SELECTIVE FLEXIBLE PAVEMENT REHABILITATION BASED ON FORENSIC INVESTIGATION AND DEFLECTION ANALYSIS: SEVENTEEN YEARS CASE STUDY IN VIRGINIA

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ABSTRACT

This paper describes the effectiveness of combining forensic investigation and Falling Weight Deflectometer (FWD) deflection analysis in selecting the most economical best performing rehabilitation remedy for a prematurely failing thin flexible pavement. The project is a four lane divided primary road, about 3 miles long and part of Route 3 in Lancaster County, Fredericksburg District, Virginia. The two west bound lanes were constructed in 1992 with pavement structure consisting of 4.5 inches asphalt concrete on top of 6 inches dense graded aggregate, which rested on a 6 inches soil cement treated layer, on top of the natural subgrade. Within two years of service, it showed white stains at the surface, but no distresses were observed. In 1998 several areas in truck lane failed in fatigue and alligator cracking. The first rehabilitation activity, in 1998, was to mill and replace the asphalt layers, a total of 4.5 inches, without identifying the failure mechanism. This activity proved ineffective and the pavement failed in the same mode but more severely in 1999. Determination of the failure mechanism based on forensic investigation and deflection testing was finally considered, in 2000. The failure mechanism showed that dense plain aggregate which was loaded with fines acted as a weak link between the top and bottom stiff layers and lead to entrapment of moisture (in the absence of pavement edgedrain) and the premature failure due to the truck loading in the truck lane. Based on the forensic investigation and FWD deflection testing, it was decided to remove the asphalt layers and in-place cement stabilize the plain aggregate layer for the truck lane only to provide much stronger pavement by eliminating the weak link. This unique and selective rehabilitation approach resulted in two different treatments one for the truck lane, where most of the heavy loading is applied, and one for the passing lane where light loading is applied. The pavement has performed very well during the last eight years without any signs of distresses. This paper documents the lessons learned from this project, over a span of 17 years.
INTRODUCTION
Developing a rehabilitation strategy requires collecting background data as well as field data. The Pavement Condition Report, as-built plans, and traffic information are some of the resources used to prepare rehabilitation strategy recommendations. A thorough field investigation of the pavement surface condition, combined with a current deflection study and coring, knowledge of the subsurface conditions, thicknesses of existing flexible pavement layers, and a review of drainage conditions are all necessary for developing a set of appropriate rehabilitation strategies. Often times the cores and visual inspection records will not provide sufficient information to allow for selecting a cost-effective rehabilitation strategy that meets the budget and performance constraint of the project [1, 2]. Falling Weight Deflectometer (FWD) analysis provides an excellent and efficient tool for evaluating the structural performance of pavements. Although FWD testing reduces the amount of destructive testing, successful FWD analysis cannot be performed without an adequate field diagnosis program. Combining the FWD analysis with an adequate field diagnosis program leads to better understanding of pavement performance, and hence to more accurate and cost-effective rehabilitation strategies. In this paper, the effectiveness of using the field diagnostic and FWD analysis for pavement rehabilitation selection is discussed through a case study.

The subject project is a four lane divided primary road, about 3 miles long and part of Route 3 in Lancaster County, Fredericksburg District, Virginia. The two west bound lanes were constructed in 1992 with pavement structure consisting of 4.5 inches asphalt concrete on top of 6 inches dense graded aggregate, which rested on a 6 inches soil cement treated layer, on top of the natural subgrade. Within two years of service, it showed white stains at the surface, but no other distresses were detected. Limited field investigation including shoulder trenching did not reveal the cause of the white stains. In 1998, several areas in truck lane failed in fatigue and alligator cracking. The first rehabilitation activity, in 1998, was to mill and replace the asphalt layers, a total of 4.5 inches and therefore removed the symptoms only. This activity was ineffective, since the actual failure mechanism was not identified, and the pavement failed in the same mode but more severely within one year.

Determination of the failure mechanism based on forensic investigation including truck lane cross trenching and deflection testing was finally considered. The failure mechanism showed that the dense plain aggregate subbase was out of tolerance in fines (>15% of materials passing the 200 sieve) acted as a weak link between the top and bottom stiff layers and lead to entrapment of moisture (in the absence of pavement edgedrain) and the premature failure due to the heavy axle loading in the truck lane. The passing lane did not show any sign of distresses.

OBJECTIVES
This paper documents the effectiveness of combining forensic investigation and FWD deflection analysis in selecting the most economical best performing rehabilitation remedy for a prematurely failing thin flexible pavement. This paper documents the efforts that were experienced on this project, over a span of 17 years. Benefit/cost (B/C) ratio analysis will be highlighted and discussed. B/C ratio of the selected rehabilitation and the savings resulting from eliminating disruption to the traveling public and the traffic control operation associated with the rehabilitation provided the highest return on the investment. The specific objectives of this paper are as follows.

1. Document the results and the analysis of the FWD deflection testing conducted.
2. Document the results and the analysis of the forensic investigation performed on this segment of the road.

3. Document the effectiveness of combining forensic investigation and FWD deflection analysis in selecting the most economical, best performing rehabilitation remedy for a prematurely failing thin flexible pavement.

4. Document B/C ratio of the selected rehabilitation and the savings resulting from eliminating disruption to the traveling public and the traffic control operation associated with the rehabilitation.

INVESTIGATION METHODOLOGY

The investigation methodology consisted of the following:

- Historical data collection
- Field Visits and shoulder trenching
- Laboratory testing
- Deflection testing
- In depth field investigation

Historical Data

Originally this segment of Route 3 was two lanes and was expanded to four lanes in 1992 with a pavement structure consisting of 4.5 inches of asphalt concrete (1.5 inch surface course over 3 inches Base course) on top of 6 inches of dense graded aggregate layer of Type I, size 21A (dense graded aggregate, Table 1 shows design ranges for 21A and 21B dense graded aggregate used by Virginia Department of Transportation (VDOT)), on top of a 6 inches cement treated sandy (silt) soil on top of the naturally existing sandy soil. In 1994, the pavement showed white stains in the surface layer in isolated spots [Figure 1]. The white stain was evident of fines pumping from the underlying aggregate layer. The pavement was cut (trenched) and was found moist. FWD deflection readings taken indicated some excessive deflections. The recommendation was to watch the pavement for signs of failure related to lack of drainage, especially during the spring season. During 1998, several areas were failing in the travel lane [Figure 2 and 3]. The asphalt surface and base in both lanes were milled and replaced with the same thickness. This year the road has failed in the travel lane (right wheel path specifically) in two areas totaling about 0.27 miles. These pavement areas were repaired with full-depth. The pavement conditions at the failed sections in 1999 [Figure 4] are worse than the conditions before repairs in 1998.

<table>
<thead>
<tr>
<th>TABLE 1 Design Range for Dense Graded Aggregates (3)</th>
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<tbody>
<tr>
<td>Amounts finer than each laboratory sieve (square openings(^1)) (% by weight)</td>
</tr>
<tr>
<td>Size No.</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>21A</td>
</tr>
<tr>
<td>21B</td>
</tr>
</tbody>
</table>

\(^1\)in inches, except where otherwise indicated. Numbered sieves are those of the U.S. standard series.
FIGURE 1 Initial cracking and white stains in the right wheel path in year 1994.

FIGURE 2 Progressive fatigue with white stains in the right wheel path in year 1998.
FIGURE 3 Close up showing heavy white stains in the right wheel path (1998) before removal and overlaying.

FIGURE 4 Progressive fatigue condition in 1999, after only one year since the placement of the overlay.
Field Investigation

Field visits revealed the following pavement distresses and general observation (in Year 1999):

- Observed white stains at the surface course.
- Failure occurred in the right wheel path of truck lane.
- Failure occurred in superelevation and transition areas.
- Failure occurred in about 1/4 mile of the road, along the project.
- Surface course appeared open
- Right wheel path and left wheel path have slightly different "color" in the field
- Present pavement failed in alligator cracking after seven months
- AC pavement was wet at the layer interfaces.
- Fines were found in the base AC sample along with discoloration.
- There was 2.75 miles of serviceable pavement.
- The 1/4 mile of problem areas was patched at full depth to the top of the soil cement.
- No edge drains were designed for this road
- Road occurred in both cut and fill section
- There was 2' of undercut, geosynthetic mat, and imported backfill for road construction in 1992

Laboratory Testing

- Total voids of surface AC sample of failure area was high at 14.9 %
- Total voids of the base AC sample of failure area was 10.6%
- The 21-A subbase mixture sample was out of specification for four sieves and contained mica. Liquid Limit (LL) = 27.4%.
- The 21A shoulder sample was out of specification for three sieves, LL=23.1%
- Soil adjacent to the shoulder had LL of 17.2 %
- AC samples passed the gradation.

Deflection Testing

Deflection testing was employed to compare the composite stiffness data from 1994 and 1999 FWD tests. Composite Stiffness (load over deflection under the plate) Plots, for 1994, 1999 and 2000 are shown on the same graph in Figure 5. The graph shows that the average stiffness is 500 Ibf/mil (17.85 kgf/mm) (which is a very low value) and no noticeable improvement in the pavement structure performance during the years 1994 through 1999 were observed Therefore, the problem was not corrected in the 1998 rehabilitation.

IN DEPTH FIELD INVESTIGATION
Core Investigation showed that there is difference in pavement densities in the outside wheel path and the inside wheel path. The top layer (89.5%) was less dense than the base layer (91.2%) in the outside wheel path. To obtain accurate samples regarding moisture/water related problem, a roller blade cutter (slicer) was used to open and expose the pavement layers in a dry condition, as shown in figure 6 (a) and (b).

FIGURE 6 (a) Trenching the right wheel path (b) Asphalt cutting wheel
The pavement failure mechanism is based on Observations and Data Collected. The mechanism is as follows:

The 21-A aggregate should have been a 21-B aggregate in order to provide drainage. The 21-A had more fines than usual (18%). Moisture in this layer decreased its strength [Figures 7 and 8]. Both the AC surface and base layers were more "open" mixtures than usual. This allowed surface moisture to infiltrate into the 21-A aggregate layer.

The weak layer described above was introduced very early during the pavement service life. The AC layers could not bridge over the weak aggregate layer. Therefore, the AC layers did not support the load and failed. Pumping of fines from the 21-A aggregate layer accelerated the failure of the AC layers.

In the travel lane, the surface and base layers had slight differences in densities. The inside wheel path (left) showed equal densities in the surface and base AC layers. The outside wheel (right) showed the surface layer to be less dense than the base layer for 85% of samples. This was the weakest part of the AC layers and apparently was the first to fail due to the wet condition and loading combination.

Field observations, 20 MAY 99, (which included a 38 ft. cut in the travel lane as part of a full depth repair) confirmed the above. The subbase soil cement was strong, solid, and without obvious wide cracks. Free moisture and fine slurry were seen perched on top of the existing 21-A aggregate layer. Moisture and free moisture were also viewed throughout the existing 21-A layer.

FIGURE 7 Pavement section showing AC and aggregate layer.
PAVEMENT DESIGN AND ANALYSIS

Pavement designs for different conditions were calculated based on differing conditions to come up with different recommendations.

a. The existing pavement design requirement was calculated for existing traffic (1997) conditions.
b. The existing pavement design with a weakened aggregate layer was calculated for existing traffic (1997).
c. The recommended pavement design was calculated for future traffic volumes (2015).
d. Traffic data for 1997 AADT is 101 ESALs and projected to design year 2015 is 157 ESALs.

The comparison between a. and b. shows a thicker base material is needed in the pavement structure to compensate for the weak aggregate layer. The design in c. shows the cement stabilization of the existing aggregate makes good use of the 21-A and its high fines. It accommodates future traffic with a thickness close to today's existing thickness which also, maintains the existing road profile.

PAVEMENT REHABILITATION RECOMMENDATIONS

The following rehabilitation options were considered for this section.
a. The recommended repair was to salvage materials, correct the problem and deliver pavement product that is to last 30 years. It includes the following: Mill surface and base AC layers, cement stabilize existing 6 inches 21-A aggregate in-place, replace with 1.5 inches AC top and 3 inches AC base. Install edge drains.
b. Place a 1.5 inch AC surface course to both lanes to seal and add structural strength. Poor 21-A layer remains in place.

c. During a dry period (say 2 weeks without rain), let the existing 21-A aggregate layer become dryer, and seal both lanes with latex slurry seal to keep surface water from entering the 21-A layer.

d. Do the same as c. without a dry period for the case of urgency or a particularly wet season.

e. Do nothing. Leave remaining pavement subject to any future patch work as it develops.

Service Lives Comparison
The recommendations are for a 30-year life, 2.75 miles and some options include multiple installations. They are compared below in Table 2.

<table>
<thead>
<tr>
<th>Option</th>
<th>Total Cost</th>
<th>Life</th>
<th>Public Loss</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>$898,000</td>
<td>20</td>
<td>1 in 30 yr</td>
<td>High initial cost</td>
</tr>
<tr>
<td>b</td>
<td>$111,000</td>
<td>4</td>
<td>12 in 30 yr</td>
<td>Wet, poor 21-A remains</td>
</tr>
<tr>
<td>c</td>
<td>$54,000</td>
<td>2</td>
<td>Multiple losses</td>
<td>Buys time pay as you go</td>
</tr>
<tr>
<td>d</td>
<td>$54,000</td>
<td>2?</td>
<td>Multiple losses</td>
<td>Buys time pay as you go</td>
</tr>
<tr>
<td>e</td>
<td>?</td>
<td>1?</td>
<td>Multiple losses</td>
<td>Be ready to patch soon</td>
</tr>
</tbody>
</table>

LESSONS LEARNED AND CONCLUSIONS
Based on the forensic investigation and FWD deflection testing, it was decided to remove the asphalt layers and in-place cement stabilize the plain aggregate layer for the truck lane only to provide much stronger pavement by eliminating the weak link. This unique and selective rehabilitation approach resulted in two different treatments one for the truck lane, where most of the heavy axle loading is applied, and one for the passing lane where light loading is applied. The pavement has performed very well during the last 8 years without any signs of distresses. Figure 9 shows the pavement condition before and after rehabilitation. Figure 9 shows the FWD test results for 2005 along with 1994, 1999 and 2000. From the FWD data as shown in Figure 10, it can be seen that there is considerable increase in pavement strength after rehabilitation.
FIGURE 9 Pavement condition before and after rehabilitation.

FIGURE 10 Composite stiffness profile for before and after rehabilitation.
These points are valued for the impact on future designs and investigations:

1. The original design and project construction records should be available for the future to assist in determining the failure mechanism.

2. For asphalt concrete, compaction requirement needs to be reconsidered. Virginia Department of Transportation (VDOT) specification calls for 3%-6% total voids in asphalt concrete, when compacted in the laboratory. This requirement needs to be correlated to the voids truly achieved in the field, and also to whether the compacted product is tight enough to provide a balance between stability and the reduction in the infiltration of water.

3. The 21-A aggregate should not be specified for design with an ADT greater than 1000. It is especially so with high fines (18%, -200) and a high mica content.

4. There should be a clear means to specify the two aggregate, Materials 21-A and 21-B. The use of one-test processing tolerance is a serious mistake and should be eliminated. The reason is one will end up with a product that does not serve the pavement performance, since the sieve requirements widen without regard to the function of the specified materials.

5. If the specification for process tolerances for laboratory sieves is maintained, then one should have a sufficient number of tests to keep the allowable ranges within the sieves that define the product.

6. The importance of reasonable truck traffic loading cannot be overemphasized. One should capitalize on the continuous count sites much more often, since traffic data has the greatest impact on the pavement design.

REFERENCES

