FULL-DEPTH RECLAMATION (FDR) – PROPOSAL FOR MECHANISTICAL-EMPIRICAL DESIGN PARAMETERS - FEEDBACK FROM THE REGINA BYPASS PPPS PROJECT

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Abstract

The Regina Bypass Project, the largest transportation infrastructure project in Saskatchewan's history, consists of the design and build as well as 30 years of regular maintenance of a free flow highway. It is composed of approximately 60 km - 2x2 lanes including about 40 km of new construction (greenfield) and 20 kilometres of rehabilitated existing pavement (brownfield). The Regina Bypass brownfield section was opened to traffic in late 2017.

For the rehabilitation of the existing pavement (brownfield), it was suggested Full Depth Reclamation (FDR), a process that rebuilds damaged asphalt by recycling the existing pavement into a strong and durable base. Unlike conventional materials (Hot Mix Asphalt), there is little information with regards to the design of pavement composed of FDR, its mechanical behaviour, and its durability.

This is why, five years after the opening to traffic of the Regina Bypass, a major follow-up program was carried out to evaluate the quality and the mechanical performances of the FDR material. This article intends to give a detailed presentation and analysis of the results of this program.

Keywords: FDR; Mechanistic-empirical pavement design; pavement condition follow-up.

1. INTRODUCTION

The Regina Bypass project includes two different pavement structures: a conventional Hot Mix Asphalt (HMA) pavement structure composed of new materials was suggested for the greenfield sections whereas a pavement based on on-site recycled material (FDR) was selected for the brownfield sections. For both the greenfield and the brownfield sections, a progressive pavement design was carried out. This means that the initial pavement structure, suggested in the construction phase, was designed for a reduced period (15 years instead of 30 years). Then, the fatigue life of the pavement structure is extended progressively over its entire service period thanks to the operations expected in the maintenance plan (including overlays). As the main objective of this investigation campaign is the evaluation of the FDR mechanical properties, the rest of this article is focused on the pavement structure of the brownfield sections.

The FDR (Full-Depth Reclamation) is a process that rebuilds damaged asphalt by recycling the existing pavement into a strong and durable base. In the Regina Bypass project, it involved in-place cold treatment of the existing pavement on a 20cm thickness (i.e., pulverization of 20 cm of the existing pavement and injection of 2.3% of foamed asphalt and 1% of cement). This FDR is made of 50% content Reclaimed Asphalt Pavement (RAP) and 50% natural aggregates coming from the existing granular subbase. The selected initial pavement structure for the rehabilitation of the existing pavement is described in Table 1. The long-term maintenance plan consists of three successive 5cm asphalt concrete (AC) overlays at respectively 12, 24 and 32 years after the end of the works, increasing progressively the total thickness of the structure as described in table 1.

Table 1. Description of the long-term maintenance plan – evolution of the pavement structure

Structure	Initial structure 2017 - 2029	Maintenance #1 2029 - 2041	Maintenance #2 2041 -2049	Maintenance #3 2049 - 2062
Traffic (Mesals 8t)	13.341	16.225	12.419	22.916
Wearing course	5.0cm AC	10.0cm AC	15.0cm AC	20.0cm AC
Intermediate layer	7.0cm High Modulus asphalt concrete			
Base course	20.0cm FDR treatment			
Subbase course	20.0cm existing granular layer			
Subgrade	CBR of 5%			

2. PAVEMENT FOLLOW-UP PROGRAM DESCRIPTION

The follow-up program that was carried out for the evaluation of the FDR material properties involved many onsite tests combined with numerous laboratory tests. All these tests are briefly described below in Table 2.

Table 2. Onsite and laboratory tests description

	Field and laboratory tests	Description	Number / frequency
Field	GPR	Measures the thicknesses of the layers	Continuously
	FWD	Measures the pavement deflection	Every 200 meters
	Pavement coring	Evaluates the thicknesses and material condition	More than 40 cores
Laboratory	Void content	According to NF EN 12697-7 [1]	8
	Bonding conditions	According to LC 25-010 and -011 [2] and [3]	2
	Stiffness (NAT)	According to NF EN 12697-26 - Annex C [4]	7
	Stiffness (2PB)	According to NF EN 12697-26 - Annex A [4]	6
	Fatigue (2PB)	According to NF EN 12697-24 - Annex A [5]	18

3. EVALUATION OF THE MECHANICAL PROPERTIES OF THE FDR

3.1 GPR Survey

The GPR survey was conducted on both fast and slow lanes of the two directions of the highway. The measurements of the total thickness of the Hot Mix Asphalt (wearing course + intermediate course) as well as the thickness of the FDR are presented in the figure 1 below. Only the measurements of the slow lane of Direction A are presented. Similar results were observed on the other lanes (fast lane of Direction A and the two lanes of Direction B)

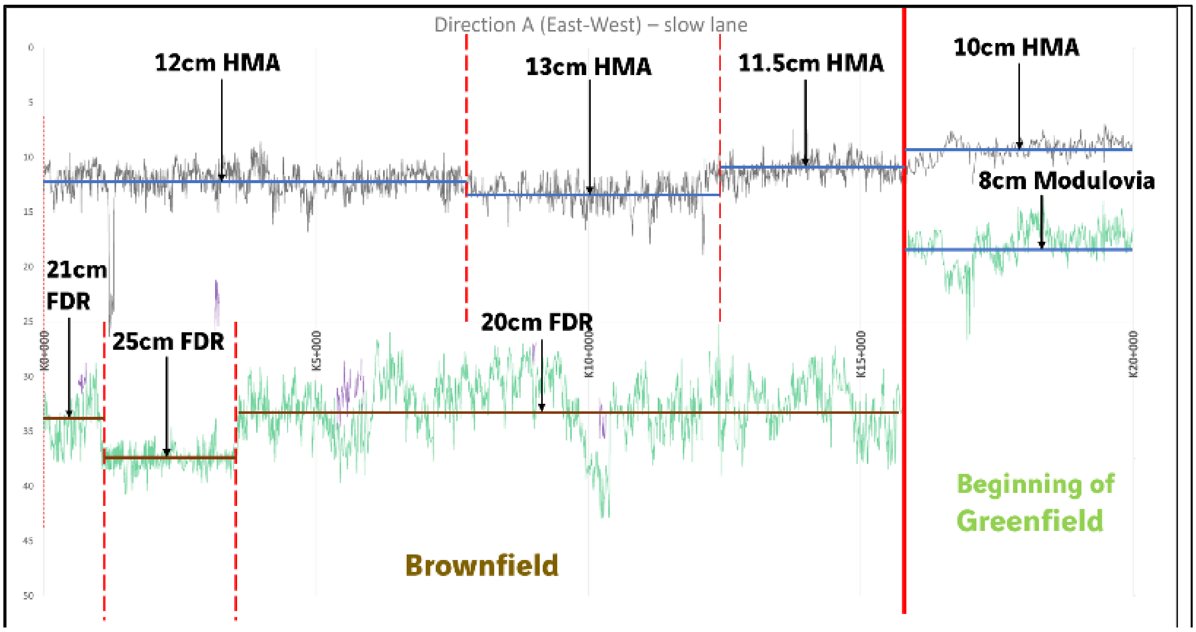


Fig. 1. GPR measurements of the slow lane of Direction A (East-West)

The measurements on Direction A show that, on average, the pavement structure of the brownfield section is composed of 12 to 13 cm HMA and 20 to 25 cm of FDR material. This is consistent with the pavement structure proposed in the design phase.

3.2 Pavement deflection measurements - FWD

The deflection measurements were performed using a Falling Weight Deflectometer (FWD) with a plate diameter of 30cm and 9 sensors located under the plate and respectively at a spacing from the center of the plate of 200mm, 300mm, 450mm, 600mm, 900mm, 1200mm, 1500mm and 1800mm. The measurements were done with a spacing of approximately 200m. The average value and the standard deviation measured at each geophone are given in the table 3.

Table 3. Average deflection and standard deviation (Sd) at each geophone (µm)

Geophone	D0	D1	D2	D3	D4	D5	D6	D7	D8
Average	398	311	273	227	189	130	94	71	57
Sd	49	46	47	45	41	34	26	20	15
Characteristic bowl (Average + 1.6xSd)	479	392	352	299	252	179	130	97	76

Knowing the relatively high load level that was applied during the FWD testing (70kN), the measured deflections are quite low which proves that the pavement is in good structural condition [10]. Moreover, the deflections are quite homogenous for each geophone with limited standard deviations which means that the quality of the pavement, and especially the FDR layer, is overall homogenous over the entire brownfield section.

3.3 Back-calculation analysis

The back-calculation is a numerical procedure used to determine the structural properties of the pavement layers, especially the stiffness of each layer, based on the deflection measurements (FWD). It requires knowing the exact composition of the studied pavement structure (number of layers, type of materials and thicknesses).

The average thicknesses of the HMA and FDR measured in the brownfield sections are respectively 12cm and 20cm.Therefore, the following pavement composition is considered in the back-calculation analysis: 12cm of HMA, 20cm of FDR, 20 cm of the granular subbase course and the subgrade. The asphalt concrete temperature was about 25° C. Based on the characteristic deflection bowl given in table 3, the back-calculation analysis was carried out using the French software Alize v1.5 [6] and the results are provided in table 4.

Table 4. Results of back-calculation analysis of the granular material and the subgrade, the adjusted modulus, calculated as suggested in the 1993 AAHSTO Design Pamphlet (Correction coefficient C of 0.35 for the subgrade and 0.62 for the granular subbase) [11], are consistent with the modulus proposed in the design phase.

	Modulus E1(MPa)	Modulus E2(MPa)	Modulus E3(MPa)
Material	Granular (10 cm)	Granular (10 cm)	Subgrade
Raw modulus	323	200	100
Adjusted modulus	323xC = 200	200xC = 124	100xC = 35

3.4 Pavement cores

The pavement cores that were extracted from the brownfield sections (see examples of samples in figure 2) show that the average thicknesses are consistent with those proposed in the design (12cm HMA and 20cm FDR). The visual inspection shows that the layers are in perfect condition with an excellent bonding between the layers (HMA and FDR). Void content measurements of the FDR show that it varies between 9% and 17% (measured according to NF EN 12697-7, see table 2).

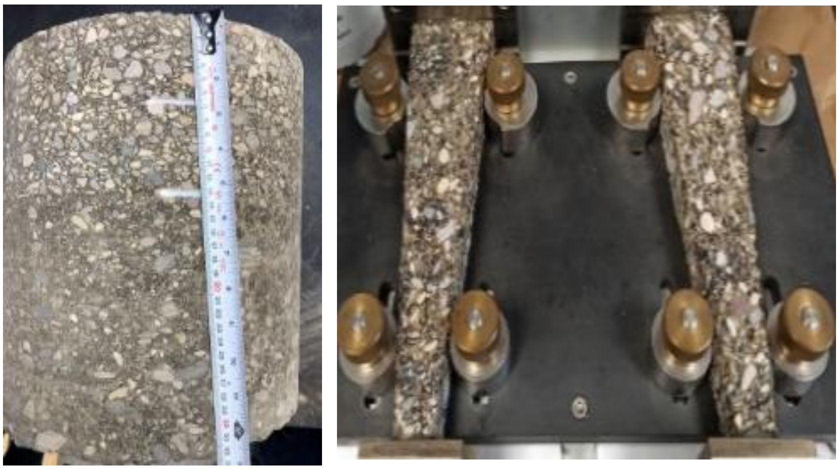


Fig. 2. Left: example of the extracted cores showing the asphalt concrete (top part of the cores) as well as the FDR (bottom part of the cores) – Right: Trapezoidal specimen for 2PB fatigue test.

3.5 Laboratory tests

Interface bonding condition

Interface bonding condition is analyzed based on the Quebec traction test [2][3]. According to Quebec DOT, the minimum requirement to consider a good bonding is 0.20MPa at 20°C ± 1.0°C. The maximum stress at breaking at 20°C measured on the extracted cores varies between 0.35 and 0.41MPa which proves that the bonding between the HMA and the FDR layers is of high quality.

Stiffness of the FDR

NAT modulus: determined based on indirect traction method, according to NF EN 12697-26 annex C [4]. The test conditions involved two temperatures (3.1°C and 10°C) and one loading time of 124ms. The results for the 7 performed tests on the extracted cores are given in the table below:

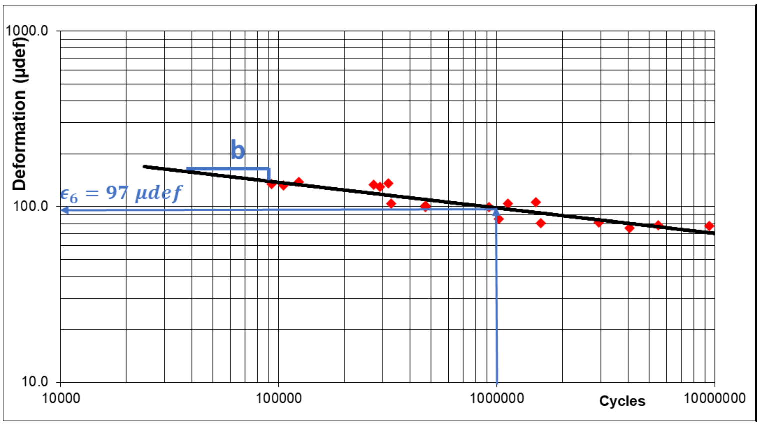
Table 5. NAT modulus test results (average from 7 tests)

NAT Modulus (MPa) – 124ms	
T = 3.1°C	T = 10°C
5207	4418

The measured NAT modulus on the cores is of the same order of magnitude as that of a conventional HMA, which means that the FDR is in good condition.

2PB modulus on cores: measured based on the NF EN 12697-26 [4]. The test conditions involved a temperature of 15°C and a load frequency of 10 Hz. The average measured modulus at 15°C and 10Hz is around 3700MPa. This value is close to the measured NAT modulus at 10 °C, 124ms (see table 5). Corrected at 3°C, based on the master curves of similar materials [7], the modulus would be at around 4800MPa.

Fatigue resistance of the FDR: measured in the laboratory on 18 trapezoidal specimens sawed from the extracted cores (see figure 2). The test conditions, based on the French standard NF EN 12697-24 annex A [5], involved a temperature of 10° C and a frequency of 25 Hz. The results are shown in the figure 3 below:



$\boldsymbol{\epsilon_6 = 97\mu def}$: the strain leading to failure of the sample under 10^6 loading cycles.

$\mathbf{b = -0.178}$: the slope of the fatigue curve

$\boldsymbol{SN = 0.26}$: the standard deviation of the number of cycles causing failure.

Fig. 3. Fatigue curve of the FDR

The results of the fatigue resistance of the FDR show that all fatigue parameters of the FDR are very similar to a conventional HMA, especially e6 and b.

4. MECHANISTIC DESIGN– FATIGUE PARAMETERS OF THE FDR

As mentioned earlier, a progressive pavement design was carried out for the Regina Bypass project. The FDR layer is initially designed to have a fatigue life of 6 years associated with a risk of 10% (probability of structural failure according to the French M-E design method [9]), then the fatigue life of the pavement structure is extended progressively over its entire service period thanks to the overlaying high modulus asphalt concrete as well as the operations expected in the maintenance plan. Those operations will increase the fatigue life of the pavement by maintaining the level of service and limiting the risk below 10% over the duration of the concession.

The objective of this section is to define the value of the calibration coefficient $\boldsymbol{k_c}$ of the French M-E (Mechanistic-Empirical) design method [9] so that the fatigue life of the FDR is compliant with the initial design (≥ 6 years) and survey report about the good condition of the pavement after 5 years, based on the fatigue parameters of the FDR measured in the laboratory. The calibration coefficient $\boldsymbol{k_c}$ reflects the empirical component of the French M-E design method allowing the adjustment between the theoretical behaviour and feedback from experience reflecting real behaviour observed on pavements in service (kc is equivalent to a constant transfer function of the MEPDG method).

It is worth mentioning that this fatigue life that was considered in the initial design is very conservative and surely does not reflect the real fatigue life of the FDR which is much higher as the survey report and the cores show. This conservative life fatigue was initially considered mainly to avoid having too thin overlays. The calculations carried out based on this fatigue life give therefore a minimum value of the parameter $\boldsymbol{k_c}$.

4.1 Pavement ME design input parameters

Traffic: The traffic data as well as the maintenance plan expected in the Regina bypass project are described in table 1.

FDR design parameters: All the design parameters (modulus and fatigue parameters) necessary to carry out a ME design according to the French method [9] are described in table 6 for the FDR. Fatigue parameters are derived from laboratory test results presented in figure 3. Given the reproducibility of the fatigue test (R = 8.3µdef) [5], a more conservative value was considered for ϵ_6 (90 instead of 97µdef).

Table 6. FDR mechanical properties and design parameters

Modulus (MPa) (3°C, 10Hz)	Fatigue parameters						
	Risk	ϵ_6	-1/b	Sh	SN	k_θ [7]	ks
4800	10 %	90µdef	5	2.5cm	0.3	1.157	0.95

4.2 Determination of the calibration coefficient kc

The calculation of the allowable traffic N (fatigue life) of the FDR according to the French ME method [9] is given by the following formula (1)

$$N = \left(\frac{\epsilon_t}{\epsilon_6 \times k_s \times k_c \times k_r \times k_\theta}\right)^{\frac{1}{b}} \times 10^6 \qquad (1)$$

ϵ_t is the maximum strain at the bottom of the FDR layer created by the reference axle 80 kN. It can be determined using the French software Alize [6]. Knowing the cumulated traffic over the 6 first years of the Regina Bypass highway (N = 6.31 Mesals 80 kN), the fatigue parameters (ϵ_6 and b) thanks to laboratory tests results, and the other parameters (ks and kr) which are derived from the French standard NF P 98-086 [9], the calibration parameter kc can be determined using the formula (1). The calculations lead to a minimum value (as mentioned earlier) of the calibration coefficient kc of 1.4.

The calibration coefficient kc of the FDR is higher than the kc of conventional HMA. However, the kc parameter given in the French guide on the pavement rehabilitation [10] for in place recycled materials is around 1.6 while the kc parameter of a typical cold road base asphalt including active filler has been assessed to 1.7 with the accelerated fatigue full scale test at LCPC [8]. These values found in the literature (kc between 1.6 and 1.7) seem to be more realistic than the minimum value that was calculated based on the conservative fatigue life of 6 years.

Figure 4 gives the risk and the damage evolution of the FDR and the HMA base course if we consider a more realistic kc parameter (1.7 instead of 1.4). In this case, the fatigue life of the FDR is around 15 years (risk below 10%) which seems more realistic given the current condition of the pavement, and by the end of the concession (2049) the damage of the HMA remains far below 1.0 for the initial risk (see figure 4). The expected final risk at the end of the concession for the HMA remains below 1% which is compliant with this kind of highway projects [9].

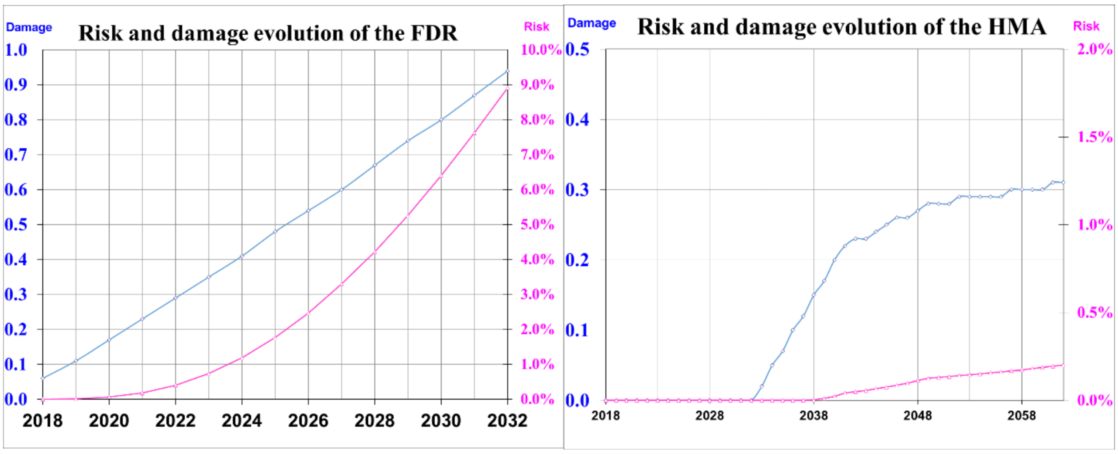


Fig. 4. Risk and damage evolution of the FDR and the HMA (kc =1.7)

5. CONCLUSIONS

The Full-Depth Recycling (FDR) is a cost-effective and sustainable alternative to traditional roadway reconstruction. This process was selected for the rehabilitation of the existing pavement of the Regina Bypass project (brownfield sections). 5 years after the completion of the works and the opening to traffic of the Regina Bypass highway, the FDR is proven to be an excellent solution through a major follow-up program composed of onsite as well as laboratory tests.

The GPR study showed that the thickness of the FDR is compliant with the thickness that was defined during the design phase of the project. Moreover, the deflection measurements confirmed that the pavement is in very good structural condition. Furthermore, the results of the laboratory tests have shown a high-quality bonding between the FDR and the HMA layers and a very fair modulus (around 4800MPa at 3°C and 10Hz). Besides, the fatigue resistance test, resulting from an unprecedented test campaign for this kind of material, showed excellent results for the FDR. The fatigue parameters of the FDR turn out to be very similar to conventional HMA, especially $\epsilon_6$and the slope b.

This study shows also that the FDR can be designed using the French M-E design method. The recommended fatigue parameters of the FDR are as follows: ϵ_6 = 90 µdef, slope -1/b = 5, SN =0.3 and a calibration coefficient kc between 1.4 (conservative lower limit) and 1.7 (more realistic value). Complementary studies are currently conducted on in-place recycled materials to specify more accurately this coefficient kc.

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