Portland Cement Stabilized Full Depth Reclamation of the Pt. Michaud Beach Road

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ABSTRACT

Many rural Canadian highways receive minimal levels of maintenance, in part due to reducing budgets, escalating costs, and the extensive degree of repairs needed throughout the pavement network. Portland Cement stabilized Full Depth Reclamation (PC-FDR) presents an attractive repair option for pavements suffering from subgrade and base failures as well as asphalt concrete deterioration. The Point Michaud Beach Road was selected as a candidate for evaluating the first PC-FDR in Nova Scotia. The asphalt concrete road exhibited extensive cracking and distortions that were indicative of base and subgrade failures while supporting very light traffic volumes. PC-FDR involves stabilizing a pulverized layer of asphalt concrete and granular base using small amounts (typically 4-6%) of Portland cement to provide a strong and frost-resistant base layer for supporting a new wearing surface, while minimizing the potential for reflective shrinkage cracking. A micro-cracking technique was also employed to further reduce the susceptibility of the material for large shrinkage cracks. Quality control of the micro-cracking process was performed using a Slab Impulse-Response test to monitor the reduction in the quasi-static stiffness of the stabilized material. Comparative testing before and after repair using Ground Penetrating Radar and a Falling Weight Deflectometer indicated a substantial increase in the predicted service life of the pavement. Prior to repair, twenty-two percent of the section was predicted to exhibit asphalt concrete fatigue failure in less than three years compared to less than three percent exhibiting fatigue failure in the stabilized material after twenty years of service, with no subgrade rutting or asphalt concrete fatigue failures. The combination of a full depth repair technique and the expected increase in durability will tend to reduce overall maintenance requirements and costs compared to conventional repair methods, counteracting the increased difficulty of managing infrastructure maintenance due to reduced budgets and escalating costs.

INTRODUCTION

Most agencies who manage public highway infrastructure maintenance have been faced with increasing demand and decreasing budgets. In many cases, this has lead to a systemic decrease in the overall condition of the highway network, particularly in the case of rural roads and highways. Rural pavements generally carry low volumes of traffic, tend to be designed using Hot Mix Asphalt (HMA), are constructed using locally available materials, and also tend to receive less frequent maintenance over their service life since a lower proportion of the travelling public uses them. In many cases, the granular materials used in rural pavements tends to be pit run gravels containing higher proportions of silt and/or clay materials, instead of higher quality granular base or subbase materials used in major highways that are produced from crushed rock. The use of lower quality materials, coupled with the use of standardized empirical pavement designs for use on various subgrade soils, and a generally higher tolerance for damage levels on rural pavements prior to maintenance has created a network of rural highways with a heavy demand for repair budget allocations. Often, fatigue damage and base or subgrade related distortions, cracking and rutting become so severe that an uneconomical thickness of hot mix asphalt concrete overlay is required to provide sufficient strength to withstand the movement of the underlying damaged pavement structure. In this case, other repair alternatives such as Full Depth Reclamation (FDR) provide an attractive option for rebuilding the damaged upper layers of the pavement structure.

FDR entails pulverizing and re-binding the existing asphalt concrete pavement structure, typically with an asphalt or Portland cement, in order to provide a strong and durable base layer for supporting a new wearing surface. The pulverization of the damaged asphalt concrete layers removes the capacity for the damaged layers to induce reflective cracking in an overlay. Proper design of the thickness and modulus of the FDR material is needed to minimize the required thickness of HMA and to ensure the stress experienced by the subgrade and base materials is minimized to control the development of further base or subgrade distortions in the pavement. The cost-effectiveness of the repair depends upon the up-front costs which include the construction effort, materials and trucking, etc. as well as the expected performance of the rehabilitated pavement.

This paper describes an experimental study of the rehabilitation of the Pt. Michaud Beach road, located on Route 247 near L'Ardoise, Nova Scotia, in October, 2007, using a Portland Cement stabilized FDR (PC-FDR) approach. Pre-repair and post-repair testing was conducted on the pavement section using a Falling Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR) to characterize the pavement structure and materials, and to model the expected performance against a full depth replacement of the HMA.

PC-FDR REPAIR METHOD

The Pt. Michaud Beach Road was the first PC-FDR project constructed in Nova Scotia. The project was 6.8 km in length, from Sta. 5+000 at the intersection with St. Peters-Forchu Road, to the parking lot entrance of the beach at Sta. 11+800. It appeared from visual inspection of the pavement surface that the HMA thickness was inadequate to minimize stresses developed in the base and subgrade materials. The pavement exhibited high levels of distress in the form of localized fatigue cracking and extremely heavy base/subgrade distortions and pavement edge failures which created very large cracks in the pavement surface and a very rough ride. Furthermore, various sections of the pavement were constructed on wet marshland, so moisture content and expected low modulus values within the subgrade soil may have contributed to the observed distress levels. The section was considered to be an appropriate candidate for FDR because of the severity of distress and the necessity for strengthening the overall pavement section in order to reduce the vertical stress on the subgrade and reduce pavement distortions in the future. PC-FDR was selected as the repair methodology because of favorable experiences reported with the technology in the United States and the availability of technical support from the Cement Association of Canada and the Portland Cement Association. The use of PC-FDR in rehabilitating the Pt. Michaud Road section was to serve as a trial project by which the Province of Nova Scotia could evaluate the effectiveness of the technology and the difficulties in its application.

Aside from the general savings in energy, emissions, and cost from reduced trucking and materials realized by reusing in-situ materials, the expected benefits of PC-FDR included a relatively high elastic modulus, reduced moisture susceptibility, increased wet-dry and freeze-thaw durability of the overall pavement, and reduced construction delays.

One of the primary concerns with the PC-FDR was the assumption that it was susceptible to shrinkage cracking, as previously experienced in using soil-cement in earlier Nova Scotian highway projects. In reality, PC-FDR is designed using much less Portland cement (typically 4-6%) than is used in soil-cements (typically 20%) in order to achieve a design 7-day compressive strength of only 2.1-2.8 MPa (300-400 psi). The design concept is to provide sufficient strength and stiffness to perform well as a pavement material, but minimize the potential for shrinkage cracking, and the related susceptibility for reflective cracking into an asphalt overlay. Furthermore, a microcracking method, shown to significantly reduce the occurrence of reflective cracks in asphalt overlays placed on PC-FDR (1)(2), would be used on the Pt. Michaud Road project. Microcracking involves rolling the stabilized mat with a vibratory steel drum roller, after an initial curing period of 24-48 hours, with sufficient passes to reduce the modulus by at least 40%. This creates a network of fine microcracks throughout the mat which enable shrinkage strains to be generally distributed throughout the layer via numerous small crack openings instead of single large macrocracks. The smaller crack openings distributed over a large area reduce the local strains imparted to the HMA overlay and the initiation of reflective cracking in the asphalt concrete.

PRE-REPAIR EVALUATION

Thickness and deflection testing of the pre-rehabilitation pavement test section was completed on September 5, 2007. GPR was used to estimate the asphalt concrete pavement and granular material thickness, while a Dynatest® heavy weight deflectometer was used to measure deflections. A 40 kN load (representing a single wheel of the standard 80 kN axle load) was applied to the pavement through a 300 mm loading plate to create surface displacements measured at offsets of 0, 200, 300, 450, 600, 900, 1200, 1500, and 1800 mm from the load. Figure 1 shows the simultaneous GPR and FWD testing being conducted on the pre-rehabilitation pavement surface. The GPR-based thickness measurements were computed using constant average velocities throughout the asphalt and granular layers, calibrated using drilled cores from the asphalt concrete and test pits dug at the shoulder of the pavement. The exact asphalt core locations were marked in the GPR data to ensure accuracy in the calibration. The asphalt concrete was found to have a mean thickness of 132 mm with a standard deviation of 29 mm, while the mean granular layer thickness was 297 mm with a standard deviation of 52 mm. Samples of the granular and subgrade materials were also collected by AMEC for classification and gradation analysis.

Two layers of granular materials were observed along the test section, consisting of 60-150 mm of Class A brown silty sand with gravel and 150-250 mm of Class B grey gravel with sand. The subgrade fill material was classified as a brown silty sand with gravel, except at Station 6+155 where a reddish brown clayey sand with gravel was observed. Figure 2 shows the gradation of the second granular material obtained from test pit 4 at Sta. 8+250, as well as samples of the two different subgrade materials observed from test pits 2 and 6, at Sta. 6+155 and Sta. 10+680, respectively.

The unique layer thicknesses measured using GPR at each deflection test location were used in backcalculating the elastic modulus of the asphalt concrete, granular materials and subgrade using ELMOD® 5.0 at 138 different locations along the section, spaced at approximately 100-meter intervals and staggered by 50 meters in opposing lane directions. Figure 3 shows the variation in the elastic moduli for these materials over the length of the test section, with the asphalt concrete modulus normalized to 25 ºC. Various locations where soft subgrade soil occurs (< 30 MPa) can be observed throughout the section.

The mean asphalt modulus, listed in

Table 1, is considerably lower than typical (3000-4000 MPa) values expected for new asphalt concrete, indicating a generally high levels of damage, which was supported by the visual evidence of distress along the section.

The layer thicknesses and moduli were used to calculate the tensile strain at the bottom of the asphalt concrete layer and the vertical stress on the subgrade, based on linear elastic layered theory using ELSYM-5. These stresses and strains were used to evaluate the number of load applications required before failure, using the Asphalt Institute equations for subgrade rutting, shown in Equation 1, and asphalt concrete fatigue, shown in Equation 2 (3).

$$N_{f,AC} = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3} \qquad (1)$$

where:

$N_{f,AC}$ is the load applications until fatigue failure of the asphalt concrete;
ε_t is the tensile strain at the bottom of the asphalt concrete layer;
E_1 is the 25 Hz dynamic elastic modulus of the asphalt concrete; and,
f_1 = 0.0796, f_2 = 3.291, and f_3 = 0.854 are empirically established parameters.

$$N_{f,SG} = f_4(\varepsilon_v)^{-f_5} \qquad (2)$$

where:

$N_{f,SG}$ is the load applications until rutting failure of the subgrade;
ε_v is the vertical stress being applied to the subgrade;
$f_4 = 1.365(10^{-9})$ and $f_5 = -4.477$ are empirically established parameters.

While the resulting strains exceed the 50-300 $\mu\varepsilon$ range which is generally assumed to represent linear elastic behavior in asphalt concrete, the resulting service life estimates appear to match the distress levels visually observed on the pre-rehabilitation pavement surface. Figure 4 shows the variation in the predicted service life using the fatigue and rutting models described previously, based on the number of load applications to failure and the design traffic of 274 ESAL/year. It is evident that asphalt concrete fatigue is the limiting failure mode at all test locations, with approximately 22% of the section exhibiting less than three years of remaining service life. Severe cracking and distortions in the pavement surface indicated a loss of base/shoulder support near the pavement edge in many locations. It was expected that the FDR would provide a strong base layer that will help prevent these local support loss failures.

PC-FDR MATERIAL DESIGN AND CONSTRUCTION

The mixture design of the PC-FDR material was conducted by Jacques Whitford and was based on the optimum moisture content to achieve maximum dry density and the optimum Portland cement content to achieve a 7-day UCS of 2.1-2.8 MPa. The design job mix formula, expressed as percentage by mass, consisted of 47% Recycled Asphalt Pavement (RAP) and 47% of the in-place granular material, with 6% Portland cement. Figure 6 shows the gradation of the in-place granular materials, RAP and blended job mix aggregate used for design of the PC-FDR material. The optimum moisture content of 5.9% resulted in a maximum dry density of 2052 kg/m^3 using standard Proctor compaction. The 7-day UCS of the mixture was 2.2 MPa. Additional design considerations may include permeability and freezing and thawing durability (4).

The total asphalt concrete thickness plus a portion of the upper granular layer were pulverized using a Wirtgen WR2500S reclaimer/mixer to a total depth of approximately 200 mm. The pulverization process breaks down the damaged asphalt concrete to a granular material and mixes it with the upper portion of the granular base materials, creating a well blended mixture of RAP and base aggregate. This material was re-compacted immediately after pulverizing to permit use by local traffic until the Portland cement stabilization process could be started.

Portland cement was later added using a modified drop spreader directly onto the compacted pulverized granular material. This was followed by the Wirtgen WR2500S which re-pulverized and mixed the granular material plus the Portland cement to a depth of approximately 150 mm. Moisture was added through the WR2500S from a water supply truck during the pulverization process to achieve the optimum moisture content required for compaction. A Dynapac sheepsfoot roller was used to achieve deep compaction of the PC-FDR material after the mixing process, followed by final grading to specifications, and compaction using a steel vibratory roller. The equipment train used in stabilizing the material is shown in Figure 7.

The completed PC-FDR base was moist-cured for seven days using water sprayed over the surface of the material across each lane width via an array of nozzles positioned behind a water supply truck. After 24-48 hours of curing, the same steel drum vibratory roller that was used for final compaction was used to create a network of fine microcracks in the PC-FDR using the maximum vibration setting. Moisture curing, which continued for seven days following the cement stabilization process, enabled the PC-FDR material to recover from the microcracking process by regaining its strength and stiffness, yet retaining the network of weakened fracture planes. Microcracking also serves to permit moisture ingress into the PC-FDR to aid in internal curing, replacing moisture consumed during hydration.

The roller pattern required to achieve the desired 40% reduction in stiffness was established using an Olson Instruments Freedom NDT PC system with a Slab Impulse-Response (Slab IR) module which provided the near-surface stiffness, k (MN/m), of the layered pavement system. The Slab IR test consists of a field computer and data acquisition system, an instrumented 3 lb impulse hammer, and a 4.5 Hz geophone. The pavement stiffness is measured as the slope of the mobility (variation in force/displacement over frequency) curve between 30-80 Hz. The Slab IR system used for measuring the PC-FDR stiffness, shown in Figure 7, was preferred over testing using the FWD since it was less expensive, provided a fast measurement technique (1-

2 minutes per location) and results were displayed immediately on the computer, making it suitable for establishing the required number of complete roller passes in real time.

Figure 8 shows the effects of three full roller passes (one full pass entails travel both forward and reverse along the subsection) resulting in 46%-56% stiffness reductions in half of the test locations, with 16%-35% reductions in the remaining locations. Four full passes were recommended for ensuring that the 40% minimum stiffness reduction was achieved in the majority of the PC-FDR material.
Figure 9 demonstrates the difference in surface smoothness between the pre-microcracked (top) and post-microcracked (bottom) PC-FDR.

Approximately 65 mm of Type C-HF asphalt concrete was later placed over the PC-FDR layer to provide additional strength and a durable wearing surface for the rehabilitated pavement system.

POST-REPAIR EVALUATION

Follow-up testing of the rehabilitated pavement was conducted using both GPR and FWD on November 15, 2007. The mean asphalt thickness was measured to be 61 mm with a standard deviation of 12 mm. The interface between the PC-FDR layer and the underlying granular material was not well defined in the GPR data except where strata reflections within the granular materials appeared to be cut off as a result of the pulverization. It is expected that the PC-FDR mixture did not differ enough in electrical properties from the underlying granular materials to produce identifiable reflections in the data. An estimate of the variations in PC-FDR thickness was made by tracking the bottom ‘edge’ of this relatively reflection-less zone in the GPR data. The mean thickness of the PC-FDR was estimated to be 165 mm with a standard deviation of 16 mm.

Backcalculation procedures tend to be insensitive to the asphalt concrete modulus when its thickness is less than approximately 75 mm, so a nominal layer modulus of 2750 MPa was set as a constant for the backcalculation and may be considered to be representative of local asphalt mixtures placed at 92.5% compaction. Setting the asphalt modulus to a fixed value enabled the backcalculation procedure to evaluate the moduli of the remaining material layers. However, it was necessary to also fix the modulus of the granular materials to its average stiffness of 282 MPa as measured in the pre-rehabilitation deflection testing in order to produce acceptably small errors between the measured and modeled deflections. The granular layer modulus was not expected to be significantly altered by the repair since its structure remained relatively unchanged by the process, except where its surface had been incorporated into the PC-FDR layer.

The mean elastic modulus of the PC-FDR was 7465 MPa with a standard deviation of 4684 MPa. The large standard deviation is expected due to a combination of material variability coupled with variations in the backcalculation arising from maintaining constant asphalt and granular layer moduli. The mean subgrade modulus was 106 MPa with a standard deviation of 30 MPa. This increase from the pre-rehabilitation subgrade modulus is thought to be a result of ditching that was completed as part of the rehabilitation project, which is assumed to have lowered the relatively high moisture content of the subgrade soil. Figure 10 shows the variation in the post-rehabilitation layer moduli over the length of the test section. Similar trends with respect to the 'soft spots' in the subgrade moduli before and after repair can be observed.

The service life analysis considered fatigue in the asphalt concrete and the PC-FDR, as well as rutting in the subgrade, based on the appropriate stresses and strains under a 40 kN load using the backcalculated moduli at each deflection location. The NCHRP fatigue model for cement stabilized materials (4) was used and is sown in Equation 3. A relationship between modulus of rupture and elastic modulus was provided by Dr. Tom Scullion (5) of the Texas Transportation Institute and is shown in Equation 4. The failure mode predicted for every test location was always fatigue of the PC-FDR. On average, 14.7 million repetitions of the single wheel 40 kN design would be required to cause fatigue failure in the PC-FDR for this specific pavement system, while the required repetitions for subgrade rutting failure and asphalt fatigue were one to four orders of magnitude higher. However, given that some of the test locations exhibited considerably lower PC-FDR modulus values, or thin pavement thickness which led to excessive tensile stress at the bottom of the PC-FDR layer, a certain proportion of the pavement will exhibit fatigue failure at considerably lower load repetitions. Over a 20-year design period, using 274 ESAL/year and assuming no traffic growth, the model predicts approximately only 3% of the pavement section will exhibit fatigue failure in the PC-FDR layer.

$$N_{f,CTB} = \frac{0.972(\beta_{c1}) - (\sigma_t / M_R)}{0.825(\beta_{c2})} \qquad (3)$$

where:

$N_{f,CTB}$ is the load applications until fatigue failure of the cement treated base;
σ_t is the tensile stress being applied to the cement treated base;
M_R is the modulus of rupture of the cement treated base; and,
$\beta_{c1} = 1.0645$ and $\beta_{c2} = 0.9003$ are field calibration factors

$$M_R = 7.3\sqrt{E_{FDR}/1200} \qquad (4)$$

where:

M_R is the modulus of rupture of the cement treated base; and,
E_{FDR} is the elastic modulus of the cement treated base.

It is interesting to compare the performance of the rehabilitated section to that of the original pavement structure, as if it were new. Using an asphalt concrete thickness of 132 mm and 3100 MPa elastic modulus, placed on 297 mm of 282.3 MPa granular base and a 37.9 MPa subgrade (measured mean value reduced to 70% for spring thaw conditions), only 5964 repetitions of the 40 kN design load would be required to cause fatigue failure in the asphalt concrete. Considering the design traffic volume of 274 ESAL/year, this translates to approximately 21.7 years of expected service life. This comparison is supported by reports of the life cycle cost benefits reported by the Ministère des Transports du Québec. PC-FDR offers superior performance in terms of its benefit/cost ratio when life cycle costs are considered, with most reclamation techniques exhibiting performance gains of 10-48% compared to asphalt resurfacing (6).

It becomes obvious that this pavement system provides far more capacity than is required for the very low traffic volume of 274 ESAL/year. Using a typical 20 year design period and assuming zero growth in traffic volumes, Table 2 lists the total ESAL and the ESAL/year required over a 20-year design life to cause fatigue failure of the PC-FDR in a range of 10-50%. Considering that almost 22% of the pre-repair pavement section had less than three years of service life remaining, Table 2 indicates that the rehabilitation has resulted in an increase in capacity of approximately 112,700 ESALs from the pre-repair condition. This data may be useful as a guide in determining if a particular highway may be a suitable candidate for PC-FDR using a similar combination of 150 mm PC-FDR overlain with 65 mm of asphalt concrete, if similar granular and subgrade conditions exist.

A less expensive alternative to a hot-mix asphalt overlay might be to apply a chip seal wearing surface to the PC-FDR. Various thicknesses of PC-FDR were modeled, over a typical range of PC-FDR moduli, using 250 mm of 150 MPa granular materials placed on 50 MPa subgrade in order to evaluate the predicted fatigue performance of the PC-FDR. Table 3 lists the total number of ESALs required to cause fatigue failure of the PC-FDR layer, according to various thicknesses and moduli.

Table 4 lists the same information in terms of the number of ESAL/year assuming zero growth in traffic volumes.

Considering the average modulus measured from the PC-FDR layer on the Point Michaud Road test section, it appears from Tables 3 and 4 that a suitable alternative design using 225 mm of PC-FDR plus a chip seal surface treatment may provide adequate fatigue resistance. More typical rural highway volumes may require PC-FDR thickness ranging from 250-275 mm in accommodating 30-500 thousand ESAL/year, while higher volume highways with 1.25 to 5 million ESAL/year may provide suitable candidates for repair using at least 300 mm of PC-FDR. It is cautioned that the actual design should consider the distribution of elastic moduli values provided in the recycled pavement layer and the effect this will have on the model for predicting fatigue life of a particular project. Figure 11 shows the distribution of the backcalculated elastic modulus values from the Point Michaud Road PC-FDR material. The moduli exhibit significant variability compared to a new HMA, but this tends to be typical of recycled materials. Approximately 33% of the modulus values are below 5000 MPa, which according to

Table 4, would result in a similar percentage of fatigue failure over 20 years if the granular and subgrade moduli were 150 MPa and 50 MPa, respectively, and the design traffic were 802 ESAL/year.

An optimal design should include prior detailed testing of a candidate rehabilitation section to determine the granular and subgrade moduli, remaining service life of the pavement structure, and to assess the requirements for ditching/drainage improvements. It should also be noted that many rural highway candidates contain varying thicknesses of existing asphalt concrete and underlying granular materials, so it is recommended that thickness surveys of potential rehabilitation candidates also be conducted in order to evaluate the relative proportions and properties of RAP and granular materials that will be available for producing the desired thickness of PC-FDR material. Other design aspects to consider may include evaluating aggregate blends and cement content required to help prevent moisture ingress/suction into the recycled material (7)(8).

The fatigue models used in this study indicate that the use of this technology for rehabilitating rural highways in Nova Scotia may significantly decrease life cycle maintenance costs by providing considerable increases in fatigue life and reductions in subgrade rutting and asphalt concrete fatigue. Given comparable average 2008 construction costs to other paving methods listed in Table 5, and the expected improvements in service life, the method appears to provide a very promising cost-effective repair method for significantly damaged rural highways. Further research should evaluate the performance of this material in the extreme exposure conditions that exist with regards to frost heave and repeated cycles of freezing and thawing. Additional research should examine mechanistic characterization and performance modeling of various repair techniques to determine the appropriateness of each method.

CONCLUSIONS

Approximately 22% of the Point Michaud Road project exhibited less than three years of remaining service life, according to the Asphalt Institute fatigue model, and appeared to closely reflect the condition of the road based on visual inspection of the pavement cracking. The combination of 150 mm of PC-FDR overlain with 65 mm of Type C asphalt concrete increased the fatigue service life of Point Michaud Road by approximately 112,700 ESAL, or 411 years of current traffic loading. The predicted failure mode of the rehabilitated pavement was always fatigue cracking of the PC-FDR prior to fatigue failure of the asphalt concrete wearing surface or 10 mm of permanent rutting in the subgrade. According to the fatigue models, PC-FDR provides significantly longer service life under traffic loading, compared to a total of 5964 ESAL, or 21.7 years, attainable by full depth replacement of the asphalt concrete. The rehabilitated pavement is not expected to fail under the existing traffic loading, unless a certain portion of the truck traffic impacts significantly heavier loads than the standard 40 kN design load to the pavement.

Predicted fatigue life was evaluated for various PC-FDR pavement thicknesses, ranging from 225-300 mm, with a non-structural chip seal wearing surface. A minimum thickness of 225 mm may be used for very low volume rural roads such as Point Michaud Road. PC-FDR thickness in the range of 250-275 mm may be more appropriate for more typical rural collector highway volumes of 30-500 thousand ESAL/year, while 300 mm appears to provide sufficient capacity for high volume (1.25 – 5 million ESAL/year) highways. Future design work should include detailed thickness surveys and in-situ material characterization in order to evaluate the materials and remaining service life of the existing pavement, the PC-FDR thickness required for the design period traffic volume, and the expected relative proportions of RAP and granular base in the proposed PC-FDR in case additional corrective aggregate or RAP may be required.

PC-FDR appears to provide a significant improvement in the expected service life of Point Michaud Road. This rehabilitation method may considerably reduce the life cycle maintenance costs for rural highways in Nova Scotia. Further research should evaluate the performance of the PC-FDR material against rupture caused by frost heave and material degradation through repeated cycles of freezing and thawing. Furthermore, mechanistic evaluation and performance modeling for various repair alternatives should be conducted to support the appropriateness of each method.

REFERENCES

1. Scullion, T. (2002). “Precracking of Soil-Cement Bases to Reduce Reflection Cracking”, Transportation Research Record 1787, Transportation Research Board, Washington, D. C.

2. Sebesta, Stephen. (2005). “Use of Microcracking to Reduce Shrinkage Cracking in Cement Treated Bases”, Transportation Research Record 1936, Transportation Research Board, Washington, D. C.

3. National Cooperative Highway Research Program (NCHRP) (2007). Washington, DC. NCHRP 1-37A Design Guide, http://www.trb.org/mepdg/guide.htm. Accessed Dec. 1, 2007.

4. Miller, H.J., Guthrie, W.S., Crane, R.A., Smith, B. (2006). “Evaluation of Cement-Stabilized Full-Depth-Recycled Base Materials for Frost and Early Traffic Conditions”, http://www.rmrc.unh.edu/Research/past/P28/p28final.pdf. Accessed Dec. 7, 2007.

5. Scullion, Tom (2007). Personal e-mail communication. December, 16, 2007.

6. Bergeron, G. (2005) “The Performance of Full-depth Reclamation and Cold In-place Recycling Techniques in Quebec”, Annual Conference of the Transportation Association of Canada, Calgary, Alberta.

7. Guthrie, W.S., Cooley, D., and Eggett, D. (2005) “Effects of Reclaimed Asphalt

Pavement on Mechanical Properties of Base Materials", Transportation Research Record 2005, Transportation Research Board, National Research Council, Washington, D.C., pp. 44-54.

8. Scullion, T., and Saarenketo, T. (1997). "Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials", Transportation Research Record 1577, Transportation Research Board, National Research Council, Washington, D.C., pp. 37-44.

Figure 1 - Simultaneous GPR and FWD data collection on the pre-rehabilitation pavement surface.

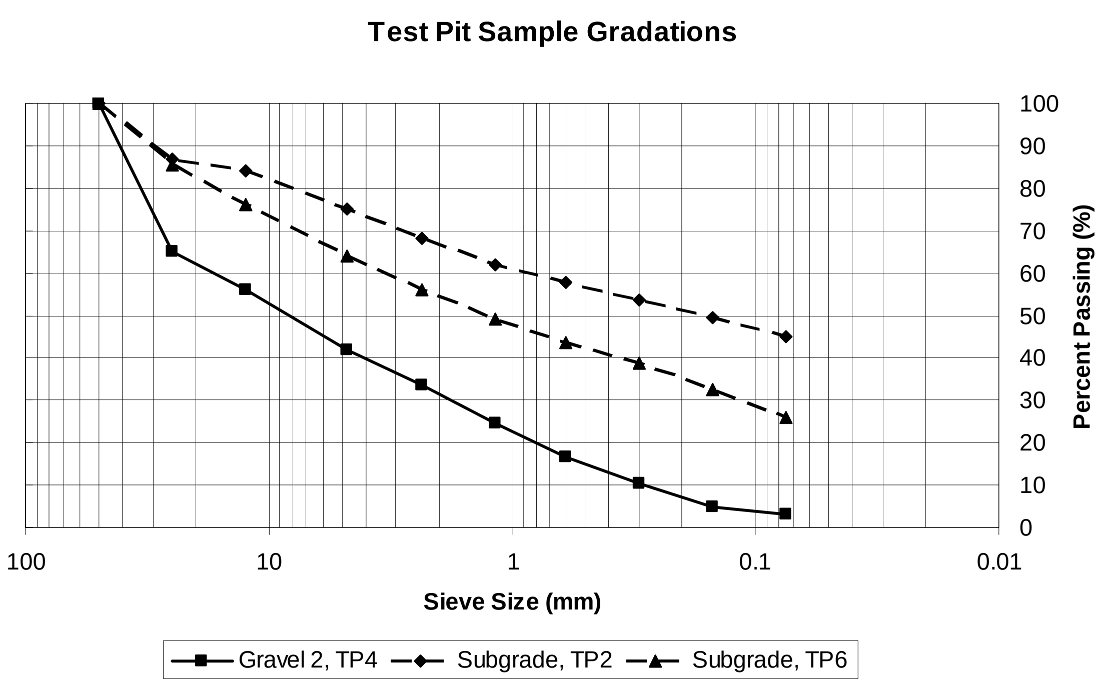

Figure 2 - Gradations of test pit material samples.

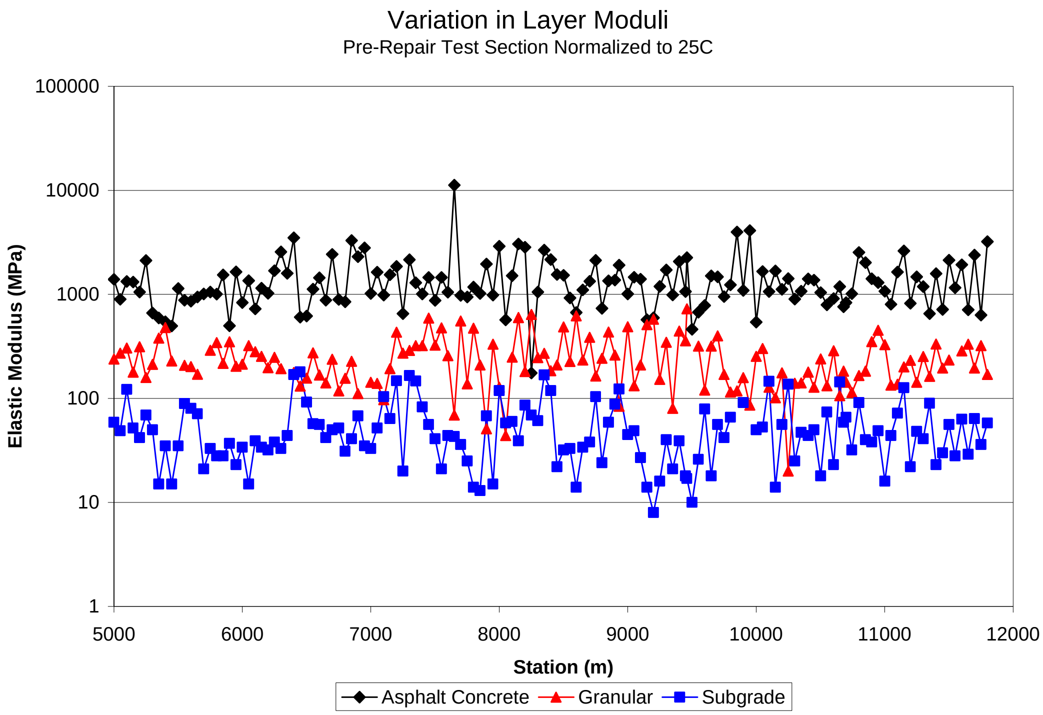

Figure 3 - Variation in moduli for asphalt concrete, granular base, and subgrade.

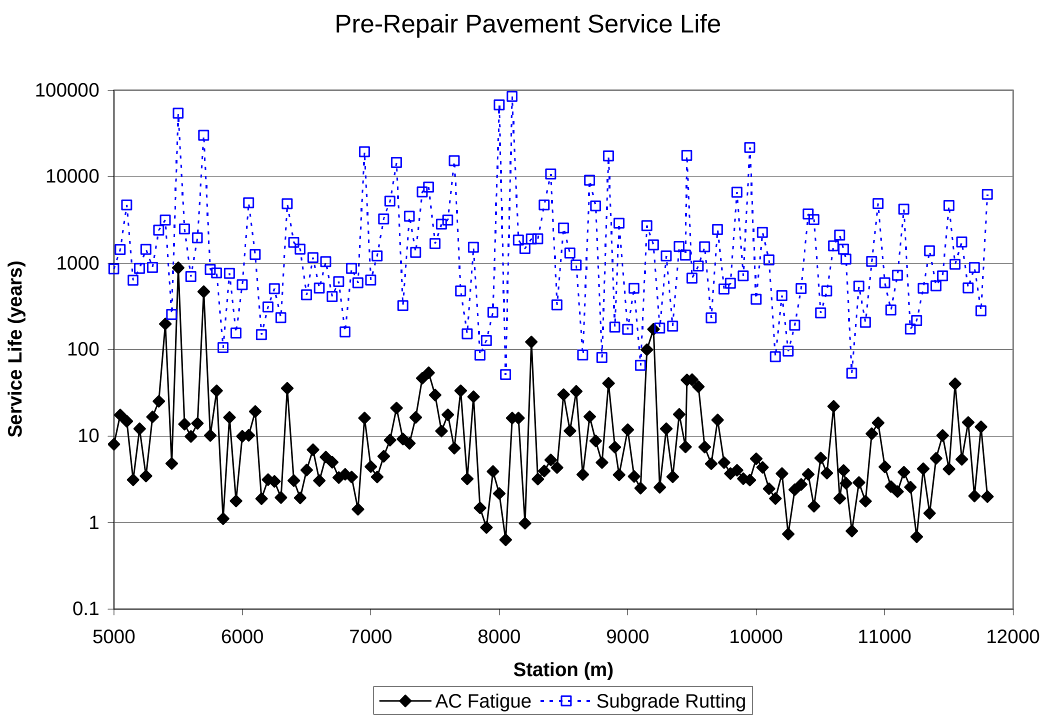

Figure 4 - Predicted service life of the pre-repair test section.

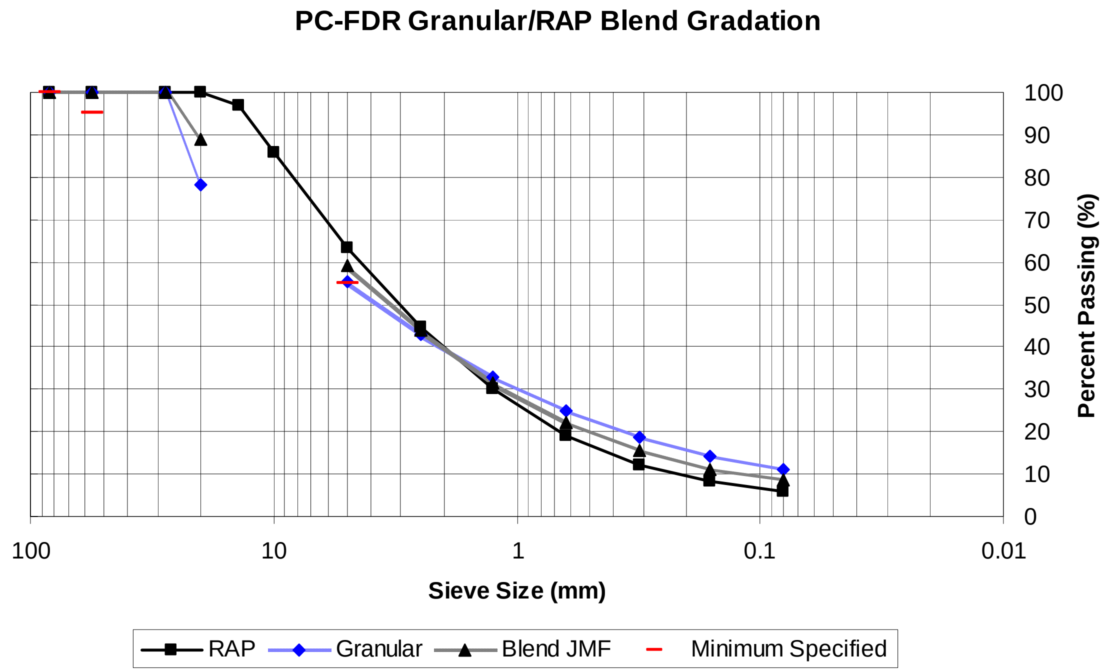

Figure 5 - Gradation of the in-place granular materials, RAP, and blended job mix aggregate used in the PC-FDR mixture design.

Figure 6 - Stabilization of the FDR.

Figure 7 - Slab IR test system used to measure PC-FDR pavement stiffness.

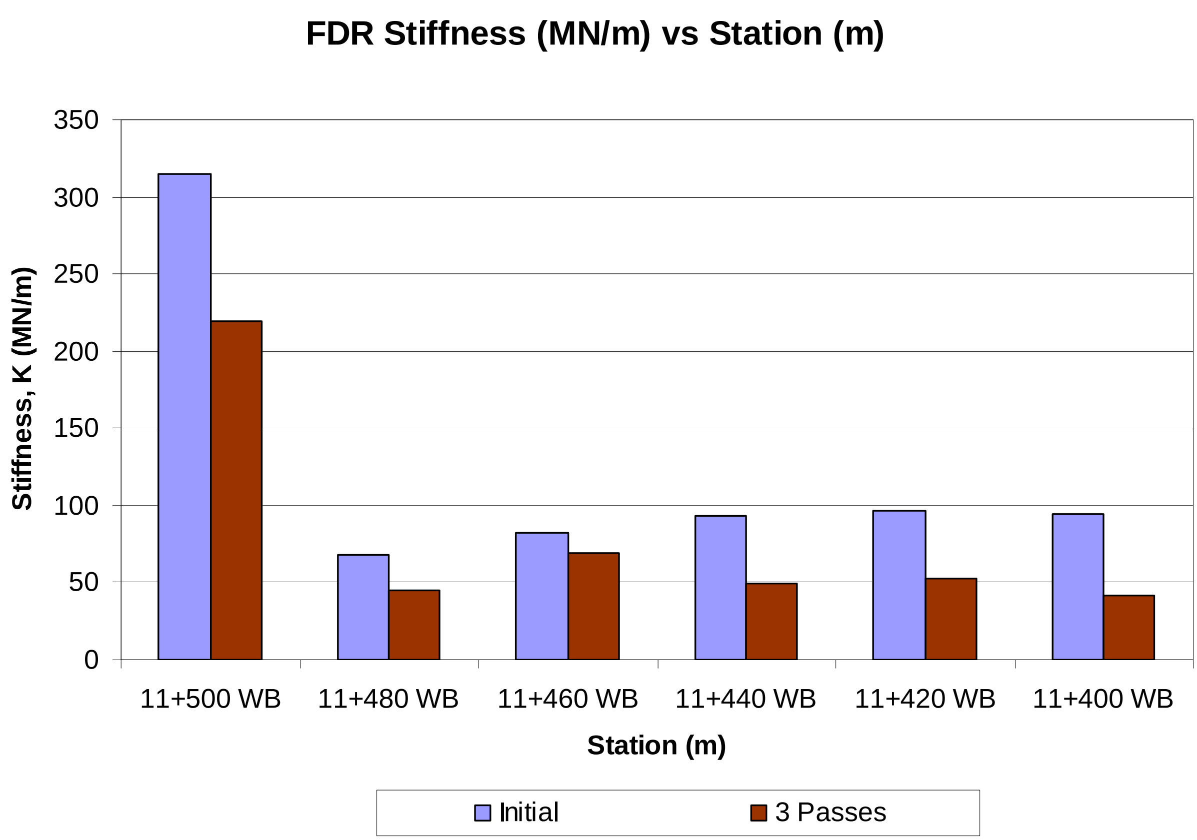

Figure 8 - Stiffness reductions resulting from three complete roller passes.

Figure 9 - Comparison between pre-microcracked (top) and post-microcracked (bottom) PC-FDR.

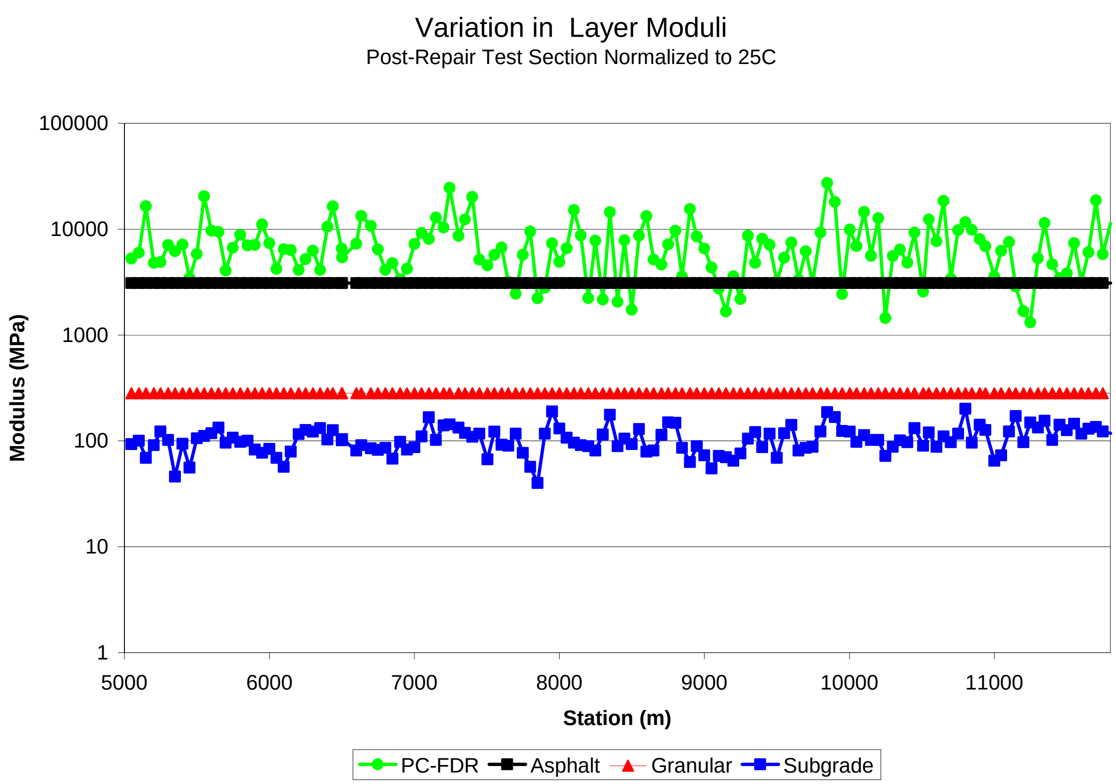

Figure 10 - Variations in post-rehabilitation elastic moduli.

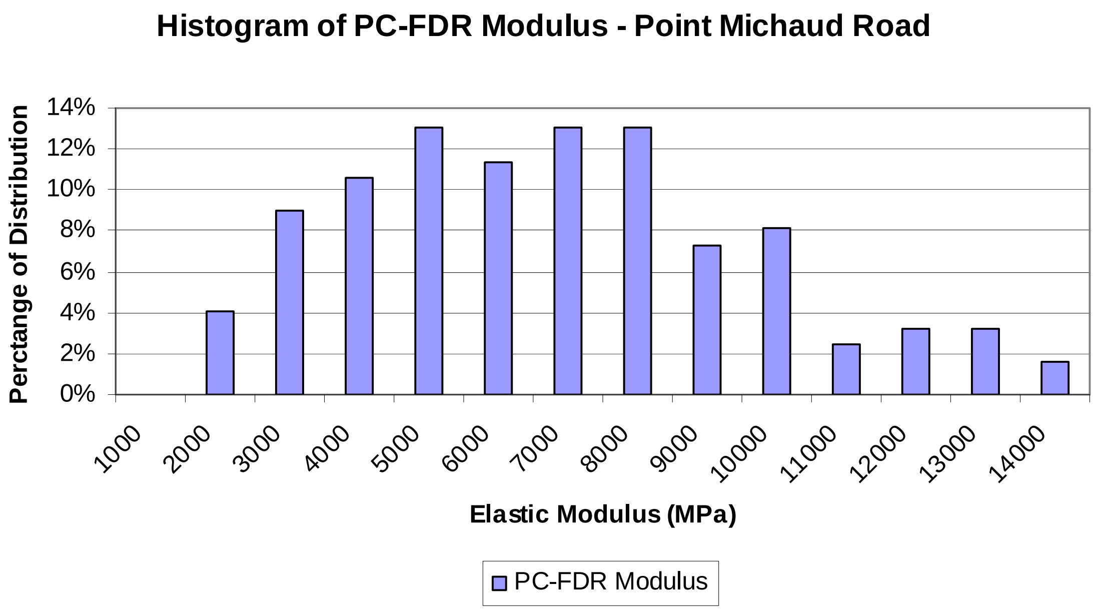

Figure 11 - Histogram of PC-FDR modulus values for Point Michaud Road.

Table 1 - Backcalculated pre-repair layer moduli.

Material	Mean (MPa)	Standard Deviation (MPa)
Asphalt Concrete	1443.4	1105.0
Granular	282.3	135.4
Subgrade	54.2	37.5

Table 2 - Design traffic required for various levels of PC-FDR fatigue.

	Level of Overall PC-FDR Fatigue Failure					
	10%	15%	20%	30%	40%	50%
Total ESAL	37082	63313	99002	171717	279272	397484
Annual ESAL/yr	1850	3150	4950	8575	13950	19875

Table 3 - Design traffic required (Total ESAL) for PC-FDR fatigue failure with chip seal surface treatment.

PC-FDR Modulus (MPa)	PC-FDR Thickness			
	225 mm	250 mm	275 mm	300 mm
3000	1283	75029	1.8 (10^6)	22.0 (10^6)
4000	5033	244899	5.0 (10^6)	54.5 (10^6)
5000	16035	663479	11.9 (10^6)	116.2 (10^6)
6000	43084	1.5 (10^6)	24.7 (10^6)	219.2 (10^6)
7000	100907	3.2 (10^6)	46.0 (10^6)	376.9 (10^6)
8000	211768	6.0 (10^6)	79.2 (10^6)	602.8 (10^6)
9000	407731	10.4 (10^6)	90.9 (10^6)	909.4 (10^6)

Table 4 - 20 Year Design traffic required (ESAL/yr) for fatigue failure in a PC-FDR + chip seal surface treatment repair over typical range of PC-FDR moduli.

PC-FDR Modulus (MPa)	PC-FDR Thickness			
	225 mm	250 mm	275 mm	300 mm
3000	64	3,751	89,269	1,101,708
4000	252	12,245	250,754	2,726,661
5000	802	33,174	596,008	5,810,804
6000	2,154	77,380	1,234,213	10,962,065
7000	5,045	159,790	2,302,213	18,846,457
8000	10,588	299,732	3,958,102	30,138,611
9000	20,387	522,334	6,364,999	45,469,410

Table 5 – Examples of 2008 paving repair costs in Nova Scotia by method.

Method	Cost per km
Widening + Gravel sandwich: 160 mm Type 1 gravel + 1 lift CHF	$390,000
Foamed FDR + 1 lift CHF	$378,000
Partial Depth CIP	$324,000
HMA leveling + overlay	$332,000
PC-FDR + 1 lift CHF	$349,000
PC-FDR + 1 lift CHF	$315,000