consistent trend in the changes to AREA parameter. The lack of a definite trend was due to the high variability observed in deflections measured by Dynaflect’s fourth and fifth sensors. The high variability is perhaps due to the fact that Dynaflect does not impart adequate loading to composite pavement structures to produce significant end sensor deflections.

- **Backcalculated $E_p$ and k-value**: The observed changes in $E_p$ for both stages of rehabilitation were not consistent with expectations.
• **Effective thickness (Deff):** Deff was a good predictor of overall pavement structural capacity. For the before milling to after milling rehabilitation stage, Deff changed significantly for 5 of the 9 projects evaluated. After HMA overlay placement, 8 of the 9 projects experienced a significant increase in Deff, as expected.

Based on the reasonable trends observed in S1, SPR, and Deff, it was concluded that there were some significant changes in after milling and after HMA overlay placement.

**Implications of Observations**

The following conclusions were drawn from the results summarized in the preceding sections:

• **Issue #1: Backcalculation of Ep.** Backcalculated Ep estimates were not consistent with expectations. Thus, there is no clear relationship between before and after milling Ep. Current ODOT approach for estimating after milling Deff is based on before milling Ep. This approach is questionable.

• **Issue #2: Impact of Milling on Deff.** The information presented shows that for approximately half of the projects evaluated, milling 1.5 to 3 inches of existing HMA does significantly affect Deff, a key factor used in determining HMA overlay thickness required. There is, therefore, a need to correct Deff to account for the effect of milling. A correction procedure developed as part of this research is presented in the following sections.

**Adjustment of Deff to Account for the Effect of Milling**

**Effectiveness of Current Procedure**

The current ODOT HMA overlay design procedure computes effective pavement thickness as follows:

\[
D_{eff} = \frac{D_{new}}{E_{eff}} = \frac{h_{AC}}{2} + h_{PCC} \\
\frac{E_{eff}}{E_p}^{0.33} = \frac{E_{eff}}{E_p}^{0.33} \quad \text{Eq. 22}
\]

where

\[
D_{eff} = \text{effective thickness} \\
D_{new} = \frac{h_{AC}}{2} + h_{PCC} \\
h_{AC} = \text{asphalt layer thickness} \\
h_{PCC} = \text{PCC layer thickness} \\
E_{eff} = \text{effective modulus of composite layer} \\
E_p = \text{backcalculated modulus of the composite layer}
\]

The current ODOT procedure for determining after milling Deff is based on the hypothesis that using the after milling pavement thickness and the before milling Ep and k-value in equation 22
is sufficient to accurately characterize after milling $D_{\text{eff}}$. The validity of this hypothesis was tested by estimating after milling $D_{\text{eff}}$ using the following two methods:

- Method 1: Current ODOT procedure (applying equation 22 using before milling $E_P$ and $k$-value and after milling pavement thickness).
- Method 2: Applying equation 22 (with after milling $E_P$, $k$-value, and after milling pavement thickness).

The estimates of $D_{\text{eff}}$ computed using methods 1 and 2 was compared using ANOVA. The comparison (ANOVA) results are presented in table 98. The results of the comparison indicate that there was a significant difference in $D_{\text{eff}}$ for 5 out of the 9 projects evaluated when $D_{\text{eff}}$ is computed using methods 1 and 2. Thus, a new approach for estimating $D_{\text{eff}}$ is warranted. The framework for the new correction procedure is presented in the following section.

Table 98. ANOVA results for comparison of methods 1 and 2.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Computing Method</th>
<th>Number of Data Points</th>
<th>Mean $D_{\text{eff}}$</th>
<th>Duncan’s Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERI-6</td>
<td>Method 1</td>
<td>7</td>
<td>8.11</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>7</td>
<td>7.82</td>
<td>A</td>
</tr>
<tr>
<td>FAY-71</td>
<td>Method 1</td>
<td>6</td>
<td>8.48</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>8.46</td>
<td>A</td>
</tr>
<tr>
<td>FAY-MAD</td>
<td>Method 1</td>
<td>6</td>
<td>9.85</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>7.59</td>
<td>B</td>
</tr>
<tr>
<td>GRE-4</td>
<td>Method 1</td>
<td>6</td>
<td>8.43</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>6.15</td>
<td>B</td>
</tr>
<tr>
<td>JEF-7</td>
<td>Method 1</td>
<td>6</td>
<td>7.24</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>4.76</td>
<td>A</td>
</tr>
<tr>
<td>MOT-40(04)</td>
<td>Method 1</td>
<td>8</td>
<td>3.74</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>8</td>
<td>3.12</td>
<td>A</td>
</tr>
<tr>
<td>MOT-4(SB)</td>
<td>Method 1</td>
<td>6</td>
<td>6.47</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>3.07</td>
<td>B</td>
</tr>
<tr>
<td>ROS-35</td>
<td>Method 1</td>
<td>11</td>
<td>9.27</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>11</td>
<td>6.53</td>
<td>B</td>
</tr>
<tr>
<td>WAY-30</td>
<td>Method 1</td>
<td>6</td>
<td>11.04</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Method 2</td>
<td>6</td>
<td>5.67</td>
<td>B</td>
</tr>
</tbody>
</table>

*Method 1: use measured after milling $E_P$ and $h_P$ to estimate $D_{\text{eff}}$, method 2: use measured before milling $E_P$ and after milling $h_P$ to estimate $D_{\text{eff}}$.

New Framework for Estimating After Milling $D_{\text{eff}}$

The framework for a more accurate and reliable procedure for estimating after milling $D_{\text{eff}}$ is as follows:

- Estimate $D_{\text{eff}}$ using a more objective and reliable overall pavement structural capacity indicator (e.g., maximum deflection $S_1$).
  - Develop a new relationship for estimating $D_{\text{eff}}$.
- Use correction factors as appropriate to adjust before milling $S_1$ to after milling $S_1$.  

238
Develop correction factors that can be used to adjust measured before milling \( S_1 \) to after milling \( S_1 \). Correction factors will be based on factors such as:

- The depth of milling.
- Percent change in pavement thickness (before to after milling).
- Existing pavement condition (particularly condition of the portions of existing HMA milled off as this affects \( E_P \)).

- Use the \( D_{eff} \) prediction model and after milling \( S_1 \) (i.e., adjusted before milling \( S_1 \)) to estimate after milling \( D_{eff} \).

The key components of the proposed framework were developed as part of this project and are presented in the following sections.

Model for Estimating \( D_{eff} \)

Just as for \( SN_{eff} \), a review of the ODOT data assembled indicated a strong correlation between \( S_1 \) and \( D_{eff} \). A model relating \( S_1 \) to \( D_{eff} \) developed using the data assembled from the nine projects evaluated is as follows:

\[
D_{eff} = 4.5931S_1^{-0.5821}
\]  
Eq. 23

Model statistics

\[ R^2 = 0.91 \]
\[ N = 181 \]
\[ SEE = 0.65 \text{ in} \]

A plot of measured and predicted \( D_{eff} \) using equation 2 is presented in figure 153. Figure 154 shows a plot of predicted \( D_{eff} \) and actual data obtained from the structural evaluation of pavements (after milling).

![Figure 153. Plot showing predicted versus measured \( SN_{eff} \).](image-url)
Maximum Deflection Adjustment Factors

The current ODOT HMA overlay design procedure computes maximum deflection $S_1$ as follows:

$$d_0 = \frac{w_0 k \ell^2}{P} = f\left(\frac{a}{\ell}\right)$$  \hspace{1cm} \text{Eq. 24}

where
- $d_0$ = normalized maximum deflection, mils
- $w_0$ = maximum deflection (Dynaflect sensor 1), mils
- $a$ = 2.257 in
- $P$ = applied loading (1000 lbs)
- $k$ = modulus of subgrade reaction, psi/in
- $\ell$ = radius of relative stiffness, in

Thus, deflection from Dynaflect $S_1$ is computed as follows:

$$w_0 = \frac{P f\left(\frac{a}{\ell}\right)}{k \ell^2}$$  \hspace{1cm} \text{Eq. 25}

All variables are as previously defined. Milling off portions of the HMA layer will impact $k$ and $\ell$ (as a key input for computing $\ell$ is $E_p$). Thus, a correction factor to account for changes in $w_0$
due to the impact of milling is warranted. The model for computing after milling \( w_0 \) will thus be as follows:

\[
S_{1,AM} = \alpha \left( \frac{P \cdot f \left( \frac{a}{l} \right)_{BM}}{k_{BM} \ell_{BM}^2} \right) = \alpha \cdot S_{1,BM}^{\beta} \quad \text{Eq. 26}
\]

where \( \alpha \) and \( \beta \) are correction factors based on the percent of HMA thickness milled off. Using the data collected from the projects evaluated, the final form of equation 26 was developed as follows:

\[
S_{1,AM} = \left( 3.3512 \cdot FRACMILL + \frac{52.902}{PCR} \right) \cdot S_{1,BM}^{0.9331} \quad \text{Eq. 27}
\]

Where

- \( S_{1,AM} \) = estimate of after milling maximum deflection
- \( FRACMILL \) = fraction of existing HMA layer milled off
- \( BMTHK \) = before mill pavement thickness, in
- \( AMTHK \) = after mill pavement thickness, in
- \( PCR \) = before rehabilitation pavement condition rating
- \( S_{1,BM} \) = estimate of existing pavement (before milling) maximum deflection, mils

Note that due to the limitations in the dataset used to develop equation 27, it is valid only under the following conditions:

\[
0 < FRACMILL < 0.30 \\
50 < PCR < 80
\]

These bounds on the \( FRACMILL \) and \( PCR \) parameters are not expected to significantly hinder minor composite pavement rehabilitation design with HMA overlays since ODOT’s typical current practice is covered by the dataset used. However, for more significant milling operations, where the \( FRACMILL \) and \( PCR \) values are expected to be outside the bounds noted, it is recommended that ODOT perform deflection testing after milling and use the \( S_1 \) from those tests to compute the adjusted \( D_{eff} \) from equation 23.

All the inputs to equation 27 can be obtained from current ODOT procedure and planned rehabilitation activities (including pavement thickness after milling and before mill maximum deflection).

Figure 155 shows a plot of measured and predicted after milling \( S_1 \). Sensitivity analysis results showing the effect of percent milling and \( PCR \) are presented in figures 156 through 158. The plots show reasonable trends for the adjusted \( D_{eff} \).
Figure 155. Plot of measured and predicted after milling $S_1$. 

Figure 156. Plot showing the effect of milling depth and PCR on adjusted $D_{\text{eff}}$ for a max. deflection (before milling) of 0.2 mils.
Figure 157. Plot showing the effect of milling depth and PCR on adjusted $D_{\text{eff}}$ for a max. deflection (before milling) of 0.5 mils.

Figure 158. Plot showing the effect of milling depth and PCR on adjusted $D_{\text{eff}}$ for a max. deflection (before milling) of 1.82 mils.
CHAPTER 21. SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Summary

A comprehensive literature review was performed to identify the state of the practice for incorporating the effect of milling into the design of HMA overlays of flexible and composite pavements. Although some agency design manuals specify the replacement depth for every inch of milled pavement, the basis for these recommendations is not documented thoroughly. Most current practice appears to be policy based and empirical. Very few studies have addressed the topic rigorously and even those that have addressed it have done so within the context of their specific procedures which cannot be extrapolated into general practice. A review of current practice to determine structural coefficients for superior paving materials (e.g., Superpave, PMA, and SMA) revealed that the layer coefficients are determined primarily as a function of mixture characteristics such as angularity, percent crushed faces, and laboratory determined modulus.

A review of ODOT’s HMA overlay design procedure identified areas requiring further investigation and improvements. Two levels of recommendations—one for medium- to long-term implementation consideration and the other for immediate implementation—were developed based on the research findings. For the medium- to long-term, it is recommended that ODOT consider using a deflection response measurement system such as the FWD which can more accurately characterize the subgrade modulus and other pavement properties in conjunction with a procedure such as the 1993 AASHTO Guide or AASHTO’s interim mechanistic-empirical pavement design guide (MEPDG) developed under NCHRP projects 1-37A (Hallin et al., 2004) and 1-40D (Darter et al., 2006). In the short-term, ODOT can implement the modified overlay design procedure developed under this study. However, since this procedure is empirical, it needs to be applied within the inference space of the models developed. Further, it needs to be verified by performing side-by-side overlay designs using this method and the current version of DOITOVER program and comparing the outputs.

A framework was developed to quantify the impact of milling and replacement on key structural response and material parameters that affect pavement overlay design. The structural response parameters of interest to this study were surface deflections, SPR, and SN_eff (for flexible pavements) and Deff (for composite pavements) measured directly or computed from deflection data before milling, after milling, and after HMA overlay placement. Material properties such as backcalculated Ep, Mr (for flexible pavements), and k-value (for rigid pavements), used in ODOT’s overlay design process, were not used to quantify pavement structural capacity since they were found not to be consistent as the rehabilitation progressed from pre-milling to post-milling to post-overlay stage for a given project.

A project database containing the following information was developed:

- As-built plans.
- Future traffic information.
- Pavement condition rating and visual condition logs.
- Deflection data before and after milling and after overlay.
- Coring.
These data were available for 17 projects representing overlays typically constructed by ODOT. The database played a central role in guiding the design modifications under this study. A summary of the results of detailed structural analysis performed is presented in the following sections.

Data Adequacy

As noted previously, a total of 17 individual projects (8 HMA overlaid flexible pavements and 9 HMA overlaid composite pavements) were evaluated. On these projects, mill depths ranged from 1.5- to 4-in and HMA overlay thicknesses ranged from 1.3- to 8.5-in. The depths of milling and HMA overlay thickness indicate that the selected projects were subjected to typical ODOT minor rehabilitation only. Therefore the findings and conclusions presented are limited in nature and apply only to existing ODOT flexible or composite pavement subjected to minor rehabilitation.

Existing Pavement Condition

All the projects evaluated were generally in fair to poor condition (PCR ranging from 55 to 75). Also, an examination of cores extracted as part of this study indicated that the underlying pavement material (HMA or PCC) were generally in fair to good condition with no obvious signs of moisture damage.

Characterizing Pavement Structural Capacity for HMA Overlay Design

- Raw-deflection based indices, e.g., maximum surface deflection, $S_1$, (after appropriate temperature adjustments), spreadability index $SPR$, and AREA, followed expected trends as the rehabilitation proceeded from pre-milling, to post-overlay for both flexible and composite systems that were being rehabilitated.
- From a procedural and software standpoint, the current ODOT temperature corrections, backcalculation process for in situ layer characterization, and HMA overlay thickness calculation procedure appear to be working as intended. No major deficiencies were identified.
- The low magnitude of the last sensor deflections ($S_5$) from the Dynaflect cause the subgrade resilient modulus, $M_r$, to be unstable (see chapter 18 for additional discussion). $M_r$ is a key input to the HMA overlay thickness determination process of existing flexible pavements. The instability of the $M_r$ was attributable to the fact that the magnitude of $S_5$ deflections observed in this study were low (a result of the lower magnitude of loading imparted to the pavement by the Dynaflect as well as the relatively thick structures evaluated in this study) and are in a range where the $M_r$-$S_5$ relationship is very sensitive to this input. The $S_5$ deflection is, on average, approximately 10 times lower than the last sensor deflection ($w_7$) from te FWD.
- Because $E_p$ and ultimately $SN_{eff}$, are dependent on $M_r$ in the current ODOT HMA overlay design process for existing flexible pavements, an unstable $M_r$ causes a corresponding instability in the computation of these parameters as well.
- Estimates of $M_r$ from the FWD were less variable and more consistent (see chapter 18 for details) Thus, $E_p$ and $SN_{eff}$ calculated using the FWD computed $M_r$ in conjunction with the AASHTOWare DARWin program appeared to be more reasonable and consistent.
Similar to the observations found on flexible pavement projects, even for composite pavement projects, the backcalculated $E_p$ and k-value parameters from ODOT’s overlay design software were not found to be consistent from one rehabilitation stage to another. This was attributable to the fact that the AREA parameter—a key deflection based index in the overlay design process for composite pavements—was unstable due to the low magnitudes of the fourth and fifth sensor deflections from the Dynaflect.

**Effectiveness of Current ODOT Procedure for Characterizing After Milling Pavement Structural Capacity**

The current ODOT procedure for estimating after milling $SN_{eff}$ and $D_{eff}$ were found to be inadequate. In general, the before milling $SN_{eff}$ was 17.4 percent higher when compared to the after milling $SN_{eff}$ for flexible pavements and the before milling $D_{eff}$ was 13.1 percent higher than the after milling $D_{eff}$ for composite pavements. The differences could be mainly attributed to two main factors—condition of existing pavement prior to rehabilitation and to the fraction of the milling HMA thickness when compared to the original thickness. A definite need was therefore identified to correct the pre-milling $SN_{eff}$ and $D_{eff}$ to reflect these factors. Additionally, the current estimates of $SN_{eff}$ and $D_{eff}$ in the ODOT HMA overlay design process are based on the backcalculated effective pavement elastic modulus $E_p$ which was noted in the previous section to be an unstable parameter. Therefore, the reliance of these estimates on $E_p$ also needs to be removed until such a time that this parameter can be reliably estimated through a better deflection testing process.

**Adequacy of Current ODOT Layer Structural Coefficients used for New “Superior” HMA Materials**

For routine policy based mill and fill, replacing existing HMA with new “superior” materials did not appear to change pavement structural capacity significantly. This may be due to many factors including the fact that the project evaluated in this study had substantially thick pavement structures and therefore replacing a relatively small portion of the HMA did not significantly impact structural capacity. Therefore, there was insufficient data available to recommend changes to the current ODOT procedure in this regard.

**Conclusions**

The following conclusions were drawn from the work performed under this project:

- The project database appears to be adequate for developing guidance on the impact of milling and replacement on ODOT’s flexible and composite pavement overlay design process for typical ODOT policy based minor rehabilitation overlays.
- Deflection testing of today’s ODOT pavement structures (which have gradually evolved to be multilayer pavements of substantial structural thickness) using the Dynaflect results in low magnitude surface deflections which causes instability in the backcalculated pavement subgrade moduli ($M_r$) and effective pavement moduli ($E_p$) which are key inputs in the overlay thickness design process.
The current ODOT model used to compute $M_r$ is very sensitive to the range of $S_5$ values produced by Dynaflect for typical ODOT pavements (see chapter 18). Therefore, there may be the need to apply higher loading during deflection testing to yield more reasonable $M_r$ values. The higher loading can be obtained from deflection testing devices such as the FWD. Another approach is to recalibrate the existing $M_r$–$S_5$ relationship based on the Dynaflect $S_5$ deflections to actual lab tested subgrade soil $M_r$.

Based on a review of the changes in the deflection indices, it appears that the ODOT procedure will need to be modified to accommodate the impact of milling, particularly for the more substantial milling depths. Two strategies are recommended:

- **Short-term strategy**—Adopt correction factors derived in this research to (1) account for milling in estimating the $S_{neff}$ and $D_{eff}$ computations for flexible and composite pavements, respectively after suitable verification that this process work effectively and (2) adjust subgrade $M_r$ estimated from the Dynaflect to a laboratory $M_r$ to more accurately quantify $S_{neff}$.
- **Long-term strategy**—Adopt a deflection measurement system such as the FWD that will provide more reasonable backcalculated quantities of $M_r$ and use it in conjunction with existing design tools that have integrated.

There was insufficient data for characterizing the layer coefficients of new “superior” HMA materials.

**Recommendations for Future Work and Additional Data Needs**

The following actions are recommended for further consideration:

- **Coring and examination of cores**:
  - Coring at least every 500-ft to ascertain pavement structure and layer thicknesses is recommended during structural evaluation where project plans do not.
  - The cores should also be examined for moisture damage and debonding.
- **Visual examination**:
  - A more detailed visual distress survey prior to minor rehabilitation is warranted to determine existing pavement condition more precisely as it is a key input for estimating after milling pavement structural capacity (see chapter 19 and 20).
- In the medium to longer term, ODOT should investigate the use of FWD for deflection testing as deflections obtained from FWD will characterize pavement subgrade strength more accurately and reliably.
- The FWD can be used in the current ODOT DOITOVER framework with suitable modifications or with AASHTOWARE DARWin or the newly developed Mechanistic-Empirical Pavement Design Guide.
- In the short term ODOT can improve on current procedure for characterizing after milling pavement structural capacity by implementing the changes presented in this report into the current ODOT HMA overlay design procedure (DOITOVER) after careful verification. The main changes to current ODOT HMA overlay design procedure will be in section 6.2 (Steps 1, 5, and 6) and section 6.3 (steps 1 and 5) of the ODOT HMA Overlay Design Procedure for flexible and composite pavement, respectively. Note that these changes are based on the projects evaluated under this study.
REFERENCES


ODOT. Pavement Design and Rehabilitation Manual. Ohio Department of Transportation, Columbus, Ohio, January 1999.

APPENDIX A—REVISED ODOT OVERLAY DESIGN PROCEDURE

Overlays are used to remedy functional or structural deficiencies of existing pavements. It is important that the designer consider the type of deterioration present in determining whether the pavement has a functional or structural deficiency, so that an appropriate overlay type and design can be developed.

Functional deficiency arises from any conditions that adversely affect the highway user. These include poor surface friction and texture, hydroplaning and splash from wheel path rutting, and excess surface distortions. It is important to understand that functional deficiencies can accelerate a structural deficiency.

Structural deficiency arises from any conditions that adversely affect the load-carrying capability of the pavement structure. These include inadequate thickness as well as cracking, distortion, and disintegration. It should be noted that several types of distress (e.g., distresses caused by poor construction techniques, low-temperature cracking) are not initially caused by traffic loads but do become more severe under traffic to the point that they also detract from the load-carrying capability of the pavement.

Maintenance overlays and surface treatments are sometimes placed as preventive measures to slow the rate of deterioration of pavements. This type of treatment includes thin AC overlays and various surface treatments which help keep out moisture.

The following abbreviations for pavement and overlay types are used in this chapter:

- AC: Asphalt concrete
- PCC: Portland cement concrete
- JPCP: Jointed plain concrete pavement
- JRCP: Jointed reinforced concrete pavement
- CRCP: Continuously reinforced concrete pavement
- AC/PCC: AC-overlaid Portland cement concrete (JPCP, JRCP, or CRCP)
6.1 IMPORTANT CONSIDERATIONS IN OVERLAY DESIGN

6.1.1 Analysis Section Delineation

The first step in the overlay design process is the delineation of basic analysis sections. The objective is to determine boundaries along the project length that subdivide the rehabilitation project into statistically homogeneous pavement sections possessing uniform pavement cross sections, subgrade support, construction histories, and pavement condition. If more than one pavement section is identified, the analysis should be done separately. Once an analysis is done for all pavement sections within a project, practical construction and cost considerations must be used to decide whether separate overlay designs should be developed for each analysis section or which sections should be combined.

In determining pavement sections, there are two cases that may be encountered:

1. Case I - Accurate Historic Data Unavailable - If a review of historic data discloses little useful information, an NDT study should be conducted, first, along with a visual distress survey. Deflection testing should be done in the outer wheel path of the lane adjacent to the outer shoulder for multi-lane facilities. For two-lane highways, testing in the outer wheel path in one direction is normally sufficient unless there are obvious differences in conditions in each section. If that is the case, then a similar test pattern should be conducted in each direction. When prior information concerning section boundaries is unavailable, the testing should be conducted with deflections taken at equal intervals of 300 to 500 feet. This pavement response data should be analyzed (plotted on a profile or statistically) to delineate the boundaries of the sections. The engineer should then make an evaluation regarding the practicality of these section lengths for constructability and cost-effectiveness. A general guideline for a minimum section length is 0.5 mile.

The analysis sections determined through the combined use of NDT and engineering judgment are then used as the basis for conducting any destructive tests (coring) necessary to determine pavement layer material and subgrade type and thickness. In turn, this information is then used to verify and/or modify the previously established sections.

2. Case II - Accurate Historic Data Available - When accurate historic traffic, construction, and design information regarding a specific pavement is available, the engineer has a relatively good idea as to section boundaries prior to any field testing. In this case, NDTs are
conducted at 10 to 15 test points randomly selected in each section to verify and modify (if needed) the preliminary sections selected. If necessary, a destructive sampling plan can be developed to further examine the appropriateness of the selected analysis sections.

6.1.2 Pre-overlay Repair

Deterioration in the existing pavement includes visible distress as well as damage which is not visible at the surface but which may be detected by other means. How much of this distress should be repaired before an overlay is placed? The amount of pre-overlay repair needed is related to the type of overlay selected. If distress in the existing pavement is likely to affect the performance of the overlay within a few years, it should be repaired prior to placement of the overlay. Much of the deterioration that occurs in overlays results from deterioration that was not repaired in the existing pavements. The designer should also consider the cost tradeoffs of pre-overlay repair and overlay type. If the existing pavement is severely deteriorated, selecting an overlay type which is less sensitive to existing pavement condition may be more cost-effective than doing extensive pre-overlay repair.

The cause of rutting in an existing AC pavement must be determined before an AC overlay is designed. An overlay may not be appropriate if severe rutting is occurring due to instability in any of the existing pavement layers. Milling can be used to remove the rutted surface and any underlying rutted asphalt layers.

The removal of a portion of an existing AC surface frequently improves the performance of an AC overlay due to the removal of cracked and hardened AC material. Significant rutting or other major distortion of any layer should be removed by milling before another overlay is placed; otherwise, it may contribute significantly to rutting of the overlay.

Recycling a portion of an existing AC layer may be considered as an option in the design of an overlay. This has become a very common practice. Complete recycling of the AC layer may also be done (sometimes in conjunction with the removal of a deteriorated base course).

Full-depth repairs and slab replacements in JPCP and JRCP should be PCC, doweled or tied to provide load transfer across repair joints. Full-depth repairs in CRCP should be PCC and should be continuously reinforced with steel which is tied or welded to reinforcing steel in the existing slab to provide load transfer across joints and slab continuity. Full-depth AC repairs should not
be used in CRCP prior to placement of an AC overlay, and any existing AC patches in CRCP should be removed and replaced with continuously reinforced PCC.

6.1.3 Reflection Crack Control

Reflection cracks are a frequent cause of overlay deterioration. The thickness design procedures in this chapter do not consider reflection cracking. Additional steps must be taken to reduce the occurrence and severity of reflection cracking. Some overlays are less susceptible to reflection cracking than others because of their materials and design. Similarly, some reflection crack control measures are more effective with some pavement and overlay types than with others.

Reflection crack control measures which have been beneficial in some cases include the following:

(1) Sawing and sealing joints in the AC overlay at locations coinciding with joints in the underlying AC may be effective in controlling the deterioration of reflection cracks. This technique has been very effective when applied to AC overlays of jointed PCC pavements when the saw cut matches the joint or straight crack within an inch.

(2) Increased AC overlay thickness reduces bending and vertical shear under loads and also reduces temperature variation in the existing pavement. Thus, thicker AC overlays are more effective in delaying the occurrence and deterioration of reflection cracks than are thinner overlays. However, increasing the AC overlay thickness is a costly approach to reflection crack control.

Reflection cracking can have a considerable (often controlling) influence on the life of an AC overlay. Deteriorated reflection cracks detract from a pavement's serviceability and also require frequent maintenance, such as sealing and patching. Reflection cracks also permit water to enter the pavement structure, which may result in loss of bond between the AC overlay and existing AC surface, stripping in either layer, and softening of the granular layers and subgrade. For this reason, reflection cracks should be sealed as soon as they appear and resealed periodically throughout the life of the overlay. Sealing low severity reflection cracks may also be effective in retarding their progression to medium and high severity levels.
6.1.4 Traffic Loading

The overlay design procedures require the 18-kip equivalent single-axle loads (ESALs) expected over the design life of the overlay in the design lane. The estimated ESALs must be calculated using the appropriate flexible pavement or rigid pavement equivalency factors. The appropriate type of equivalency factors for each overlay type and existing pavement type are given in the following table.

<table>
<thead>
<tr>
<th>Existing Pavement</th>
<th>Overlay Type</th>
<th>Factors to Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible</td>
<td>AC</td>
<td>Flexible</td>
</tr>
<tr>
<td>JPCP/JRCP/CRCP</td>
<td>AC or PCC</td>
<td>Rigid</td>
</tr>
<tr>
<td>Flexible</td>
<td>PCC</td>
<td>Rigid</td>
</tr>
<tr>
<td>Composite(AC/PCC)</td>
<td>AC or PCC</td>
<td>Rigid</td>
</tr>
</tbody>
</table>

An approximate correlation exists between ESALs computed using flexible pavement and rigid pavement equivalency factors. Converting from rigid pavement ESALs to flexible pavement ESALs requires multiplying the rigid pavement ESALs by 0.67. For example, 15 million rigid pavement ESALs equal 10 million flexible pavement ESALs. Five million flexible pavement ESALs equal 7.5 million rigid pavement ESALs. Failure to utilize the correct type of ESALs will result in significant errors in the overlay designs. Conversions must be made, for example, when designing an AC overlay of a flexible pavement (flexible ESALs required) and when designing an alternative PCC overlay of the same flexible pavement (rigid ESALs required). Throughout this section, ESALs are designated as rigid ESALs or flexible ESALs as appropriate.

The type of ESALs used in the overlay design depends on the pavement performance model (flexible or rigid) being used. In the overlay design procedures presented in this section, the flexible pavement model is used in designing AC overlays of AC. The rigid pavement model is used in designing AC and PCC overlays of PCC and ACC/PCC pavements.

6.1.5 Subdrainage

The subdrainage condition of an existing pavement has a great influence on how well the overlay performs. A subdrainage evaluation of the existing pavement should be conducted. Improving poor subdrainage conditions will have a beneficial effect on the performance of an overlay.
Removal of excess water from the pavement structure will reduce erosion and increase the strength of the base and subgrade, which in turn will reduce deflections. In addition, stripping in AC pavement and “D” cracking in PCC pavement may be slowed by improved subdrainage.

Installation of edge drains, maintenance of existing edge drains, or other subdrainage improvement should be done prior to placement of the overlay if a subdrainage evaluation indicates a need for such an improvement.

6.1.6 Structural versus Functional Overlays

The overlay design procedures in this section provide an overlay thickness to correct a structural deficiency. If no structural deficiency exists, an overlay thickness less than or equal to zero will be obtained. This does not mean, however, that the pavement does not need an overlay to correct a functional deficiency. If the deficiency is primarily functional, then the overlay thickness should be only that which is needed to remedy the functional problem. If the pavement has a structural deficiency as well, a structural overlay thickness which is adequate to carry future traffic over the design period is needed.

6.1.7 Pavement Widening

Many AC overlays are placed over PCC pavements in conjunction with pavement widening (either adding lanes or adding width to a narrow lane). Widening requires coordination between the design of the widened pavement section and the overlay, not only so that the surface will be functionally adequate, but also so that both the existing and widening sections will be structurally adequate. Many lane widening projects have developed serious deterioration along the longitudinal joint due to improper design. The key design recommendations are as follows:

Rehabilitation with Overlays

1. The design "lives" of both the overlay and the new widening construction should be the same to avoid the need for future rehabilitation at significantly different ages.
2. The widened cross section should generally closely match the existing pavement or cross section in material type, thickness, reinforcement, and joint spacing. However, a shorter joint spacing may be used.
3. A widened PCC slab section must be tied with deformed bars to the existing PCC slab face. The tie bars should be securely anchored and consistent with ties used in new
pavement construction (e.g., No. 5 bars, 30 inches long, grouted and spaced no more than 30 inches apart).

(4) A reflection crack relief fabric may be placed along the longitudinal widening joint.

(5) The overlay should always be the same thickness over the widening section as over the rest of the traffic lane.

(6) Longitudinal subdrainage should be placed if needed.

6.2 Thickness Design for AC Overlay on AC Pavements

If the overlay is being placed for some functional purpose such as roughness or friction, a minimum thickness overlay that solves the functional problem should be placed. If the overlay is being placed for the purpose of structural improvement, the required thickness of the overlay is a function of the structural capacity required to meet future traffic demands and the structural capacity of the existing pavement. The required thickness to increase structural capacity to carry future traffic is determined by the following equation.

\[ SN_{ol} = a_{ol} \cdot D_{ol} = SN_{req} - SN_{eff} \]

where

- \( SN_{ol} \) = Required overlay structural number
- \( a_{ol} \) = Structural coefficient for the AC overlay
- \( D_{ol} \) = Required overlay thickness, inches
- \( SN_{req} \) = Structural number required to carry future traffic
- \( SN_{eff} \) = Effective structural number of the existing pavement

The required overlay thickness may be determined through the following design steps.

**Step 1: Existing pavement design and construction**

(1) Thickness and material type of each pavement layer.
(2) Available subgrade soil information (from construction records, soil surveys, county agricultural soils reports, etc.)
(3) Coring at 500-ft intervals to confirm information derived from steps 1 and 2 and to assess material condition (e.g., stripping, debonding, etc.)
(4) Visual condition surveys to roughly quantify various types of cracking, e.g., alligator, longitudinal, thermal, etc.
Step 2: Traffic analysis

Predicted future 18-kip ESALs in the design lane over the design period (W_{18}).

Step 3: Deflection testing

Measure deflections in the outer wheel path at an interval sufficient to adequately assess conditions. Intervals of 100 to 500 ft is recommended. Areas that are deteriorated and will be repaired should not be tested.

Step 4: Adjustment of \(w_1\) to Standard Temperature

The stiffness of asphalt concrete varies with temperature. The temperature of the AC mix during deflection testing must be determined so that the collected deflections and back calculated modulus can be adjusted to those corresponding to a standard temperature, 68 °F. Typically, only temperature of the surface layer changes significantly with ambient temperature. The base and subbase courses are much less susceptible to temperature variation due to their location in the pavement structure and due to the lower asphalt content in these courses. Therefore, temperature adjustment is performed based on the thickness and temperature of the surface asphalt concrete layer only. The deflection \(w_5\), which is the farthest measured deflection from test loads, reflects mostly the reaction of subgrade and is not susceptible to the change of mechanical properties of upper layers. As a result, no temperature adjustment is performed for \(w_5\).

1. Determine the Average Temperature of Surface AC Layer

   Obviously, the most direct way to determine the temperature of the asphalt layer during an NDT deflection test is to physically measure the temperature. However, it must be recognized that fairly high temperature gradients may exist with depth into the asphalt layer. Therefore, the measure of the only the pavement surface temperature will not suffice as an accurate measure of the average temperature of the entire layer. The thicker the asphalt layer the greater the need to evaluate the temperature for the entire layer rather than simply relying on surface temperature measurements.

   An alternative procedure that may be used to estimate the average pavement temperature during an NDT test has been developed by Kentucky. This procedure requires: (1) pavement surface temperature during the NDT test, and (2) average air temperature data at
the site for 5 previous days before the NDT test. Knowing this information, Figure 6.1 can be used to estimate the pavement temperature at various depths within the total asphalt layer thickness. The temperature parameter used in Figure 6.1 is the sum of the measured pavement surface temperature plus the average air temperature for the last 5 previous days.

The mean temperature of the AC layer is calculated by:

\[ T_{\text{mean}} = \frac{T_1 + T_2 + T_3}{3} \]

where

- \( T_{\text{mean}} \) = mean temperature of AC layer
- \( T_1 \) = temperature at 1 inch depth of AC layer
- \( T_2 \) = temperature at mid depth of AC layer
- \( T_3 \) = temperature at the bottom of AC layer

(2) Temperature Adjustment Factor, \( A_j \)

The temperature adjustment factor is determined using the curve in Figure 6.2. This is the curve recommended by the 1993 AASHTO Guide for asphalt concrete pavement with granular or asphalt-treated base.

(3) The Adjusted \( w_1 \)

The deflection \( w_1 \) is adjusted by the following equation:

\[ w_{1a} = A_j w_1 \]

**Step 5: Estimation of Backcalculated Subgrade \( M_R \)**

The equation below is employed to determine the backcalculated resilient modulus of subgrade, \( M_R \).

\[ M_R = \frac{0.24P}{d_r \ast r} \]
where \( P \) = applied load, pounds
\[ P = 1000, \text{ lbs} \]
\( dr \) = deflection at distance \( r \) from the applied load, inch
\( r \) = radial distance from load, inches

**Step 6: Determine Effective Structural Number of Existing Pavement, SNeff**

For all AC overlays on AC pavements where pre-overlay repairs do not involve milling portions of the existing AC layer, effective structural number of the existing pavement, SNeff, is determined using the deflection, \( w_{1a} \), and the equation below (see figure 6.2*):

\[
SN_{eff} = 2.3418 \left( \frac{w_{a}}{w_{1a}} \right)^{-0.733}
\]

where, \( w_{1a} \) = temperature adjusted deflection \( w_1 \) (see step 4).

The deflection \( w_{1a} \), which is the nearest measured deflection from test loads, reflects the overall pavement structural capacity. It varies with pavement layers material condition, strength, and thickness. Milling portions of the existing AC layer as part of pre-overlay repairs could affect \( w_{1a} \). Therefore, for all AC overlays on AC pavements where pre-overlay repairs does involve milling portions of the existing AC layer, SNeff of the milled pavement, is determined using the condition and thickness adjusted deflection, \( w_{1a,R} \), which is estimated as follows:

\[
w_{1a,R} = \left( 2.6322PCTMILL + \frac{76.1152}{PCR} \right) * w_{1a}^{0.8891}
\]

where,
- \( w_{1a,R} \) = adjusted \( w_{1a} \)
- \( PCTMILL \) = \( \frac{BMTHK - AMTHK}{BMTHK} \) * 100
- \( BMTHK \) = before mill pavement thickness
- \( AMTHK \) = after mill pavement thickness
- \( PCR \) = before rehabilitation pavement condition rating
- \( w_{1a} \) = temperature adjusted deflection, \( w_1 \) (see Step 4)
Figure 6.1 Predicted pavement temperature

Figure 6.2*. Effective structural number versus temperature adjusted or temperature, pavement condition, and thickness adjusted deflection.
**Step 7 Determine Required Structural Number, SN_{req}**

The objective of this step is to determine the total structural number (i.e., structural capacity) of a new pavement required to carry the anticipated traffic loading during the overlay design period. The AASHTO design equation for flexible pavement is used.

The AASHTO design equation for flexible pavements is an empirical procedure derived from the 1958-60 AASHTO Road Test data. The basic design equation gives the relationship between a pavement structural requirement (structural number, SN) and the number of 18-kip equivalent single axle loads (ESAL) that the pavement can carry before a selected terminal serviceability value is reached.

The pavement structural requirement is defined by the structural number as follows:

\[ SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \]

where

- \( SN \) = pavement structural number, a number (weighted thickness) representing the required strength of the entire pavement structure;
- \( a_1, a_2, a_3 \) = layer coefficients that represent the quality of the surface, base, and subbase layers, respectively;
- \( D_1, D_2, D_3 \) = the thicknesses, in inches, of the surface, base, and subbase layers, respectively; and
- \( m_2, m_3 \) = drainage coefficients representing the drainage characteristics of the base and subbase layers, respectively.
Figure 6.2. Temperature Adjustment Factor
(From 1986 AASHTO Guide for Design of Pavement Structures)
Figure 6.3 AASHTO  Design chart for flexible pavements based on using mean values for each input. (AASHTO 1993)
The nomograph in Figure 6.3 illustrates the steps. The following inputs are required:

1. Reliability level (R).
2. Overall standard deviation (So).
3. Future (projected) 18-kip ESAL applications for the overlay design period (W_{18}).
4. Effective resilient modulus of the roadbed soil (M_R).
5. Design serviceability loss over the overlay design period (ΔPSI).

The overall standard deviation term, s_o, includes two parts of variation: the variation of traffic and the variation of pavement. According to the 1993 AASHTO Guide, the traffic portion of s_o is estimated to be about 0.1, and the pavement portion is about 0.25 for rigid pavement and 0.35 for flexible pavement. Therefore, the total standard deviation is 0.35 for rigid pavement and 0.45 for flexible pavement, respectively.

In the ODOT procedure, the back calculation and thickness design is performed for each and every measured deflection basin. The final design overlay thickness is determined based on the desired reliability level and the mean and standard deviation of required overlay thickness at each point. The pavement variations, due to materials, environment, and construction, is included within the procedure. Therefore, in using the AASHTO equation to determine the required thickness, only that portion of standard deviation related to traffic variation, i.e., 0.1, is used.

The back calculated resilient modulus for subgrade must be modified before being used in the AASHTO design equation. According to research conducted by AASHTO, the back calculated subgrade resilient moduli are usually much higher than the field core test results. To be consistent with the laboratory-measured value used for the AASHO Road Test soil in the development of the flexible pavement design equation, a correction factor of C = 0.225 is recommended. Therefore, the following design M_R should be used in determination of SN_{req}:

\[
Design \ M_R = 0.225 \ M_R
\]

**Step 8: Determine Required Overlay Thickness, D_{over}**

The required overlay structural number is the difference of required structural number, SN_{req}, and effective structural number of existing pavement, SN_{eff}:
The required overlay thickness is determined as follows:

\[ D_{\text{over}} = \frac{SN_{\text{req}} - SN_{\text{eff}}}{a_{\text{ol}}} \]

where \( a_{\text{ol}} \) is the structural coefficient for the AC overlay.

The 1993 AASHTO Design Guide suggest a structural coefficient of 0.44 for new overlay AC material. Thus, an \( a_{\text{ol}} \) coefficient of 0.44 is used in the computer program. However, the current ODOT Location and Design Manual assumes a structural coefficient of 0.35 for all asphalt concrete materials (404, 402, 301, 448, 446). A smaller \( a_{\text{ol}} \) value yields more conservative result, i.e., thicker AC overlay. The selection of structural coefficient may be modified as ODOT conducts further research.

**Step 9: Find Design Overlay Thickness Using Statistical Calculation**

The above steps 4 through 8 are carried out for each and every location within the design section where deflection measurements were made. The statistical mean and standard deviation of the required overlay thickness are then calculated. The design overlay thickness is determined by:

\[ H_{\overline{\text{over}}} = \overline{D_{\text{over}}} + Z_R s_{\text{over}} \]

where \( H_{\overline{\text{over}}} \) = design overlay thickness  
\( \overline{D_{\text{over}}} \) = mean value of \( D_{\text{over}} \) within the design segment  
\( s_{\text{over}} \) = standard deviation of \( D_{\text{over}} \) within the design segment  
\( Z_R \) = reliability term, based on the chosen reliability level \( R \)

### 6.3 Thickness Design for AC Overlay on Rigid or Composite Pavements

The ODOT procedure for designing AC overlay on rigid and composite pavements is presented here. In this procedure, rigid pavement is considered as a special case of composite pavement with the asphalt concrete surface layer thickness, \( h_{ac} \), equals zero. In most composite pavements, their structural behaviors are dominated by the underlying concrete slabs, unless the slabs were
broken-and-seated before overlay. Therefore, for most situations, it is reasonable to use the AASHTO rigid pavement design equation to determine the required pavement thickness. Currently, no unique design equation is available for composite pavements.

The back calculation and overlay design process is carried out for each measured Dynaflect data point. The final design overlay thickness is then determined based on the desired reliability level and mean and standard deviation of the required overlay thickness.

If the overlay is being placed for some functional purpose such as roughness or friction, a minimum thickness overlay that solves the functional problem should be placed. If the overlay is being placed for the purpose of structural improvement, the required thickness of the overlay is a function of the structural capacity required to meet future traffic demands and the structural capacity of the existing pavement. The required overlay thickness to increase structural capacity to carry future traffic is determined by the following equation.

\[ D_{ol} = A(D_{req} - D_{eff}) \]

where

- \( D_{ol} \) = Required thickness of AC overlay, inches
- \( A \) = Factor to convert PCC thickness deficiency to AC overlay thickness
- \( D_{req} \) = Slab thickness to carry future traffic, inches
- \( D_{eff} \) = Effective equivalent PCC slab thickness of existing pavement, inches

The A factor, which is a function of the PCC thickness deficiency, is given by the following equation:

\[ A = 2.2233 + 0.0099(D_{req} - D_{eff})^2 + 0.1534(D_{req} - D_{eff}) \]

AC overlays of conventional JPCP, JRCP, and CRCP have been constructed as thin as 2 inches and as thick as 10 inches. The most typical thicknesses that have been constructed for highways are 3 to 6 inches. The required overlay thickness may be determined through the following design steps.
Step 1: Existing Pavement design.

1. Existing AC surface thickness
2. Existing PCC slab thickness
3. Type of load transfer (mechanical devices, aggregate interlock, CRCP)
4. Type of shoulder (tied PCC, other)
5. Coring at 500-ft intervals to confirm information derived from steps 1 and 2 and to assess material condition (e.g., stripping, debonding, etc.).
6. Visual condition surveys to roughly quantify various types of cracking, e.g., alligator, longitudinal, thermal, etc.

Step 2: Traffic analysis.

Predicted future 18-kip ESALs in the design lane over the design period. Use ESALs computed from rigid pavement load equivalency factors

Step 3: Deflection testing

Measure slab deflection basins along the project at an interval sufficient to adequately assess conditions. Intervals of 100 to 1,000 feet are typical. Measure deflections in the outer wheel path.

Step 4: Back calculation of k of subgrade

Based on measured Dynaflect deflection data, back calculate the modulus of subgrade reaction, k. The back calculation procedure for rigid/composite pavements described in section 5 is used. This back calculation is performed for each and every deflection basin collected.

Step 5: Determine effective thickness of existing pavement

For all AC overlays on composite pavements where pre-overlay repairs does not involve milling portions of the existing AC layer, effective thickness of the existing pavement, \( D_{\text{eff}} \), is determined using the deflection, \( w_1 \), and the equation below (see figure 6.4*):

\[
D_{\text{eff}} = 4.5931 w_1^{-0.5821}
\]
where \( w_1 \) = maximum deflection (no temperature corrections).

Figure 6.4*. Effective thickness versus temperature adjusted or temperature, pavement condition, & thickness deflection.

The deflection \( w_1 \), which is the nearest measured deflection from test loads, reflects overall pavement structural capacity. It varies with pavement layers material condition, strength, and thickness. Milling portions of the existing AC layer as part of pre-overlay repairs could affect \( w_1 \).

Therefore, for all AC overlays on composite pavements where pre-overlay repairs does involve milling portions of the existing AC layer, \( D_{\text{eff}} \) of the milled pavement, is determined using the condition and thickness adjusted deflection, \( w_{1,R} \), which is estimated as follows:

\[
W_{1,R} = \left( 3.3512PCTMILL + \frac{52.902}{PCR} \right) * W_{1,BM}^{0.9331}
\]

where,

- \( w_{1,R} \) = estimate of after milling maximum deflection
- \( PCTMILL \) = percent of existing HMA layer milled off
  \[ = \left( \frac{BMTHK - AMTHK}{BMTHK} \right) * 100 \]
- \( BMTHK \) = before mill pavement thickness
Step 6: Determine required new pavement thickness, $D_{req}$

The new PCC slab thickness required to carry future design traffic is determined by using the 1993 AASHTO rigid pavement design equation.

The following inputs are required:

1. Reliability level ($R$).
2. Overall standard deviation ($S_0$).
3. Future (projected) 18-kip ESAL applications for the overlay design period ($W_{18}$).
4. Effective modulus of subgrade reaction ($k$).
5. Design serviceability loss over the overlay design period ($\Delta PSI$).
6. Concrete elastic modulus, $E_c$.
7. Concrete modulus of rupture, $S'_c$.
8. Load transfer coefficient, $J$.
9. Drainage coefficient, $C_d$.

The reliability term, $Z_R$, in the 1993 AASHTO equation can be considered to represent how conservative the calculated results will be. The reliability level $R$, as defined in percentage, represents the probability that the designed thickness exceeds the actual required thickness. The higher the reliability, the more conservative the result will be. Value of reliability may be determined based on classification of the route.

The overall standard deviation term, $S_0$, includes two parts of variation: the variation of traffic and the variation of pavement. According to the 1993 AASHTO Guide, the traffic portion of $S_0$ is estimated to be about 0.1, and the pavement portion is about 0.25 for rigid pavement and 0.35 for flexible pavement. Therefore, the total standard deviation is 0.35 for rigid pavement and 0.45 for flexible pavement, respectively.

In the ODOT procedure, the back calculation and thickness design is performed for each and every measured deflection basin. The final design overlay thickness is determined based on the desired reliability level and the mean and standard deviation of required overlay thickness at each point. The pavement variations, due to materials, environment, and construction, is

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMTHK</td>
<td>after mill pavement thickness</td>
</tr>
<tr>
<td>PCR</td>
<td>before rehabilitation pavement condition rating</td>
</tr>
<tr>
<td>$W_{1\text{BM}}$</td>
<td>estimate of existing pavement (before milling maximum deflection)</td>
</tr>
</tbody>
</table>
included within the procedure. Therefore, in using the AASHTO equation to determine the required thickness, only that portion of standard deviation related to traffic variation, i.e., 0.1, is used.

The modulus of subgrade reaction, $k$, back-calculated from NDT data is a dynamic value. The AASHTO design equation requires the static modulus of subgrade reaction as its input. According to the research results presented in the 1993 AASHTO Guide, the effective static modulus of subgrade reaction is approximately 1/2 of the effective dynamic value.

$$k_{\text{static}} = 0.5 k_{\text{calculated}}$$

For new concrete slab, the following input values may be assumed: elastic modulus of concrete, $E_c = 5 \times 10^6$ psi, modulus of rupture of concrete, $S_c' = 650$ psi, load transfer coefficient, $J = 3.2$ for JPCP and JRCP and $J = 2.6$ for CRCP, and drainage coefficient, $C_d = 1.0$.

The nomograph in Figures 6.6 illustrates the steps to obtain the design new slab thickness.

**Step 7: Determine AC overlay thickness**

The required AC overlay thickness is calculated by:

$$h_{\text{over}} = A(D_{\text{req}} - D_{\text{eff}})$$

Where $A$ is the PCC-to-AC thickness conversion factor:

$$A = 2.2233 + 0.0099(D_{\text{req}} - D_{\text{eff}})^2 - 0.1534(D_{\text{req}} - D_{\text{eff}})$$

**Step 8: Statistical calculation to determine design thickness**

Steps 4 through 7 above are carried out for each and every location within the design section where deflection measurements were made. The statistical mean and standard deviation of the required overlay thickness are then calculated. The design overlay thickness is determined by:

$$H_{\text{over}} = \bar{h}_{\text{over}} + Z_{\rho}S_{\text{over}}$$

where $H_{\text{over}} = \text{design overlay thickness}$
\[ \overline{D_{over}} = \text{mean value of } D_{over} \text{ within the design segment} \]

\[ s_{over} = \text{standard deviation of } D_{over} \text{ within the design segment} \]

\[ Z_R = \text{standard normal deviates, a number corresponding to the chosen reliability level, } R \]
Figure 6.6. AASHTO design chart for rigid pavements based on using mean values for each input variable (Segment 2).
6.4 POTENTIAL ERRORS AND POSSIBLE ADJUSTMENTS TO THE THICKNESS DESIGN PROCEDURE

The overlay thicknesses obtained using these procedures should be reasonable when the pavement has a structural deficiency. If the overlay thickness appears to be unreasonable, one or more of the following causes may be responsible.

(1) The pavement deterioration may be caused primarily by non-load-associated factors. A computed overlay thickness less than zero or close to zero suggests that the pavement does not need a structural improvement. If a functional deficiency exists, a minimum constructable overlay thickness that addresses the problem should be placed.

(2) Modifications may be needed in the overlay design inputs to customize the procedures to specific conditions. The overlay design procedures should be tested on actual projects to investigate the need for modifications.

(3) The measured deflection data should be examined to exclude any extremely high or low values corresponding very weak or strong spots. These extreme values could skew the mean and standard deviations of required overlay thickness, especially when the number of deflections measured is small. Within a “uniform” design section, the number of deflection measurements preferably should be greater than 30.

(4) The back calculation methods used in these procedures assume a two layer system for all pavement structures. This assumption may introduce sizable errors for some pavements. However, back calculation of more than two layers is still not stable enough to be employed in a design procedure.

(5) Accurate pavement layer thickness data is very important in back calculation. Actual thickness can differ from construction plan and variations within a design section may be significant. Choosing a total pavement layer thickness value to represent a multi-layer pavement structure is not an exact science. Hence, the resulting effective moduli of the pavement and subgrade are only as good as the accuracy of the inputs.

(6) The adjustment factors to obtain design subgrade resilient modulus and effective k value from back-calculated values are approximations. Different factors may be needed for different types of soils.
(7) Determination of effective pavement thickness of existing pavements is not an easy task. AASHTO Guide recommends using condition survey or remaining life approach to estimate effective pavement thickness of existing pavements. Results from these methods could be consulted if design overlay thickness from the procedure presented in this section is not reasonable.

6.5 VERIFICATION OF THE UTOVER DESIGN PROCEDURE FOR COMPOSITE/RIGID PAVEMENTS

The following steps are used to verify the UTOVER design procedure for composite/rigid pavements:

1. A hypothetical existing (old) composite pavement with known layer thicknesses, elastic moduli and subgrade reaction modulus is defined.

2. The effective elastic modulus of the composite pavement, \( E_{P1} \), is calculated using the equivalent rigidity concept described in Section 6.3, since the thickness and elastic modulus of both AC and PCC layers are known:

\[
R_{\text{eff}} = \frac{E_{\text{eff}} h^3}{12(1 - \nu^2)} = R_1 + R_2
\]

where \( h = h_{ac} + h_{pcc} \), and

\(
R_1 - R_2 = \text{rigidity of the AC and PCC layers.}
\)

\[
E_{\text{eff}} = \frac{12(1 - \nu^2)(R_1 + R_2)}{h^3}
\]

Note \( E_{P1} = E_{\text{eff}} \).

3. The predicted pavement surface deflections corresponding to the five Dynaflect sensor locations under Dynaflect loading are computed using KENSLABS, a finite element program.
(4) With the computed deflections and known layer thickness information, the effective elastic modulus of the composite pavement layer and the modulus of subgrade reaction can be back calculated and denoted as \( E_{p2} \) and \( k_2 \).

(5) By comparing the values of \( E_{p1} \) and \( E_{p2} \), the known \( k_1 \) value and the back-calculated \( k_2 \) value, accuracy of the back calculation procedure can be determined.

(6) Accuracy of the overlay thickness design procedure is determined as follows. An overlay thickness is designed for the existing pavement by assuming an arbitrary expected future ESAL value and known pavement and subgrade moduli. After adding the hypothetical overlay to the old pavement, the effective modulus and effective thickness of the overlaid pavement are computed. The effective thickness of the pavement just overlaid should be the same or very close to the thickness required to carry future ESALs.

(7) The overall procedure is verified by using the backcalculated moduli rather than assumed known moduli during design. After the hypothetical overlay is added to the old pavement, theoretical deflections at Dynaflect sensor locations can be calculated using KENSLABS. These NDT deflections are then used by UTOVER to determine the additional overlay thickness needed. Ideally, the additional overlay thickness required should be very close to zero, i.e., no additional overlay should be needed after an overlay has just been added.

These steps are illustrated in the following case study.

CASE STUDY—

Assume an existing composite pavement has the following structure:

- AC layer \( h_{AC} = 4 \text{ in.} \) \( E_{AC} = 2 \times 10^6 \text{ psi} \) \( \nu = 0.35 \)
- PCC slab \( h_{PCC} = 8 \text{ in.} \) \( E_{PCC} = 3 \times 10^6 \text{ psi} \) \( \nu = 0.15 \)
- Subgrade (infinite depth) modulus of reaction, \( k_1 = 100 \text{ psi/in.} \)

The effective elastic modulus of the total pavement thickness above subgrade can be determined as follows:

(i) Determine the distance from bottom of slab to the neutral axis, \( c \) (see Figure 6.4):
\[
c = \frac{\left( \frac{E_{ac}}{E_{pce}} \right) h_{ac} (0.5h_{ac} + h_{pce}) + 0.5h_{pce}^2}{\left( \frac{E_{ac}}{E_{pce}} \right) h_{ac} + h_{pce}}
\]

\[
= \frac{\left( \frac{2 \times 10^5}{3 \times 10^6} \right) (4)(0.5 \times 4 + 8) + 0.5(8)^2}{\left( \frac{2 \times 10^5}{3 \times 10^6} \right)(4) + (8)} = 4.1936
\]

(ii) The rigidity of the asphalt layer is:

\[
R_1 = \frac{E_{ac} \left[ \frac{h_{ac}^3}{12} + h_{ac} (0.5h_{ac} + h_{pce} - c)^2 \right]}{1 - \nu_{ac}^2}
\]

\[
= \frac{2 \times 10^5 \left[ \frac{(4)^3}{12} + 4(0.5 \times 4 + 8 - 4.1936)^2 \right]}{1 - (0.35)^2} = 3.1952 \times 10^7
\]

(iii) The rigidity of the concrete layer is:

\[
R_2 = \frac{E_{pce} \left[ \frac{h_{pce}^3}{12} + h_{pce} (c - 0.5h_{pce})^2 \right]}{1 - \nu_{pce}^2}
\]

\[
= \frac{3 \times 10^6 \left[ \frac{(8)^3}{12} + 8(4.1936 - 0.5 \times 8)^2 \right]}{1 - (0.15)^2} = 13.1867 \times 10^7
\]

The combined rigidity of the two bonded layers can be calculated by:

\[
R_t = R_1 + R_2
\]

or

\[
R_t = \frac{E_{eq}h^3}{12(1 - \nu^2)}
\]

where \( h = h_{ac} + h_{pce} \), and
\[ \nu = \frac{v_{ac} h_{ac} + v_{pcc} h_{pcc}}{h_{ac} + h_{pcc}} \]

\[ = \frac{0.35 \times 4 + 0.15 \times 8}{(4 + 8)} = 0.217 \]

Therefore, with known layer thicknesses and elastic moduli of new AC and PCC materials, the effective elastic modulus of the combined pavement layer, \( E_{\text{eff}} \), can be determined:

\[ E_{\text{eff}} = \frac{12(1 - \nu^2)(R_1 + R_2)}{h^3} \]

\[ = \frac{12[1 - (0.217)^2] (3.1952 + 13.1867) \times 10^7}{(4 + 8)^3} = 1,087,462 \text{ (psi)} \]

i.e., \( E_{P1} = 1,087,462 \text{ psi} \)

Part 1 Test of back-calculation scheme

With the finite element model shown in Figure 6.7, in which AC layer and PCC slab are modeled as two bonded layers, the calculated deflection basin is:

\[ w_1, w_2, \ldots, w_5 = 0.8708, 0.8181, 0.6996, 0.5636, 0.4351 \text{ mils} \]

Based on the above deflection basin, the elastic modulus of pavement and subgrade reaction modulus can be calculated:

\[ k_2 = 118 \text{ psi} \]

\[ E_{P2} = 991,704 \text{ psi} \]

Ideally, \( k_2 \) should be equal to \( k_1 \), and \( E_{P2} \) should be equal to \( E_{P1} \). However, the UTOVER procedure overestimates the modulus of subgrade reaction by about 18 percent but underestimates the effective elastic modulus of the pavement by about 9 percent in this case. Considering the deflection basin is computed using a finite element program while back calculation is performed based on solutions of slab-on-grade theory, such discrepancy in results is expected. This should not be a major concern, however, since the lower pavement modulus tend to compensates the higher subgrade modulus. The resulting overlay thickness is not
expected to differ much due to this back calculation error. Also, the backcalculated $k_2$ is a “dynamic” value and will be divided by 2 to obtain a “static” value for use in the AASHTO design equation.

Part 2—Test of overlay thickness design method

The old composite pavement has been found to equivalent to a 12 in. thick pavement having a effective modulus of $E_{p1} = 1,087,462$ psi.

Assuming a new composite pavement having 4 in. of AC ($E_{ac} = 4.5 \times 10^5$) on 8 in. of PCC ($E_{pcc} = 5 \times 10^6$), this pavement may be considered, based on empirical relationship, to be equivalent to a new concrete pavement (with $E_{pcc} = 5 \times 10^6$) having a thickness of:

$$D_{new} = 8 + 0.5 \times 4 = 10 \text{ in.}$$

Using the equal rigidity method, the new composite pavement can also be found to be equivalent to a 12 in. thick pavement with a effective modulus of:

$$E_{eq} = 1,927,884 \text{ psi}$$

Therefore, a 12 in. thick pavement with a modulus of 1,927,884 psi is equivalent to a 10 in. thick new concrete slab. The question is: how many inches of concrete slab would a 12 in. thick pavement with a modulus of 1,087,642 psi equivalent to?

To answer the above question, the 12 in. pavement with a modulus of 1,087,462 psi is converted to a pavement having a modulus of 1,927,884 psi but a thickness of $h_{eq}$:

$$h_{eq} = \frac{12}{\left(\frac{1,927,884}{1,087,462}\right)^{1/3}} = 9.92 \text{ (inch)}$$

The effective new PCC slab thickness of the old composite pavement is calculated by:

$$D_{eff} = \frac{h_{eq}}{D_{new}}$$
i.e., \( \frac{D_{\text{eff}}}{10} = \frac{9.92}{12} \)

\[ D_{\text{eff}} = 8.27 \text{ (inch)} \]

Assume future traffic, \( \dot{W}_{18} = 30 \text{ million (30} \times 10^6) \text{ ESALs} \) and a reliability level, \( R = 95 \% \). The required concrete slab thickness to carry future traffic is calculated using the AASHTO equation with known subgrade reaction modulus (\( k = 100/2 = 50 \text{ psi} \)) and the following parameters: elastic modulus of new concrete, \( E_c = 5,000,000 \text{ psi} \), modulus of rupture of new concrete, \( S'_c = 700 \text{ psi} \), joint load transfer coefficient, \( J = 3.2 \), drainage coefficient, \( C_d = 1.0 \), \( \Delta \text{PSI} = 2.0 \), and standard deviation of 0.10 (traffic only).

\[ D_{\text{req}} = 10.82 \text{ in.} \]

The AC-to-PCC factor, \( A \), is determined by:

\[ A = 2.2233 + 0.0099 \times (D_{\text{req}} - D_{\text{eff}})^2 - 0.1534(D_{\text{req}} - D_{\text{eff}}) \]

\[ = 2.2233 + 0.0099 \times (10.82 - 8.27)^2 - 0.1534(10.82 - 8.27) \]

\[ = 1.8965 \]

The design asphalt concrete overlay thickness is:

\[ H_{\text{over}} = 1.8965 \times (10.82 - 8.27) \]

\[ = 4.84 \text{ in.} \]

Therefore, about 5.0 inches of asphalt overlay is needed.

The above design is based on the assumed known pavement and subgrade moduli. Typically, these moduli are unknown and must be backcalculated using deflection data. Some errors would be introduced due to inaccurate back calculation. Using one half of the backcalculated subgrade modulus, \( k_2 = 118/2 = 59 \text{ psi} \) as design input and keeping all the other parameters the same as before, the following results can be obtained:

\[ D_{\text{eff}} = 8.01 \text{ in. (PCC)} \]

\[ D_{\text{req}} = 10.77 \text{ in. (PCC)} \]

\[ H_{\text{over}} = 5.17 \text{ in. (AC)} \]
The back-calculated effective thickness, and hence effective thickness, is smaller than the previous results based on known moduli. However, the higher subgrade modulus leads to a smaller required pavement thickness. The net difference in design thickness is rather insignificant, only 0.17 inch of AC.

Assuming a 5.25-inch AC overlay is built on top of the existing composite pavement, the pavement structure after overlay is:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (in)</th>
<th>Modulus (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>5.25</td>
<td>450,000</td>
</tr>
<tr>
<td>Composite</td>
<td>12</td>
<td>1,089,845</td>
</tr>
<tr>
<td>Infinite Subgrade</td>
<td>k = 100</td>
<td></td>
</tr>
</tbody>
</table>

Using KENSLABS, the Dynaflect deflections on the above structure can be calculated:

\[ w_1, w_2, ..., w_5 = 0.6229, 0.5950, 0.5300, 0.4520, 0.3738 \text{ mils} \]

Using these “predicted” deflections, the back-calculated pavement and subgrade moduli and corresponding overlay thickness design results are:

\[ E_{P2} = 691,373 \text{ psi} \]
\[ k_2 = 114 \text{pci (dynamic value)} \]
\[ D_{\text{eff}} = 10.39 \text{ in.} \]
\[ D_{\text{req}} = 10.78 \text{ in.} \]
\[ H_{\text{over}} = 0.85 \text{ in. (AC)} \]

This indicates an additional 0.85 inches of AC overlay is needed on the overlaid pavement. Considering the approximations needed in modeling Dynaflect loading configuration and the fact that total thicknesses of the pavement is now 17.25 inches, this is a rather small error.

Several other cases with varying slab size, pavement thickness and moduli, future traffic volume, as well as subgrade moduli, have been studied to see the corresponding effects. Similarly good results are found. Increasing the slab size in the KENSLABS model improves the back-calculation accuracy since the slab-on-grade theory assumes the slab is infinitely large.