Development and Evaluation of Performance Tests to Enhance Superpave Mix Design and Implementation in Idaho

USDOT Assistance No. DTOS59-06-G-00029 (NIATT Project No. KLK479)
ITD Project No. RP 181 (NIATT Project No. KLK483)

Quarterly Progress Report – QR7
For the period
January 1 to March 31, 2009

Submitted to

U.S. Department of Transportation
Peter Belenky, COTR

And

Idaho Transportation Department
Ned Parrish, Research Manager
Michael J. Santi, PE, Assistant Material Engineer

UI Research Team

Dr. Fouad Bayomy, PI
Dr. S. J. Jung, Co-PI
Dr. Thomas Weaver, Co-PI
Dr. Richard Nielsen, Co-PI
Dr. Ahmad Abu Abdo, Post-Doc Reseracher
Mr. Seung II Baek, Graduate Research Assistant
Mr. Prashant Darveshi, Graduate Research Assistant

University of Idaho (UI)
National Institute for Advanced Transportation Technology (NIATT)
Center for Transportation Infrastructure (CTI)

April 22, 2009
1. Introduction

This is the Seventh quarter report of the project which summarizes progress during the period January to March 2009. The focus during this period addressed several tasks as will be discussed in the report.

In previous reports, a description of the project objectives and work plan has been presented. These reports are posted on the designated project reports web page at: [http://www.webs1.uidaho.edu/bayomy/CLK479-483/QReports.htm](http://www.webs1.uidaho.edu/bayomy/CLK479-483/QReports.htm).

This QR7 report focuses on progress during the 7th quarter of the project. Description of work progress is presented on a task by task basis.

2. Progress by Task

The chart in Table 1 summarizes the progress as % work completed as of March 31, 2009.

<table>
<thead>
<tr>
<th>Phase / Task</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Task % Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A: Evaluation of Mix Resistance to Deformation</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Task A1 – Review of previous studies and available data</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Task A2 – Analytical Analysis</td>
<td></td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Task A3 – Experimental Design, Binder and Aggregate Evaluation</td>
<td></td>
<td></td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td>Task A4 – Prep and Evaluation of Asphalt Mixtures</td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Task A5 – Data Analysis</td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Phase B: Evaluation of Mix Resistance to Fracture and Fatigue Cracking</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Task B1 – Literature Review</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Task B2 – Finite Element Analysis</td>
<td></td>
<td></td>
<td></td>
<td>110%</td>
</tr>
<tr>
<td>Task B3 – Development of the Fracture Test Procedure</td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Task B4 – Prep and Evaluation of Asphalt Mixtures</td>
<td></td>
<td></td>
<td></td>
<td>95%</td>
</tr>
<tr>
<td>Task B5 – Data Analysis</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Task B6 – Reliability Analysis</td>
<td></td>
<td></td>
<td></td>
<td>70%</td>
</tr>
</tbody>
</table>
| Phase C: Implementation of Research Products and Training | | | | 0%
| Task C1 – Development of Implementation Plan | | | | 0% |
| Task C2 – Training Program for ITD Personnel | | | | 0% |
| Reporting | | | | 0% |
| Tasks A6, B7 and C3 – Quarter Reports for USDOT | | | | 0% |
| Phase D: Final Report Review and Submittal | | | | 0% |
| Task D1: External peer review of the final report | | | | 0% |
| Task D2: Final report review by ITD | | | | 0% |
| Task D3: Final Report Submitted | | | | 0% |

Work performed during the report period in the various project tasks is described below:
Phase A: Evaluation of Mix Resistance to Deformation

Task A1 – Review of previous studies and available data
Since the end of the fifth quarter, no additional literature review has been completed.

The work completed in this task is estimated at about 70%.

Task A2 – Analytical Analysis
In our previous quarterly report, we showed there was a linear relationship between the viscoplastic constitutive model parameter “A” and frequency of loading at two asphalt temperatures. This study has focused on developing relationships for estimating model parameters for this viscoplastic model. Results from modeling the dynamic modulus test with the viscoplastic model showed that the key parameters for predicting pavement response under small strain dynamic loads are the pavement modulus and the parameter A. Preliminary results indicate that the model parameter back-calculated from the dynamic modulus tests can be used to successfully predict rut depths. Additional details are presented in Appendix A.

The work completed in this task is estimated at about 90%.

Task A3 – Experimental Design, Binder and Aggregate Evaluation
Binder testing: All binder testing is now completed, and has been reported in previous quarter reports. During this quarter, no additional experiments or evaluations were completed.

The work completed in this task is estimated to be about 85%.

Task A4 – Preparation and Evaluation of Asphalt Mixtures
Testing and evaluation of asphalt mixtures has focused on fatigue fracture testing and is discussed under Task B4. Gyratory Stability, E-star, Flow number and APA Testing have previously been completed. MnRoad sample preparation and testing for the Gyratory Stability, E-star, and Flow Number tests have been completed.

Work completed in this task is still estimated by about 100%.

Task A5 – Data Analysis
To verify results from the Idaho mix designs, MnRoad mix designs were acquired from selected test sections at MnRoad. Seven sections were identified and selected -- four from mainline test sections and three from the low volume road test sections. In addition, field performance data related to these sections were obtained from published MnRoad results. Laboratory tests have been completed on these MnRoad mixes. A summary of the data analysis is presented in Appendix B.

Work completed in this task is estimated by about 100%.
Phase B: Evaluation of Mix Resistance to Fracture and Fatigue Cracking

Task B1 – Literature Review on Fracture
The research team is still reviewing previous published work to isolate the main essential parameters that might have the biggest impact on fatigue and fracture life on the semi-circular notched samples.

The work completed in this task is still estimated to be about 80%.

Task B2 – Finite Element Analysis
Work in this task overlaps two phases (Task A2 and Task B2). Additional analyses have been completed to develop relationships between this viscoplastic constitutive model parameter with both frequency of loading and temperature of the asphalt pavement. The work developed using the ABAQUS software package is reported under task A2 and is presented in Appendix A.

The effort spent in this task, so far, is estimated by about 70% of the work level in this task.

Task B3 – Development of the Fracture Test Procedure
After literature review and preliminary tests, a testing protocol is being established for static and fatigue testing of semi-circular notched samples. The essential parameters are being reviewed carefully including: notch depth, strain rate, loading frequency and the resulting strain range. The preliminary results indicate that each parameter affects the pavement fatigue life. A summary of cyclic fatigue fracture testing is presented in Appendix C.

The work completed in this task so far is estimated at about 110%.

Task B4 – Prep and Evaluation of Asphalt Mixtures
Preparation of asphalt samples for fatigue and fracture are nearly complete. The work completed in this task so far is estimated at about 106%, indicating that this task is taking more effort than anticipated.

Tasks B5 – Data Analysis.
Results from cyclic fatigue fracture testing and static testing are being analyzed to develop a method for predicting fatigue and fracture behavior of asphalt pavement using only static tests. It was observed the both \( J_c \) (static loading) and \( J_{c*} \) (cyclic loading) results were sensitive to changes in mix properties (e.g., asphalt binder, asphalt content, and aggregate gradation). In addition, initial results showed that both \( J_c \) and \( J_{c*} \) generally followed the same trend. Analysis of the tests conducted to date is presented in Appendix C.

The work completed in this task so far is estimated at about 95%.

Task B6 – Reliability Analysis
The researchers continue to refine the finite element model of the APA rutting test to better correlate the results of the model with the results of the APA tests. At this point, further
adjustments are being made to the visco-elastic parameter A. These adjustments will be incorporated into the statistical parameters for A, and the regression equations for A as a function of temperature and frequency. These statistical parameters, regression equations and the finite element model will form the basis for numerical simulations of the rutting process.

The work completed in this task so far is estimated by about 70%.

3. Summary

The main outcomes that have been achieved during this quarter can be summarized as follows:

1. Results from modeling the dynamic modulus test with the viscoplastic model showed that the key parameters for predicting pavement response under small strain dynamic loads are the pavement modulus and the parameter A.
2. Preliminary results indicate that the model parameter back-calculated from the dynamic modulus tests can be used to successfully predict rut depths.
3. Test results of MnRoad mixes revealed that mixes with lower asphalt content yielded higher GS and FN values and the lower the measured rut depth.
4. Using MnRoad mixes, the E* model was verified using a two-tail t-Test. It was found there was no significant difference between the means of the measured and predicted E* values with a reliability of 99% and an R² of 0.9238.
5. It was observed that both Jc (static loading) and Jc* (cyclic loading) results were sensitive to changes in mix properties. In addition, initial results showed that both Jc and Jc* generally followed the same trend.

Appendices

Appendix A: Viscoplastic Analyses of Asphalt Pavements (Task A2)
Appendix B: Data Analysis of MnRoad Mixes (Tasks A3 and A5)
Appendix C: Fracture Test Procedure and Data Analysis (Tasks B5)
Numerical modeling of asphalt pavement for this study has implemented a simplistic viscoplastic model for estimating rutting depth under repeated loading. This viscoplastic model has been shown in previous studies to reasonably predict rutting of pavement measured in asphalt pavement analyzer (APA) tests (Pirabarooban et al. 2003, Huang and White 1997). Previous studies provide limited information on how to estimate the model parameters. This study has focused on developing relationships for estimating model parameters for this viscoplastic model.

Results from modeling the dynamic modulus test with the viscoplastic model showed that the key parameters for predicting pavement response under small strain dynamic loads are the pavement modulus and the parameter A. The modulus value for test conditions of interest can reasonably be estimated using relationships developed by Abu Abdo (2008). When using the appropriate modulus, the back-calculated values for the parameter A have been shown to be functions of asphalt pavement temperature and frequency of loading (Quarterly Report 6). The back-calculated parameters are now being used to predict rutting depths measured during APA tests. Preliminary results indicate that the model parameter back-calculated from the dynamic modulus tests can be used to successfully predict rut depths.

References


Appendix B
Progress in Tasks A3 and A5
(Prepared by: A. Abu Abdo and F. Bayomy)

Task A3 – Experimental Design

MnRoad Mixes

To verify results from the Idaho mix designs, MnRoad mix designs were acquired from selected test sections at MnRoad. Seven sections were identified and selected -- four from mainline test sections (Cells 16, 17, 19 and 20) and three from the low volume road test sections (Cells 33, 34 and 35). Those sections are identified in Figure 3. In addition, field performance data related to these sections were obtained from published MnRoad results. Laboratory tests have been completed on these MnRoad mixes. These tests included: dynamic modulus (E*), binder dynamic shear modulus (G*), Flow Number (F_N), and Gyratory Stability (GS). Analyses of test data are in progress.
MainLine
Hot Mix Asphalt Test Sections

<table>
<thead>
<tr>
<th>Year</th>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-Year</td>
<td>45°</td>
<td>65°</td>
<td>85°</td>
<td>10°</td>
</tr>
<tr>
<td>Low Depth (Inches)</td>
<td>25&quot;</td>
<td>25&quot;</td>
<td>25&quot;</td>
<td>25&quot;</td>
</tr>
</tbody>
</table>

Asphalt Binder
Binder MC Grade | 62.2 | 62.2 | 62.2 | 62.2
Design Method | Gradation | Gradation | Gradation | Gradation
Subgrade PV Value | 25 | 25 | 25 | 25
Construction Date | Sep 23 | Sep 23 | Sep 23 | Sep 23

10-Year

Low Volume Road
Hot Mix Asphalt Test Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Legend</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Selected Mixes are from Cells 16, 17, 18 and 19

Figure 3 Typical Selected Test Sections from MnRoad

QR7 Appendix B: Progress in Tasks A3 and A5 - Page 2
Task A5 – Data Analysis

MnRoad Mixes

GS Analysis

When analyzing lab and field mixes, it was found that lower asphalt contents corresponded to higher GS values, due to the increase of friction and interlocking between aggregate particles. $F_N$ test results for these mixes showed that the higher GS values corresponded to higher $F_N$ values. These results were validated using MnRoad mixes actual rutting performance data. For mixes with similar structure but different asphalt content, it was found that the lower the asphalt content, the higher GS the lower the measured rut depth was (Figure 1). Further, mixes designed to have the same mix properties except the binder grade, seemed to follow the same trend; mixes with higher GS performed better in rutting than mixes with lower GS, as shown in Figure 2.

![Figure 1: Binder Content Effects on MnRoad Mixes](image-url)
Proposed E* Model

To verify the ability of the proposed model to predict E* for asphalt mixes other than the Idaho mixes, the predicted E* values were compared with measured E* values for a different set of mixes. 168 measured data points of the seven MnRoad mixes showed that the proposed model could predict E* with correlation coefficient $R^2$ of 0.9238 (see Figure 3). Similar to the lab and other field mixes, there was no significant difference between the measured and predicted E* mean values, as a result of a two-tail statistical t-Test with $\alpha = 0.01$ (99% reliability).
Appendix C
Task B3 - Fatigue Fracture Testing and Data Analysis
(Prepared by: S. Jung and S. Baek)

Introduction

To investigate if there is a relationship between fatigue and static test results, and to develop a simplified model to predict fatigue life; 470 Semi-Circle Notched Samples (SCNS) were tested, using both static and cyclic loading tests at 21 °C. In this progress report, the followings will be discussed;

1. Development and analysis of Jc for static and cyclic tests,
2. Examination of the effects of material including asphalt binder, asphalt content, and aggregate gradation, and
3. Evaluation of the relationship of Jc between static and cyclic tests

Development of the Fracture Parameter

According to Rice (1968), the value of J-integral can be determined,

\[
J_c = \left| \frac{d}{da} \left( \frac{U}{b} \right) \right| \tag{Eq. 1}
\]

where,

\begin{align*}
U & = \text{the strain energy}, \\
b & = \text{thickness of the specimen}, \text{ and} \\
a & = \text{the notch depth}.
\end{align*}

Based on load-deflection curve shown in Figure 1, the area under the curve up to maximum load represents the strain energy (U) to failure. Three different sizes of nominal notch depth (0.5, 1.0 and 1.5 in.) for SCNS are considered to determine Jc (lbs*in/in²), and patterns of strain energy per thickness versus notch depth illustrated in Figure 1 and Figure 2 respectively.

![Load-Deflection Curve](image-url)
Materials

Seventeen Superpave mixtures were evaluated in this study. As shown in Table 1 and Figure 3, different types of asphalt binder, asphalt content, and gradation were used. To achieve effects of structure, four different types of gradations: Mix 1, Mix 2, Fine Mix, and Coarse Mix were used. Three asphalt contents were used to evaluate the effects of AC for Mix 1 and Mix 2. Eight different types of binder also were examined to achieve the effect of binder.

| Table 1 Properties of Lab Mixes |
|---------------------------------
| **Mix** | **PG** | **AC%** | **Mix Designation** |
| 1       | 70-28  | 4.90    | 1JX               |
|         | 70-28  | 5.40    | 1JX+5             |
|         | 70-28  | 4.40    | 1JX-5             |
|         | 64-28  | 4.90    | 1JX-64            |
|         | 58-28  | 4.90    | 1JX-58            |
|         | 70-22  | 4.90    | 1JX-22            |
|         | 70-34  | 4.90    | 1JX-34            |
| 2       | 64-34  | 4.35    | 2JX               |
|         | 64-34  | 4.85    | 2JX+5             |
|         | 64-34  | 3.85    | 2JX-5             |
|         | 70-34  | 4.35    | 2JX-70            |
|         | 58-34  | 4.35    | 2JX-58            |
|         | 64-22  | 4.35    | 2JX-22            |
|         | 64-28  | 4.35    | 2JX-28            |
|         | 70-28  | 4.90    | 2JX-78            |
| Coarse Mix | 70-28 | 4.90    | 1JFX              |
| Fine Mix  | 70-28  | 4.90    | 1JCX              |
Figure 3 Aggregate gradation

Data Analysis

To identify the significant variables that affect the fatigue and fracture resistance of asphalt mixes, $J_c$ results were evaluated due to changes in the following mix properties; binder grades, asphalt contents, and aggregate structures. $J_c$ values were also compared with the asphalt mix dynamic modulus ($E^*$) and the binder dynamic shear modulus ($G^*$) values at a loading frequency of 1Hz and testing temperature of 21 °C.

It was observed that both $J_c$ (static loading) and $J_c^*$ (cyclic loading) results were sensitive to changes in mix properties (Figures 4 - 7). In addition, both $J_c$ and $J_c^*$ generally followed the same trend. It was also observed that the lower end of the binder grade (i.e, PG 70-22, PG70-28, and PG 70-34) illustrated the lower $J_c$ and $J_c^*$ results (see Figure 4). These results can be explained that binder grade with lower end is designed to have better performance in colder temperatures, which reduce their ability to resist fatigue and fracture at mid temperatures. It can be seen that the values of $J_c$ and $J_c^*$ reduced with the reduction in stiffness ($E^*$ and $G^*$) of these mixes as shown in Figure 5.

Further, Initial results showed (Figure 6) that both $J_c$ and $J_c^*$ followed the same trend with regard to changes in asphalt content. Both $J_c$ and $J_c^*$ yielded the highest values at optimum asphalt content. In addition, results showed that finer mix demonstrated higher $J_c$ values (Figure 7). It can be explained that finer mix probably show more resistance to fracture due to the better bonding between the binder and the fine aggregate particles (larger aggregate surface area).
Figure 4 $J_c$ results for mixes with different lower temperatures of binder (Mix 1)

Figure 5 $E^*$ & $G^*$ results for mixes with different lower temperatures of binder (Mix 1)

Figure 6 $J_c$ results for mixes with different asphalt contents for PG 64-34
The relationship J-integral between static and cyclic tests

Based on calculated $J_c$ values for the seventeen Superpave mixtures, Multivariable General Linear Model was utilized to analyze the sensitivity of asphalt binder changes. Table 2 indicates $J_c$ values for static and cyclic tests are sensitive to asphalt binder changes.

**Table 2 Tests of Between-Subjects Effects**

<table>
<thead>
<tr>
<th>Source</th>
<th>Dependent Variable</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>Jc</td>
<td>57.475a</td>
<td>14</td>
<td>4.105</td>
<td>14.368</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>4.742c</td>
<td>14</td>
<td>.339</td>
<td>2.425</td>
<td>.020</td>
</tr>
<tr>
<td>Intercept</td>
<td>Jc</td>
<td>309.772</td>
<td>1</td>
<td>309.772</td>
<td>1084.152</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>12.000</td>
<td>1</td>
<td>12.000</td>
<td>85.924</td>
<td>.000</td>
</tr>
<tr>
<td>PG</td>
<td>Jc</td>
<td>57.475</td>
<td>14</td>
<td>4.105</td>
<td>14.368</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>4.742</td>
<td>14</td>
<td>.339</td>
<td>2.425</td>
<td>.020</td>
</tr>
<tr>
<td>Error</td>
<td>Jc</td>
<td>8.572</td>
<td>30</td>
<td>.286</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>4.190</td>
<td>30</td>
<td>.140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Jc</td>
<td>375.818</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>20.931</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>Jc</td>
<td>66.047</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jc_Cy</td>
<td>8.931</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. R Squared = .870 (Adjusted R Squared = .810)
c. R Squared = .531 (Adjusted R Squared = .312)

$J_c$ : static value, $Jc_Cy$ : cyclic value
Regression analysis was utilized to predict $J_c$ for static loading and the results are shown in Figure 8 with an $R^2=0.54$. The equation of predicted model is below;

$$U = (-5.718 \text{ lb} \times a) + (-7.077 \text{ lb} \times b) + 26.147 \text{ lb} \cdot \text{in} \quad \text{(Eq. 2)}$$

![Figure 8 Strain energy for predicted vs. test values](image)

The $J_c$ for static and cyclic tests were investigated for relationship but the results show that $J_c$ values for static and cyclic tests are not significantly different.

**Reference**