Verification of Pavement Design Methodologies Using Measured In-Situ Response on an Urban Highway

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ABSTRACT: There are a number of theoretical models used to predict pavement rutting and fatigue cracking. It is important that the parameters used in the models be measured on site and not only assumed theoretically. The best way to confirm design predictions is to use data collected from instrumented in-service pavement sections. The City of Hamilton constructed a perpetual pavement on the Red Hill Valley Parkway (RHVP) in 2007 that was designed using the AASHTO 93 methodology. To verify the pavement design and predict the performance, the City installed a pavement monitoring station consisting of two systems. The traffic system includes inductive loops and weigh-in-motion sensors. The pavement response system includes asphalt strain gauges, subgrade pressure and moisture gauges and temperature probes. The installed systems allow a comparison between the calculated and measured strains in the pavement structure due to vehicular loading. They also reflect the changes in the Hot Mix Asphalt (HMA) and other layers caused by the fluctuations in temperatures and moisture within the pavement structure. In the completed analysis, the numbers of strain repetitions applied to date were compared with the repetitions anticipated in 50 years. Also, the life of the pavement with respect to rutting and fatigue was calculated using the measured parameters and available performance models.

KEYWORDS: Traffic loading, pavement response, performance modeling.

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1. INTRODUCTION

The City of Hamilton constructed the Red Hill Valley Parkway (RHVP) in 2007 as the first municipal perpetual pavement in Canada. The total length of this section is about 7.5 km with four lanes (two lanes in each direction) and a 90 km/hour posted speed with controlled access. The pavement was designed for a traffic loading of 90 million Equivalent Single Axle Loads (ESAL's) over 50 years using the American Association of State Highway and Transportation Officials (AASHTO) 1993 pavement design methodology (AASHTO 1993) and verified using mechanistic-based methodologies including PerRoad program (Timm 2004). The pavement structure consists of a 40 mm Stone Mastic Asphalt (SMA) surface course, a 50 mm Superpave™ 19.0 upper binder course, a 70 mm Superpave 25.0 lower binder course, a 80 mm Rich Bottom Mix (RBM) layer, 150 mm of granular base, and 370 mm of subbase. More information about the design and construction of the pavement on the RHVP is given in (Uzarowski et al.2008).

2. PAVEMENT PERFORMANCE MONITORING STATION

In order to verify the performance of the pavement materials under Hamilton conditions, verify the perpetual pavement design on the RHVP, predict the performance of the pavement and validate the initial mechanistic analysis used at the design stage, the City decided to install a pavement performance monitoring station. The monitoring station includes a traffic monitoring system and pavement response system.

2.1 Traffic System

Since the RHVP is one of the main routes in Hamilton, the City decided to also install a traffic monitoring system in the pavement. The system includes traffic loops and weigh-in-motion (WIM) sensors.

Traffic loops were installed in all four lanes of the RHVP. High accuracy Kistler WIM sensors were installed in both northbound lanes and piezoelectric sensors were installed in both southbound lanes. The pavement response sensors are installed in Lane 2 (slow lane) in the northbound direction.

A typical output from the traffic system is shown in Figure 1. The number of vehicles, class, gross vehicle weight, length, speed, spacing, time and loading applied by each wheel and the total weight is recorded and stored in the traffic system. iANALYZE software (IRD 2007) developed by International Road Dynamics (IRD) is being used for traffic analysis on this project.

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(41146) LANE NB_RL  CLASS 6  GVW 10.6 tonnes  LENGTH 833 cm
SPEED 88 kph  MAX GVW 22.7 tonnes Fri Jul 17 2009 11:21:10 (2983)
AXLE    SEPARATION     LEFT WT     RIGHT WT     TOTAL WT    ALLOWABLE
           (cm)         (kg)         (kg)         (kg)         (kg)
 1                      2386         1709         4095         5670
 2          449         2386         1260         3646         7711
 3          135         2008          828         2836         7711
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Figure 1: Typical Information Recorded for a Passing Vehicle by the Traffic System

2.2 Pavement Response System

The pavement response system includes the pressure and moisture gauges in the subgrade, asphalt strain gauges at the bottom of the RBM, Superpave 25.0 and SMA layers, as well as temperature sensors in the subgrade, subbase, granular base and each asphalt layer. CTL asphalt strain gauges, type CEA-06-125UT-350, Geokon model 3500 pressure cells with scale ranges of 250 kPa and Hydraprobe soil sensors with data readings in units of water fraction by volume (wfv) were installed in the pavement structure. Two temperature trees were constructed with sensors at various heights (all of which are Maxim – ID DS18B20 Digital Thermometers) and are built into the pavement structure. The overall instrumentation system is based on the systems used for pavement monitoring of test tracks in the United States. Figure 2 shows the installation of the pressure and moisture gauges in the subgrade and at the bottom of the RBM.

Figure 2: Installation of Pressure Gauges in Subgrade and Asphalt Gauges at the bottom of the RBM.

The traffic data is synchronized with the pavement response data. The combination of these two systems not only allows for the analysis of the strains in the pavement but also the relationship with the induced strains and pressures and loads causing these strains.

3. TRAFFIC LOADING ON RHVP

The data from the traffic system recently indicated that about 34 million vehicles have used the RHVP since the opening in November 2007. Immediately after opening, the traffic volumes were between 30,000 and 35,000 vehicles per day, while in June 2009 the volumes had increased to between 55,000 and 60,000 vehicles per day.

The traffic system uses the FHWA vehicle classification system (IRD 2007). About 2.8 million Class 4 to 6 light trucks and busses, and about 1.4 million Class 7 to 13 heavy trucks have used the RHVP so far. In total, about 12.7 percent of the vehicles are trucks.

The amount of data collected at the monitoring station is large; all of the 32 channels connected to the installed sensors, for instance, are scanned 25 times per second and the data is stored in the system. For the initial analysis described in this paper, only the data collected on selected, representative days was analysed. The fall conditions were assumed to be represented by the data collected on November 24, 2008, severe winter conditions (frozen pavement) on January 18, 2009, spring conditions on March 30, 2009 and summer conditions on June 9, 2009. Table 1 shows a summary of traffic analysis on these selected days.

Table 1: Summary of Traffic on Selected Days (in Lane 2 in Northbound Direction).

Date	Daily Traffic Count (number of vehicles)	Vehicles Class 4 to 6		Vehicles Class 7 to 13		Total Daily ESAL's
		Count	Average Truck Factor	Count	Average Truck Factor	
November 25, 2009	15,895	760	0.14	1,071	2.16	2,420
January 18, 2009	8,798	155	0.08	192	1.11	226
March 30, 2009	16,455	1,015	0.16	966	2.52	2,597
June 6, 2009	17,761	1,016	0.18	1,204	2.76	3,506

The average truck factor, calculated on a daily basis, ranged from 0.08 to 0.18 for light trucks and 1.11 to 2.76 for heavy trucks. After 20 months of service, the pavement on the RHVP in Lane 2 in the northbound direction had carried about 1.9 million ESAL's. Vehicles Class 1 to

3 have almost no impact on the structural condition of the pavement and were not included in the analysis.

It was observed that a significant number of heavy vehicles had wheel loads higher than 40 kN. About 20 percent of trucks had wheel loads between 40 and 50 kN, with about 4 percent in excess of 50 kN.

The speed limit on the RHVP is 90 km/hour. Only about 10 percent of vehicles drive more than 5 km/hour below the speed limit, i.e. less than 85 km/hour.

4. TEMPERATURE AND MOISTURE VARIATIONS

The temperature is measured at six different locations in the pavement structure: the SMA surface course; the Superpave 19.0 upper binder course; the Superpave 25.0 lower binder course; the RBM layer; the granular base; and the subgrade. The measured RBM temperature was higher than the air temperature by 2°C to 10°C.

The subgrade moisture content was very low (about 4 to 6 percent) at the time of construction during the hot, dry summer of 2007. This is likely one of the main reasons why the subgrade modulus backcalculated from the FWD testing described in Section 5.0 was very high. There were some problems with the moisture sensors in the subgrade and few readings were available. As the drainage system is new and working well, the current moisture contents of the subgrade and granular base are low (only 2 to 4 percent).

5. MECHANISTIC CHARACTERISTICS OF MATERIALS

Besides the conventional characteristics such as mix gradations, asphalt cement content and volumetrics, the mix performance characteristics were also determined at the mix design stage. They included dynamic modulus, rutting resistance in the Asphalt Pavement Analyzer (APA) and fatigue endurance.

The dynamic modulus was used in the pavement performance mechanistic analysis. As the vehicle speed on the RHVP used in the analysis was assumed to be 90 km/hour, the values of the dynamic modulus determined at 5 temperatures ranging from -10°C to 54.4 °C and frequencies ranging from 0.1Hz to 25 Hz had to be extrapolated to carry out modelling. The modulus values were extrapolated to the corresponding frequency values to 90km/hr at a temperature of 21°C and for the SMA mix was 11,700 MPa and for RBM was 14,000 MPa. Table 2 shows a summary of the rutting resistance testing results. The maximum acceptable limit was 5.0 mm after 8,000 passes in the APA testing. The Superpave 19.0, Superpave 25.0 and RBM mixes exhibited very good resistance to rutting with the depth of the rut in the APA less than 5.0 mm; the SMA had exceptional resistance to rutting with the rut depth of only 3.80 mm.

Table 2: Summary of Asphalt Mix Resistance to Rutting Testing Results

Mix Type	Rut Depth in APA (mm)
Stone Mastic Asphalt	3.80
Superpave 19.0	4.89
Superpave 25.0	4.49
Rich Bottom Mix	4.64

A Falling Weight Deflectometer (FWD) load/deflection survey was carried out at a few selected locations on the surface of the granular base before the placement of the asphalt layers in the summer 2007. The backcalculated average modulus of the granular base was about 500 MPa and for subgrade close to 400 MPa. It should be noted that the construction of subgrade and granular layers was completed in 2006 and the granular base was only recompacted in 2007. The subgrade excavated for the sensors installation in 2007 was observed to be very dry and very strong.

6. PAVEMENT RESPONSE

The pavement response analysis included measurements of asphalt strains and subgrade pressure. The vertical compressive strain in the subgrade was calculated using the measured pressure values. The relationship between the applied wheel load and asphalt strains and subgrade pressure were also analyzed. Live wheel load versus strains in all asphalt layers were developed using the July 3, 2009 data. Data collection is ongoing.

6.1 Strains and Pressure in Pavement Structure

The strains were measured in the longitudinal and transverse direction in the RBM and Superpave 25.0 layers, but only the transverse direction in the SMA surface course. As the strains in the longitudinal direction were about 3 to 10 times lower than those in the transverse direction, it was assumed that they would have insignificant impact on asphalt cracking and were not included in the analysis.

Figure 3 shows an example of asphalt strains and subgrade pressures recorded for a passage of three axle truck. The changes in the voltage in the asphalt sensors were then converted into strains following the manufacturer's procedure and the provided calibration factors.

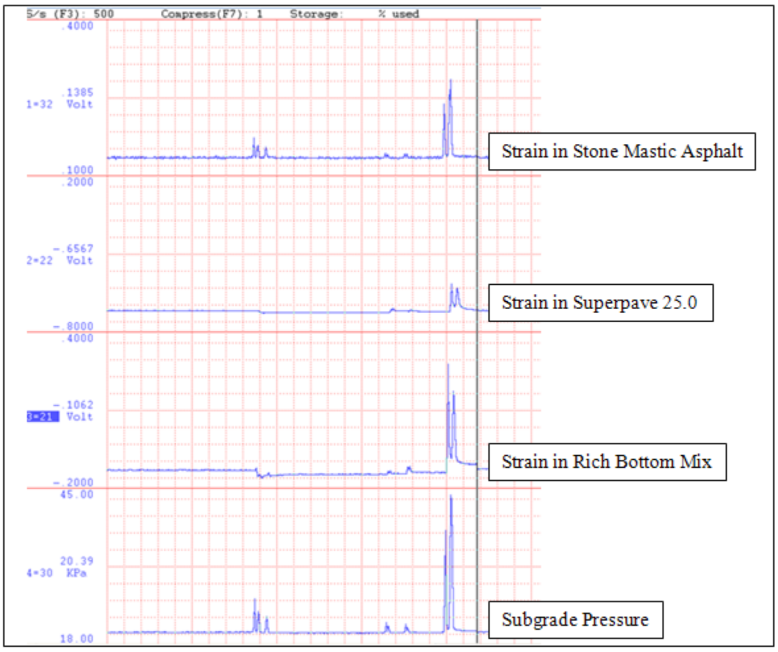

Figure 3: Example of Strains and Pressure Recorded for a Passage of a Three Axle Truck. Note: the vertical volt scale (representing strain) is different at each location.

It should be noted that, as the sensors were installed on an operating highway, not all wheels pass directly over the sensors. In the live wheel load versus strain analysis, only the loads that passed directly over the sensors were analyzed. The determination of whether a vehicle has passed over the strain gauge is determined using WIM and strain data. While the WIM data includes every vehicle that passes over the instrumentation, the strain data does not always clearly show when a vehicle has passed. The strain gauges are positioned in alternating locations throughout the lane in an effort to ensure that the maximum number of vehicles cover some of the strain gauges. The locations of the gauges were determined based on the tire wander wheel path description presented by White, 2002. When clear peaks appear in the strain data, it indicates that a vehicle has passed directly over a strain gauge and the data from these vehicles are used in the analysis. The WIM data is used to confirm the size and weight of vehicles corresponding with particular strain measurements.

Figure 4 shows an example of the relationship between the wheel load and tensile strain in the RBM determined on July 2, 2009. The transverse strain in the RBM is proportional to the applied load and the relationship is good with R^2 of about 0.8. For the standard wheel load of 40 kN, the strain in the RBM was about 28 microstrain. Figure 5 shows the wheel load versus subgrade pressure relationship determined on the same day; it is a strong linear relationship with R^2 of 0.86.

Table 3 shows an example of the strains in the asphalt layers and subgrade pressures measured on selected representative days between 11:00 am and 12:00 am. The majority of the induced strains were in the 0 to 10 microstrain range (85.8 to 100 percent of repetitions in the RBM, for instance). Only during a hot day (represented by June 9, 2009), were a few strains higher than 50 microstrain recorded in the RBM (0.4 percent).

The majority of the subgrade pressure readings were in the 0 to 5 kPa zone (87.7 percent to 100 percent). Only during a hot day were a few subgrade pressure readings higher than 15 kPa recorded (1.5 percent).

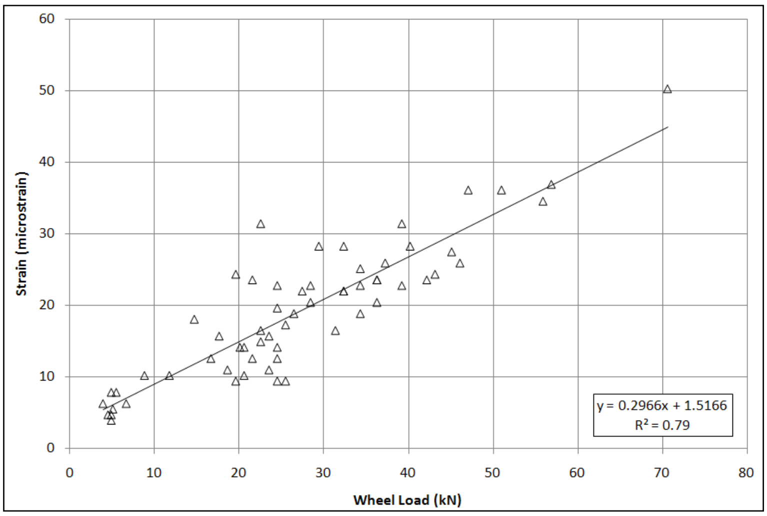

Figure 4: Relationship of Wheel Load versus Tensile Strain in RBM determined on July 2, 2009.

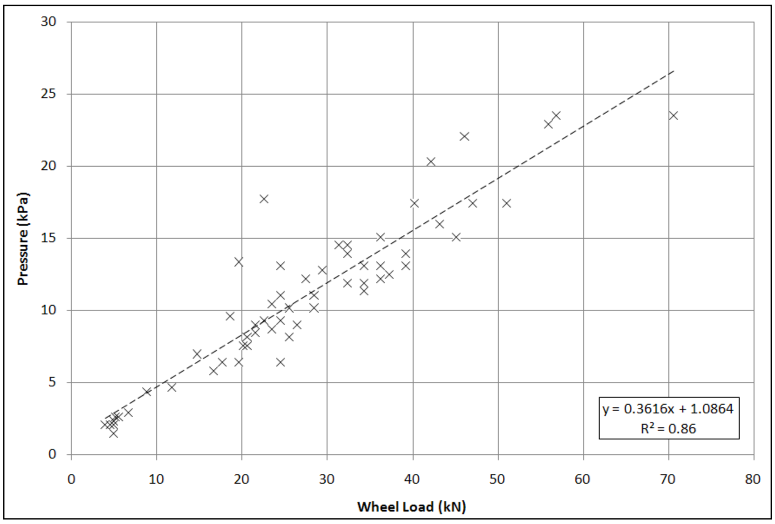

Figure 5: Wheel Load versus Subgrade Pressure determined on July 2, 2009

Table 3: Example of Strains in Asphalt and Subgrade Pressure Values Recorded in March and June

March 30, 2009						June 9, 2009					
Asphalt Strain						Asphalt Strain					
Range (με)		Number of Repetitions				Range (με)		Number of Repetitions			
From	To	SMA	SP25	RBM		From	To	SMA	SP25	RBM	
				#	%					#	%
0	10	1175	1916	1767	91.7	0	10	1576	1746	1716	85.8
10	20	74	1	125	6.5	10	20	109	109	198	9.9
20	30	4	0	32	1.7	20	30	24	42	47	2.3
30	40	0	0	2	0.1	30	40	0	6	30	1.5
40	50	0	0	0	0.0	40	50	0	0	9	0.4
50	60	0	0	0	0.0	50	60	0	0	1	0.0
Subgrade Pressure						Subgrade Pressure					
Range (kPa)		Number of Repetitions			%	Range (kPa)		Number of Repetitions			%
From	To					From	To				
0	5	1747			90.7	0	5	1754			87.7
5	10	137			7.1	5	10	156			7.8
10	15	36			1.9	10	15	61			3.0
15	20	6			0.3	15	20	28			1.4
20	25	0			0.0	20	25	2			0.1

7. PAVEMENT PERFRMANCE ANALYSIS

Mechanistic analyses were carried out in order to determine the life of the pavement with respect to rutting, bottom-up fatigue cracking and top-down fatigue cracking, assess the pavement damage to date and predict the pavement performance (Brown 1997, Ullidtz 2002). The models used in the analysis were the ones used in the Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP 2004). The analysis was done for the fall, winter, spring and summer conditions. It should be noted that the initial analysis carried out at the pavement design stage using the PerRoad program indicated that the horizontal tensile strain at the bottom of the asphalt was lower than 70 microstrain and compressive strain at the top of the subgrade was lower than 200 microstrain.

7.1 Performance Modeling

As the asphalt mixes exhibited very good to excellent resistance to rutting in the APA testing, only the rutting due to subgrade deformation was calculated. The strain in the subgrade was backcalculated using the Shell's Bisar computer program (Shell 1988) and the measured pressure values.

The subgrade modulus was also calculated using Bisar to match the measured values in each season. The backcalculated subgrade modulus was about 300 MPa in the fall and summer, dropping to about 150 MPa in the spring. These values are considered to be high.

For the subgrade strain analysis, the backcalculated modulus was divided by a factor of three (i.e., 100 MPa in the fall and summer and 50 MPa in the spring). The practice of reducing the measured subgrade modulus by a factor of 3 for the pavement designs is required by number of agencies (the AASHTO 1993 Guide for Design of Pavement Structures, for instance). It likely reflects the weakest spring conditions and the deterioration of drainage capacities over time.

A subgrade modulus of 1,000 MPa was used for frozen subgrade conditions in winter. Results of an FWD testing research in frozen and thawed subgrade conditions on another project illustrate that the value used in this analysis is conservative and in some instances frozen subgrade modulus values could be much greater, as high as 10,000 MPa.

The following model was used to calculate the life to rutting (FHWA 1997):

$$\text{Log } N = 0.955 * (\text{Log } M_r) - 4.082 * (\text{Log } \varepsilon_v) - 10.90$$

where: M_r = resilient modulus, lb/in^2 ε_v = vertical compressive strain at the top of subgrade
N = allowable number of ESAL repetitions

The bottom-up fatigue cracking was calculated using the tensile strain measured at the bottom of the RBM layer. The following model was used for the calculation (NCHRP 1986):

$$\text{Log } N = A - 3.291 * \text{Log } (\varepsilon_t/10\text{-}6) - 0.854 * \text{Log } (E/10^3)$$

where: N = number of 80-kN ESAL applications
ε_t = tensile strain at the bottom of the asphalt layers
E = complex modulus, psi
A = constant depending on percentage of cracking

The MEPDG top down cracking model was also used in the pavement performance analysis. Strain values from the in-place SMA were used in the model and the results indicated that top down cracking would not initiate within the design life of the pavement. These results may not be realistic and therefore should be further investigated.

The number of the asphalt strain and subgrade pressure repetitions calculated for the traffic to date was compared with the anticipated number of strain repetitions calculated for the design traffic loading of 90 million ESAL's, as well as the calculated pavement life with respect to rutting and fatigue. Table 4 shows a summary of pavement performance analysis. Generally, the projected life based on calculated rutting and fatigue cracking of the pavement was much higher than the actual anticipated number of asphalt strains and subgrade pressure repetitions over 50 years. Only the calculated subgrade rutting life during spring conditions was close to the anticipated number of repetitions. Therefore, rutting of subgrade should be considered as the critical pavement distress. It should be noted that the relatively high subgrade modulus values used in the analysis likely reflect the current excellent drainage conditions in the new pavement structure. If the drainage conditions deteriorate, the subgrade-induced rutting life could be significantly reduced.

Table 4: Summary of Pavement Performance Analysis

Strain (με)		Spring Conditions (2 months/year)			Warm/Hot Weather Conditions (7 months/year)		
		RBM					
From	To	Number of Repetitions (million)			Number of Repetitions (million)		
		To Date	50 Years	Calculated Life to Bottom-Up Fatigue	To Date	50 Years	Calculated Life to Bottom-Up Fatigue
0	10	4	197	1,365	12	559	6,460
10	20	0	14	139	1	45	660
20	30	0	4	37	0	11	174
30	40	0	0	14	0	7	68
40	50	0	0	7	0	2	32
50	60	0	0	4	0	0	17

Subgrade Pressure (kPa)		Spring Conditions (2 months/year)			Warm/Hot Weather Conditions (7 months/year)		
		Number of Repetitions (million)					
From	To	To Date	50 Years	Calculated Life to Rutting	To Date	50 Years	Calculated Life to Rutting
0	5	4	194	554	12	571	818,215
5	10	0	15	32	1	48	48,313
10	15	0	4	6	0	19	9,231
15	20	0	1	2	0	9	2,853
20	25	0	0	1	0	1	1,147

The initial pavement performance analysis shows that the pavement on the RHVP does meet the definition of 'perpetual' and can be anticipated to last 50 years without the need for major repairs or rehabilitations.

It is very important, however, that proper maintenance activities are applied. The resistance to subgrade rutting depends mainly on the moisture content of the subgrade material. The drainage system must therefore be maintained in good condition.

8.0 SUMMARY

The data from the traffic monitoring and pavement response system were used in the initial analysis of pavement performance on the RHVP in Hamilton. The pavement was designed as a perpetual pavement to carry traffic of 90 million ESAL's over a period of 50 years. After 20 months of service, the pavement has carried about 1.9 million ESAL's.

Mechanistic characteristics of asphalt mixes used on the RHVP were determined at the mix design stage. They included the dynamic modulus, resistance to rutting, and fatigue endurance. The measured dynamic modulus values were used in the analysis in order to compare the measured and assumed strains in the pavement structure.

The strains in the asphalt layers and subgrade pressure under applied vehicular loading were measured in the pavement response system. The relationships between the imposed wheel loads and the resulting asphalt strains and subgrade pressures were analyzed. Pavement temperature and moisture changes had a large influence on the imposed strains and pressures within the pavement system.

In the pavement performance analysis, pavement rutting and bottom-up fatigue cracking were analyzed using the measured parameters and available pavement performance models by

FHWA and NCHRP respectively. The analysis indicated that the pavement constructed on the RHVP is in fact perpetual and should last 50 years without the need for any major repair or rehabilitation. However, proper maintenance activities, such as drainage maintenance and any future crack sealing should be applied on a timely basis.

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