CHAPTER III.
RESULTS AND ANALYSIS

3.1 Watertightness Testing

This section presents the results of watertightness testing for the laboratory constructed specimens outlined in chapter two. Individual impedance and moisture content data are presented in Appendix-F and bar charts are presented in Appendix-G. No data is available at 200 exposure cycles for replications one and two because these specimens were rendered unusable by the bond testing procedure performed after 100 exposure cycles. Data is available, however, for replications three and four because the bond tests were performed after 200 exposure cycles for these specimens.

3.1.1 Existing Waterproof Paving System

High Temperature Exposure, No Membrane

For untreated wood substrate specimens without a membrane (see Figure-G.1 and Figure-G.9), measured impedance values were generally greater than 1.1 MΩ over the course of testing. There were three exceptions to the previous statement: the impedance of specimen HNN.3 was very low (14 KΩ) after seven days of ponding, but increased to greater than 1.1 MΩ after 100 exposure cycles and remained so until the end of testing at 200 cycles; for specimen HNN.4, the impedance value was greater than 1.1 MΩ after the initial seven days of ponding, it decreased to 103 KΩ after 100 exposure cycles, and returned to greater than 1.1 MΩ after 200 exposure cycles; and specimen HNN.2 started with a impedance value greater than 1.1 MΩ after the initial seven days of ponding and decreased to 150 KΩ after 100 exposure cycles. These anomalies were probably due to leakage around the perimeter of the specimens. Though the wood moisture content of the untreated wood substrate did increase over time for all of the specimens, values were typically less than 14% and never exceeded 21%.

Since there was no membrane present in any of these specimens, the system should have had a very low impedance as soon as the system became saturated. However, the elevated temperatures encountered during exposure cycling kept the wood moisture content low and thus the impedance across the entire system remained high. In addition, it was very difficult to keep these specimens saturated since the ponding solution was quickly absorbed by the untreated wood substrate and driven off into the atmosphere as water vapor.

The impedance measurements for creosote treated wood substrate specimens without a membrane (see Figure-G.2 and Figure-G.10) were consistently greater than 1.1 MΩ throughout
the entire 200 exposure cycle test period for all specimens. In addition, the wood moisture contents observed for the treated wood substrates were significantly lower than those measured for the untreated wood substrate specimens. These results indicate that the unit volume of creosote preservative treatment specified in this research reduced the rate of transmission of water through the wood.

For the pentachlorophenol treated wood substrate specimens without a membrane (see Figure-G.3 and Figure-G.11), impedance values decreased to less than 400 KΩ after 100 high temperature exposure cycles and remained below this value throughout the 200 exposure cycle test period. Wood moisture content in the treated wood substrate specimens was less than that observed in the untreated wood substrate specimens, but slightly greater than that of the creosote treated wood substrate specimens. The decline in measured impedance values after 100 exposure cycles indicates that pentachlorophenol treated wood may be a reasonably good conductor once the paving system is saturated.

High Temperature Exposure, Untreated Wood Substrate with Membrane

For the untreated wood substrate specimens using membranes (see Figure-G.1 and Figure-G.9) cycled in the high temperature exposure chamber, the impedance measurements were consistently greater than the highest reading on the measuring instruments scale, 1.1 MΩ, even after 200 exposure cycles. This is an indication that either no breach occurred in the membrane or any breach that did occur was self sealed by the elevated ambient temperature.

As the number of high temperature exposure cycles increased, the moisture content of the wood substrate decreased or remained nearly the same for all but one of the specimens, specimen number HPN.2, with Petrotac membrane. This increase in moisture content may be indicative of a leak in the edge seal for this specimen. Since the impedance remained high for this specimen, the leak was probably sealed when the outer clamp on the edge seal was tightened after removal from the exposure chamber prior to testing.

Based on the results of impedance and wood moisture content testing, a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and an untreated wood substrate will inhibit the movement of liquid water into the wood substrate after as many as 200 exposure cycles in a high temperature environment and perform better than a system not using a membrane. Further, it appears that all three membranes performed equally well under these test conditions.

High Temperature Exposure, Creosote Treated Wood Substrate with Membrane

For the creosote treated wood substrate specimens using a membrane (see Figure-G.2 and Figure-G.10) cycled in the high temperature exposure chamber, impedance values were consistently greater than 1.1 MΩ over the course of testing for all specimens. Wood moisture content for specimens with membranes decreased as the number of exposure cycles increased for
Bituthene 5000 and Petrotac, but stayed nearly constant or increased for Protectowrap M400A. Specimen HWC.3, a specimen using Protectowrap M400A membrane, had a particularly high wood moisture content value at 200 cycles, but based on the results of the corresponding impedance test, it appears that this anomaly was the result of a leak in the edge seal.

Based on the results of impedance and wood moisture content testing, it appears that a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and a creosote treated wood substrate will inhibit the movement of liquid water into the wood substrate after as many as 200 exposure cycles in a high temperature environment and perform better than a system not using a membrane. Further, it appears that all three membranes performed equally well under these test conditions.

**High Temperature Exposure, Pentachlorophenol Treated Wood Substrate with Membrane**

The impedance measurements for nearly all of the pentachlorophenol treated wood substrate specimens employing a membrane (see Figure-G.3 and Figure-G.11) cycled in the high temperature exposure chamber were greater than 1.1 MΩ. The only exception was specimen HWP.4, a specimen using Protectowrap M400A membrane, with a impedance value of 260 KΩ after 200 exposure cycles. Compared to untreated or creosote treated wood substrate specimens, wood moisture content increased significantly (to approximately 14%) for all of the membranes as the number of exposure cycles increased.

Based on the results of impedance and wood moisture content testing, it appears that a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and a pentachlorophenol treated wood substrate will inhibit the movement of liquid water into the wood substrate after as many as 200 exposure cycles in a high temperature environment and perform better than a system not using a membrane. It appears that all three membranes performed equally well under these test conditions.

**Low Temperature Exposure, No Membrane**

For untreated wood substrate specimens without a membrane (see Figure-G.4 and Figure-G.9), impedance values generally started at greater than 1.1 MΩ after the initial seven days of ponding and declined significantly as the number of environmental exposure cycles increased. The impedance values for the low temperature specimens were already less than 61 KΩ after only 100 exposure cycles. For all specimens, the wood moisture contents increased to greater than 30% after only 100 low temperature exposure cycles.

For the creosote treated wood substrate specimens (see Figure-G.5 and Figure-G.10) cycled in the low temperature exposure chamber, impedance values for specimens made without a membrane were initially greater than 1.1 MΩ after seven days of ponding. After 100 exposure cycles, the impedance measurements for two of the four specimens remained above 1.1 MΩ while
the other two specimens decreased to approximately 870 KΩ. After 200 exposure cycles, the impedance values for both of the remaining specimens decreased to below 180 KΩ indicating that the creosote treated wood substrate became saturated and began to act as a reasonably good conductor of electrical current. The wood moisture content increased rapidly for all of the specimens, but not nearly as fast as seen in the untreated wood substrate specimens.

For the pentachlorophenol treated wood substrate specimens without a membrane (see Figure-G.6 and Figure-G.11), impedance remained above 1.1 MΩ after 100 low temperature exposure cycles for two of the four low temperature specimens, but decreased to below 260 KΩ for the remaining two specimens. The two specimens exposed to 200 low temperature exposure cycles decreased to below 300 KΩ. After 100 exposure cycles, the pentachlorophenol treated wood substrate specimens did not perform as well as the creosote treated specimens in terms of impedance, however this difference became much less pronounced after 200 exposure cycles. The wood moisture content of these specimens increased in a similar manner to that observed for the creosote treated wood substrate specimens.

**Low Temperature Exposure, Untreated Wood Substrate with Membrane**

For the untreated wood substrate specimens using membranes cycled in the low temperature exposure chamber (see Figure-G.4 and Figure-G.9), impedance values remained above 1.1 MΩ after 100 exposure cycles for all specimens, but decreased to below 760 KΩ in four of six specimens after 200 cycles. The other two specimens had impedance measurements greater than 1.1 MΩ after 200 cycles. While each membrane had at least one specimen with lower impedance readings after 200 exposure cycles, the Protectowrap M400A membrane specimens had a significantly slower increase in wood moisture content as the number of exposure cycles increased.

Based on the results of impedance and wood moisture content testing, a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and an untreated wood substrate will slow the movement of liquid water into the wood substrate after as many as 100 exposure cycles in a low temperature environment. After 200 exposure cycles, the watertightness of the system will be severely degraded. In general, a system using a membrane will typically perform better in terms of watertightness than a system without a membrane. Further, it appears that Protectowrap M400A membrane performs slightly better after 100 exposure cycles under these test conditions, but all three membranes performed similarly after 200 exposure cycles.

**Low Temperature Exposure, Creosote Treated Wood Substrate with Membrane**

For specimens (see Figure-G.5 and Figure-G.10) made with Bituthene 5000 membrane, measured impedance values were initially greater than 1.1 MΩ for all specimens and remained above that level for all but one specimen. The impedance of specimen LBC.1 decreased to 580
KΩ after 100 cycles. The wood moisture content for each of these specimens increased significantly as the number of exposure cycles increased.

The impedance values for specimens made with Petrotac membrane were greater than 1.1 MΩ after the initial seven days of ponding and remained above that level for two of the four specimens (LPC.2 and LPC.4) through to the end of testing, 100 and 200 exposure cycles respectively. In contrast, the impedance of the remaining two specimens (LPC.1 and LPC.3) decreased to below 170 KΩ after only 100 exposure cycles. The impedance of specimen LPC.3 decreased to 35 KΩ after 200 exposure cycles. The wood moisture content for all of the specimens made with Petrotac increased significantly after 200 exposure cycles. The elevated wood moisture content and rapid loss of impedance in specimen LPC.3 indicates that the specimen may have had a leak in the edge seal.

For specimens made with Protectowrap M400A membrane, impedance values were consistently higher than 1.1 MΩ, even after 200 exposure cycles. The wood moisture content of these specimens increased rather significantly during low temperature exposure cycling.

Based on the results of impedance and wood moisture content testing, a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and a creosote treated wood substrate will slow the movement of liquid water into the wood substrate after as many as 200 exposure cycles in a low temperature environment. In general, a system using a membrane will typically perform better in terms of watertightness than a system without a membrane, though the specimens using Petrotac membrane did not perform as well after 100 exposure cycles.

Low Temperature Exposure, Pentachlorophenol Treated Wood Substrate with Membrane

The impedance of all the pentachlorophenol treated wood substrate specimens employing a membrane (see Figure-G.6 and Figure-G.11) was greater than 1.1 MΩ regardless of exposure cycling. Wood moisture content increased as the number of exposure cycles increased, but at a significantly slower rate than observed for untreated and creosote treated wood substrate specimens.

Based on the results of impedance and wood moisture content testing, it appears that a paving system consisting of a surface asphalt mixture, a waterproofing membrane, and a pentachlorophenol treated wood substrate will inhibit the movement of liquid water into the wood substrate after as many as 200 exposure cycles in a low temperature environment and perform better than a system not using a membrane. It appears that all three membranes performed equally well under these test conditions.
Summary of Testing for Existing Waterproof Paving Systems Using a Membrane

Watertightness testing of the existing waterproof paving systems indicated that low temperature exposure environments are more critical to system performance than high temperature environments. However, the lack of observed degradation in the high temperature exposure specimens may have been due more to the fact that the moisture content of the wood substrates was reduced by elevated test temperatures, thus significantly increasing system impedance. Since the impedance of all of the existing waterproof paving system specimens was always a function wood substrate moisture content, the watertightness testing results must be evaluated very carefully.

For the high temperature exposure environment specimens, each wood substrate appeared to perform adequately after 200 exposure cycles and always performed better than the specimens without a membrane. No distinct differences appeared between the different membranes in the high temperature exposure environment.

For the low temperature exposure environment specimens, the results of watertightness testing were not as clear and concise.

Specimens using an untreated wood substrate tended to slow the movement of liquid water after as many as 100 exposure cycles, but appeared to develop significant leaks after 200 exposure cycles. Performance of systems using a membrane was typically better than the performance of a system without a membrane. Protectowrap M400A membrane appeared to perform slightly better after 100 exposure cycles, but all three membranes performed similarly after 200 exposure cycles.

For low temperature exposure specimens made with creosote treated wood substrates, the movement of liquid water was reduced after as many as 200 exposure cycles. Specimens using a membrane typically performed better than specimens without a membrane, though those using Petrotac membrane did not perform as well after 100 exposure cycles. In both high and low temperature conditioning environments, the creosote treatment level specified in this research appeared to strongly inhibit water transmission through the wood substrate.

Specimens made with pentachlorophenol treated wood substrates cycled in low temperature exposure conditions appeared to slow the movement of liquid water into the wood substrate after as many as 200 exposure cycles. Performance was similar among the three membranes tested and all of the membranes tested performed better than specimens not using a membrane. Based on the results of wood moisture content readings, it appears that a system using a pentachlorophenol treated wood substrate specimen may perform better than systems using an untreated or creosote treated substrate in low temperature.
3.1.2 Proposed Waterproof Paving System

High and Low Temperature Exposure, No Membrane

The impedance measurements for asphalt substrate specimens not employing a membrane (see Figure-G.7 and Figure-G.8) were, as expected, initially very low (i.e., less than 0.14 $\text{M} \Omega$). In the case of high temperature exposure cycling, the impedance measurements of all the specimens increased to greater than 1.1 $\text{M} \Omega$ after 100 exposure cycles and remained at that level after 200 exposure cycles. This was probably due to densification of the asphalt at the lift interface due to the elevated ambient temperature during high temperature exposure cycling. For the low temperature specimens, the impedance measurements consistently decreased to as low as 0.016 $\text{M} \Omega$ as the number of exposure cycles increased. The reason for the steady decrease was most likely due to increased saturation of these specimens.

High Temperature Exposure, With Membranes

For the asphalt substrate specimens with membranes cycled in the high temperature exposure chamber (see Figure-G.7), the impedance measurements were typically greater than the highest reading on the measuring instrument (1.1 $\text{M} \Omega$) at 0, 100, and 200 exposure cycles. This is an indication that either no breach occurred in the membrane or any breach that did occur was self-sealed by the elevated ambient temperature in the exposure chamber. There were two exceptions to these high readings. The first occurred after 100 exposure cycles in specimen HBA.4, a specimen using Bituthene 5000 membrane, with a impedance reading of 0.58 $\text{M} \Omega$. It should be noted that the reading returned to greater than 1.1 $\text{M} \Omega$ after 200 exposure cycles, so this anomaly was most likely due to leaking in the edge seal. The second exception occurred in specimen HPA.2, a specimen using Petrotac membrane, after 100 exposure cycles with a measured impedance of 0.38 $\text{M} \Omega$. This specimen was not exposed beyond 100 cycles due to bond testing, so it is not clear whether the low reading was indicative of a leak in the edge seal or a breach in the membrane.

Low Temperature Exposure, With Membranes

For the asphalt substrate specimens with membranes cycled in the low temperature exposure chamber (see Figure-G.8), significant degradation of the waterproofing membrane is indicated by a decrease in impedance in all but two specimens after 100 exposure cycles. The impedance values for these specimens (excluding the exceptions) ranged between 0.25 $\text{M} \Omega$ and 0.011 $\text{M} \Omega$ after 100 cycles and declined, though not significantly, after 200 exposure cycles. The two exceptions occurred in specimens employing Bituthene 5000 (LBA.1 and LBA.4). Specimen LBA.1, tested to 100 exposure cycles, had a impedance of greater than 1.1 $\text{M} \Omega$. The impedance of specimen LBA.4 was greater than 1.1 $\text{M} \Omega$ after 100 exposure cycles decreasing to 0.62 $\text{M} \Omega$ after 200 exposure cycles.
Summary of Testing for Proposed Waterproof Paving Systems Using a Membrane

Watertightness testing of the proposed waterproof paving systems indicated that low temperature exposure environments are more critical to system performance than high temperature environments.

For the high temperature exposure environment specimens, each membrane appeared to perform adequately after 200 exposure cycles and performed as well as specimens made without a membrane.

For nearly all of the low temperature exposure environment specimens, membrane performance was severely degraded after only 100 exposure. Specimens made with Bituthene 5000 membrane appeared to perform better in low temperature exposure testing. Performance of systems using a membrane was typically better than the performance of a system without a membrane.

3.2 System Bond Testing

This section presents the results of bond testing for the laboratory constructed specimens outlined in chapter two. Summary data is presented in Figure-3.1, Figure-3.2, Figure-3.3, and Figure-3.4. These values are the average of two specimen replications. Individual shear strength and failure mode data are presented for each specimen in Appendix-F and bar charts of the individual data are presented in Appendix-H.

Existing System

In all cases where treated or untreated wood was in direct contact with the asphalt surface mixture, no bond strength was developed, see "No Membrane" in Figures-3.1, 3.2, and 3.3. This lack of bond was originally observed when the specimens were fabricated, so by default, the effects of environmental cycling were inconsequential.

When a membrane was present between asphalt surface material and an untreated wood base, some bond strength was developed, but in general, it was quite low, see Figure-3.1. A load-deformation plot for specimen LWN.1 representing the typical trend for specimens made with an untreated wood substrate and a membrane is presented in Figure-3.5. For Protectowrap M400A, the shear strengths were typically twice as large as those measured for specimens using the other two membranes. No distinct trends were observed among these specimens with regards to environmental exposure cycling since the bond strengths were nearly constant throughout both the hot and cold exposure cycles.

For similar specimens made with creosote or pentachlorophenol treated wood, the bond strength was nearly zero in all cases and exposure cycling appeared to have no significant effect, see Figure-3.2 and 3.3. This loss of bond strength was most likely related to deterioration of
membrane adhesive strength caused by solvents in the preservative treatments. A load-deformation plot for specimen LWC.2 representing the typical trend for specimens made with a treated wood substrate and a membrane is presented in Figure-3.6.

### Proposed System

It appears that the presence of a membrane between the surface and base asphalt mixture lifts actually reduced bond strength between the two layers, see Figure-3.4. The shear strengths for the asphalt/asphalt specimens without a membrane were the highest among all of those tested in this research. Shear strength magnitudes were more than double those observed for asphalt substrate specimens with a membrane. A load-deformation plot for specimen CNA.2 representing the typical trend for specimens made with an asphalt substrate and no membrane is presented in Figure-3.7. A load-deformation plot for specimen CBA.1 representing the typical trend for specimens made with an asphalt substrate and a membrane is presented in Figure-3.8.

While it appears that exposure cycling had no discernible effect on the proposed paving system specimens using a membrane, there was a definite trend among the asphalt/asphalt specimens not using a membrane. Cold cycle average shear values were consistently lower in the range of 68-76% of the non-exposed specimens, see Figure-3.4. The data did not reveal any significant degradation effects after 200 exposure cycles beyond those observed at 100 cycles. For the asphalt/asphalt specimens not using a membrane in the high temperature exposure chamber, shear strengths were actually higher than the strengths measured in non-exposed specimens. After 100 exposure cycles, shear strengths were 132-148% of those for non-exposed specimens and 145-256% of those for non-exposed specimens after 200 exposure cycles. This is most likely due to fusing and interlocking of the asphalt lifts due to softening of the asphalt cement at elevated temperatures. This phenomenon did not occur in asphalt/membrane/asphalt specimens because the membrane acted as a diffusion boundary layer.

Two distinct trends were apparent in the failure modes observed during bond testing. First, all but two of the wood specimens using preservative treatments failed just below the membrane (Mode I Failure) indicating that the presence of oilborne preservatives significantly degrades bond strength at that interface. Second, Protectowrap M400A typically failed within the membrane (Mode III). Beyond these two cases, no apparent trend was revealed in the failure mode data.

### 3.3 Creekside Drive Bridge Cores

Impedance, shear strength, and failure mode data are presented in Table-3.1. After one year of service, it appears that the paving system is watertight since the measured impedance is greater than the maximum magnitude available on the impedance meter, 1.1MΩ. Shear strength values for the Creekside Drive core specimens are presented in Figure-3.9. The average shear strength value of 36 psi. is in general agreement with the experimental results obtained in the laboratory for a similar system configuration. For all three specimens, failure occurred at or
above the interface between the membrane and surface asphalt (Mode V Failure). Specimen three failed within the surface asphalt, above the membrane. This would account for the higher shear strength magnitude for that specimen and indicates that the shear strength between the asphalt and membrane was greater than that of the asphalt.

Table-3.1 Impedance and Shear Data for Creekside Drive Bridge Core Samples

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Impedance (MΩ)</th>
<th>Shear Strength (p.s.i.)</th>
<th>Shear Failure Mode</th>
</tr>
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<tr>
<td>BRA.1</td>
<td>&gt;1.1</td>
<td>24.7</td>
<td>V</td>
</tr>
<tr>
<td>BRA.2</td>
<td>&gt;1.1</td>
<td>25.6</td>
<td>V</td>
</tr>
<tr>
<td>BRA.3</td>
<td>&gt;1.1</td>
<td>57.8</td>
<td>V</td>
</tr>
<tr>
<td>Average</td>
<td>&gt;1.1</td>
<td>36.0</td>
<td>-----</td>
</tr>
</tbody>
</table>
Figure-3.1: Average Shear Strengths for Existing Waterproof Paving System (Untreated Wood Base/Membrane/SM-2 Surface Asphalt Mixture)
Figure-3.2: Average Shear Strengths for Existing Waterproof Paving System (Creosote Treated Wood Base/Membrane/SM-2 Surface Asphalt Mixture)
Figure-3.3: Average Shear Strengths for Existing Waterproof Paving System (Pentachlorophenol Treated Wood Base/Membrane/SM-2 Surface Asphalt Mixture)
Figure-3.4: Average Shear Strengths for Proposed Waterproof Paving System (BM-2 Base Asphalt Mixture/Membrane/SM-2 Surface Asphalt Mixture)
Figure-3.5: Typical Load-Deformation Plot for Specimens made with an Untreated Wood Substrate and a Membrane
Figure-3.6: Typical Load-Deformation Plot for Specimens made with a Treated Wood Substrate and a Membrane
Figure-3.7: Typical Load-Deformation Plot for Specimens made with an Asphalt Substrate and No Membrane
Figure-3.8: Typical Load-Deformation Plot for Specimens made with an Asphalt Substrate and a Membrane
Figure-3.9: Shear Strengths for Creekside Drive Bridge Cores