The Performance of Full-depth Reclamation and Cold In-place Recycling Techniques in Quebec

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Abstract

The use of full-depth reclamation and cold in-place recycling techniques has been common practice at the Ministère des Transports du Québec (MTQ) since the early 1990s. In the space of 15 years, these techniques have been used on nearly 1,500 kilometres of pavement within the road network under the MTQ's responsibility.

The performance monitoring data from more than 90 projects carried out over the past 12 years and involving a total of approximately 425 kilometres was examined for purposes of this study. Pavement performance was evaluated in terms of the annual progression in road quality (measured using the International Roughness Index, or IRI) and rut depth.

The progression in these two performance indicators was established for each project and the projects were regrouped according to the functional category of the roads involved and traffic volume. This in turn made it possible to determine the performance life of the rehabilitation operations. The results were then used to conduct a cost-benefit analysis based on the average unit costs of these operations and of the maintenance work costs. The benefit/cost ratios (BCR) of the rehabilitation operations were compared to those for various projects involving solely a hot mix asphalt overlay, the most widespread pavement maintenance technique used by the MTQ.

Acknowledgements

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Introduction

The use of recycling techniques such as full-depth reclamation (FDR) with or without stabilization and cold in-place recycling (CIR) has been common practice at the Ministère des Transports du Québec (MTQ) since the early 1990s. These techniques have been used on nearly 1,500 kilometres of pavement within the road network under the MTQ's responsibility.

A number of pilot projects and laboratory studies have made it possible to describe and categorize recycled materials and to identify the cases that are best suited to these techniques. This work helped in the development of a technical guide (1) and two specifications documents (2, 3) designed to provide guidelines for using these techniques. A first summary emerging from the performance monitoring program (4), presented in 2000 (5), brought to light the great potential for using the FDR technique. Pavement performances similar to those of rebuilt or newly constructed pavements involving the use of a traditional technique were noted when the rehabilitation work was carried out according to industry best practices and a customized design was developed beforehand.

The main selection criteria and fields of application for these techniques were established on the basis of the types of distresses affecting pavement behaviour (1). Pavements displaying distresses related to the performance of their upper portions and that were relatively inactive when exposed to freezing temperatures were considered well-suited to the use of FDR or CIR. Defective pavements displaying a high cracking rate that was usually above 0.45 m/m^2, from low to high severity, and related to pavement fatigue and to thermal contraction of the bituminous surface course, were also considered well-suited to FDR or CIR techniques. Observations based on monitoring over a 10-year period (5) indicate that FDR offers a definitive solution when there is fatigue cracking, thermal cracking, potholes and peeling.

Despite the development of criteria that allow FDR and CIR to be used at the appropriate places in the network, to date, the use of these so-called recycling techniques has still been somewhat sporadic and closely tied to budget availability, knowledge of these techniques, and to a lesser extent, managers' perceptions of the work feasibility. Obviously, incorporating these methods into network-based rehabilitation strategies requires a fair evaluation of the progression in the performance of these operations in a variety of situations, as well as an estimation of costs to ensure optimal use within budget constraints.

All the data gathered in the performance monitoring program, together with the data collected across the network (6), provide a reliable database for developing an initial approach. This approach will in turn be used to evaluate the performance of the recycling operations. By combining the results of this approach with a Life-Cycle Cost Analysis (LCCA), the performance of various maintenance scenarios requiring the use of FDR and CIR can be established on the basis of a cost-benefit analysis. This will provide more representative parameters that can be integrated into the MTQ's pavement management system (7).

Recycling Techniques

In this study, the so-called recycling techniques used for road rehabilitation include full-depth reclamation (FDR) with or without stabilization, and cold in-place recycling (CIR). Since 1991, on an annual basis, the MTQ has carried out an average of 80 km of FDR (1 km = 7000m^2), in which approximately 17 % of the projects have included stabilization of the recycled materials through the addition of a hydrocarbon binder (emulsion or foamed asphalt) or a mixed binder (addition of <1.5% Portland cement or hydrated lime). The first cold in-place recycling (CIR) contract dates back to 1992. In total, more than 400 kilometres of pavement, mainly on national and regional highways, have been recycled using CIR technique.

Cold in-place recycling (CIR)

Recycling is usually done in place. A portion of the bituminous surface course (Figure 1a) is removed through cold milling to depths of between 90 mm and 100 mm. The reclaimed asphalt pavement (RAP) is then screened (D_{max} = 28mm) before the addition of a hydrocarbon binder, usually an asphalt emulsion (1.0% of asphalt added). These steps, as well as pugging and placement, are performed in one continuous operation. The resulting mix is covered by a conventional hot-mix bituminous concrete after a curing period of one to two weeks. The properties of the wearing course (mix and thickness) are determined beforehand during the structural design phase.

The performances observed on the test sections in the Quebec context clearly indicate that this treatment slows down the reflective cracking process, thereby prolonging the performance life of this operation from 2 to 5 years compared with that of simple resurfacing (8). Site characteristics (cracking rate, traffic volume) and placement conditions (compacting) are determining factors that also help explain the performance of the rehabilitation operation.

Full-depth reclamation (FDR)

This technique consists of pulverizing the bituminous surface course to its full depth, and blending in a portion of the underlying granular base material (Figure 1b). Once uniformly pulverized and mixed, usually to a depth of 300 mm, the material is graded and compacted to form a new base. Before the overlay is applied, the pulverized material can be cold-stabilized to a depth of 100 to 150 mm by adding a hydrocarbon binder (emulsion or foamed asphalt) or a mixed binder containing a hydraulic binder additive.

This method completely eliminates any cracks present in the upper portion of the pavement during the pulverization process, which largely explains the performances observed at a number of sites (5). This particular feature is vitally important in a northerly context where reflective cracking, commonly observed after simple bituminous resurfacing (BS), plays a key role in the progression observed in the performance of maintenance operations; it therefore influences their performance life.

Figure 1a: Cold in-place recycling (CIR)

Figure 1b: Full-depth reclamation (FDR)

Methodology

The benefit/cost ratio (BCR) method, currently used in pavement management (9), allows all the data characterizing both pavement performance and the costs of various rehabilitation operations planned in road maintenance scenarios to be integrated and compared in terms of their effectiveness or performance. In other words, the BCR expresses the performance gain of one maintenance scenario relative to a reference scenario, taking into account the additional investments required to attain this service level.

Performance was evaluated on several occasions for each road category and each rehabilitation operation (FDR, CIR and BR), using the IRI, which made it possible to evaluate the progression in ride comfort as measured over all sections. In each case, performance was defined by the area under the performance curve (P_i), as illustrated in Figure 2.

The performance life of rehabilitation operations is defined as the number of years before which the average ride comfort index (IRI) for a pavement segment, as it so happens, on a *contract* in this study, reaches the minor deficiency threshold values used by the MTQ, which are adjusted according to the road category (Table 1). When a pavement has reached a major deficiency threshold value, it means that the cracking rate is high, and operations such as FDR or CIR are both desirable and recommended. Based on the information available in the MTQ's pavement management system, it is estimated that approximately 25% of the pavements targeted by rehabilitation operations have reached the major deficiency threshold value. The application of a network-based rehabilitation strategy may justify carrying out a bituminous resurfacing (BR) on a particular pavement, even if it is very badly distressed (major deficiency), primarily to delay the need for heftier investments related to major reconstruction work and to optimize available budgets.

Road category	Deficiency threshold value (IRI) (m/km)	
	Minor	Major
Highway	2.2	3.5
National	2.5	4.0
Regional and collector	3.0	5.0

Table 1: MTQ pavement deficiency threshold values

The cost factor was examined in two parts: first, the direct costs paid by the MTQ, and second, the costs of the delays imposed on users during the rehabilitation work (user-delay costs).

The direct costs are those related to carrying out the work, including traffic control costs on the work site. The costs of each maintenance operation were factored in, taking into account the year in which the operation was scheduled for each maintenance scenario, in order to determine the net present value (NPV) over a 40-year analysis period. The approach taken considers the residual value, defined as the “unconsumed” proportion of the last rehabilitation operation at the end of the analysis cycle. A sample maintenance scenario (Scenario B) is presented in Figure 2.

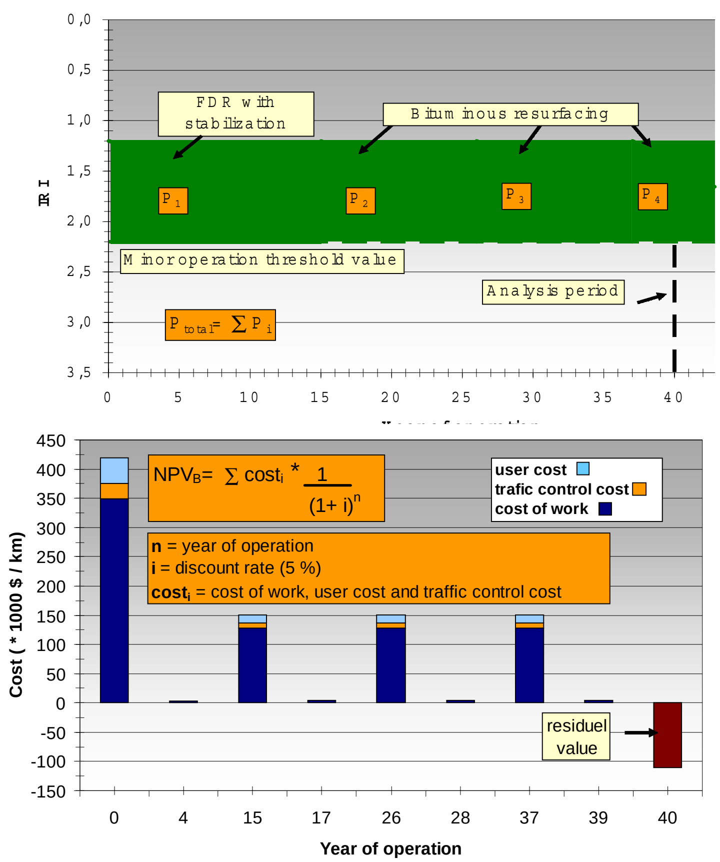


Figure 2: Maintenance scenario (B) FDR STAB: service level and net present value (NPV)

The evaluation of the user-delay cost was limited to estimating the costs associated with the delays caused by carrying out the work, using Winfrey's approach (10). Three standard projects were examined for purposes of this evaluation, each by road category. The characteristics of these sites (traffic, heavy vehicles, lane geometry, etc.) reflect the conditions observed on the project sites examined in this study and where FDR and/or CIR work was carried out (Table 2).

	Highway	National	Regional/Collector
AADT	20,000	12,000	5,000
% heavy vehicles	16	14	11
% trucks, 1 unit	30	50	55
% trucks (semi-trailers)	70	50	45
Lane width (m)	7.4	7.0	6.0 to 6.6
Cost of work ($/kilometre of pavement)			
FDR without stabilization	-	300,000	190,000
FDR with stabilization	440,000	315,000	192,000
CIR	300,000	211,000	117,000
BR	120,000	100,000	81,000
Crack sealing ($/km)	2,500 to 4,000		
User-delay costs ($/day/km)	7,116	6,874	2,709

Table 2: Pavement properties and cost of work

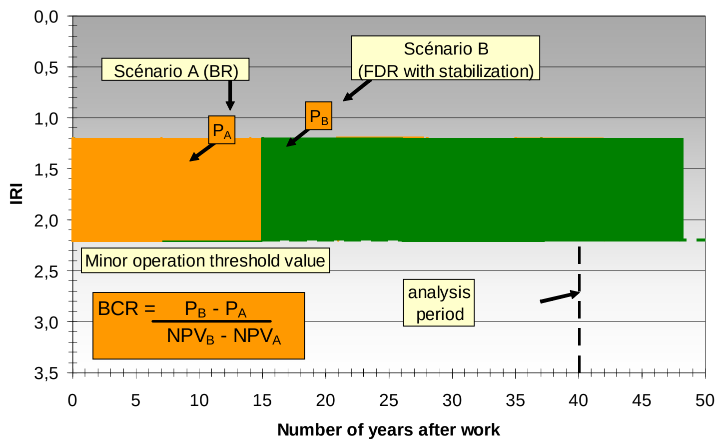
The maintenance approach most frequently used by the MTQ is that of bituminous resurfacing (BR) with profile correction through either the placement of a corrective layer or milling. It accounts for approximately 70% of the pavements that undergo rehabilitation work. In the Quebec context, the performance life of these operations (BR) is closely related to the pavement condition prior to the work and to reflective cracking, which occurs quickly. Typically, all cracks present in the old wearing course reappear on the surface within three years of placement (compacting) (11). Traffic volume and the properties of the bituminous surface course materials have significant impact on the progression in distresses, and consequently, in pavement smoothness. In this context of this study, successive bituminous resurfacing (BR) after each maintenance cycle constitutes the reference scenario for purposes of comparison.

The maintenance scenarios, as well as the costs retained for purposes of this study, reflect the current maintenance practices applied by the MTQ regarding such work. For example, crack sealing is carried out on average two years after BR work, at a rate of 2,000 metres of cracks/kilometre. After FDR or CIR treatments, the same work is carried out in the fourth year following rehabilitation work, at a rate of 1,250 metres of cracks/kilometre. All the rehabilitation operations for each scenario are summarized in Table 3. The scheduling of operations is dictated by the performance life of the rehabilitation operations, as evaluated for each road category.

Scenario	Rehabilitation operations
A (reference)	BR+BR+BR+BR+BR+ BR
B	FDR STAB+BR+BR+BR
C	CIR+BR+BR
D	FDR+BR+BR
E	FDR+CIR+BR

Table 3: Maintenance scenarios

The process of determining the benefit/cost (BCR) ratio for each scenario involves, first, evaluating the total performance (P_{total}) for the scenario, defined as the aggregate of the performances (P_i) associated with each maintenance operation. The results are then compared with those of reference scenario A as illustrated in Figure 3.



P_{ti}: total performance of scenario i
P_a: total performance of reference scenario A
NPV_i: net present value of scenario i
NPV_a: net present value of reference scenario A

Figure 3: Benefit/cost ratio (BCR)

Performance Evaluation

The performance monitoring program of MTQ pavements (14), introduced in the early 1990s (4), is subdivided into three levels, each of which involves different objectives and specific data collection and analysis activities. Level 1 monitoring aims at evaluating techniques or products and requires taking numerous measurements and conducting numerous tests on control sections. For example, level 1 monitoring is similar to that carried out in the context of the SHRP (LTPP) and C-SHRP programs. Level 2 monitoring involves evaluating project-based maintenance operations, whereas level 3 monitoring is concerned with forming a general overview of an entire series of operations or of a network-based maintenance strategy.

The results obtained from representative projects (level 2), several of which included control sections (level 1), were examined in the context of this study. For the sections subject to level 1 monitoring, the evaluation of the progression in performance included measuring surface distresses, skid resistance, ruts and the ride comfort index (RCI). In this study, only the data concerning ride comfort (IRI) and rutting measured in 199 projects that were carried out between 1992 and 2000 (Table 4) were considered for purposes of performance evaluation. These projects, involving nearly 450 kilometres of pavement, are distributed in three regions of Quebec where a greater proportion of recycling work is carried out. They are grouped according to three functional road categories: highways, national roads, and regional and collector roads. The length of the sites under study varied from 0.8 kilometre to 14.3 kilometres, and averaged 4.6 kilometres.

	Highway	**National**	**Regional or collector**
FDR WITH stabilization	5 sites (39 km)	7 sites (22 km)	16 sites (72 km)
FDR WITHOUT stabilization	- -	14 sites (68 km)	12 sites (51 km)
CIR	5 sites (28.6 km)	17 sites (97.9 km)	10 sites (44.4 km)
Bituminous resurfacing (BR)	25 sites (102.4 km)	38 sites (128.2 km)	28 sites (107 km)
Bituminous resurfacing (BR) involving major deficiencies prior to work	6 sites (20.9 km)	4 sites (20 km)	8 sites (47.8 km)

Table 4: Test sites for three road categories

The smoothness surveys were carried out under summer conditions using the MTQ's multifunction vehicle (6), which was equipped with a level-1 inertial profilometer (GMR) that met the specifications of ASTM standard E-950. The average IRI was calculated for each 100-metre segment.

Progression in the IRI

To establish "IRI vs Year" performance curves for each of the techniques, the progression in the IRI for all projects was taken into account, for each road category. The average annual values characterizing ride comfort were integrated for any given site or contract in order to establish a trend curve through a polynomial regression approach. This approach made it possible to determine the average IRI values for all the sites under study and for different years following the year in which work was carried out (Figure 4).

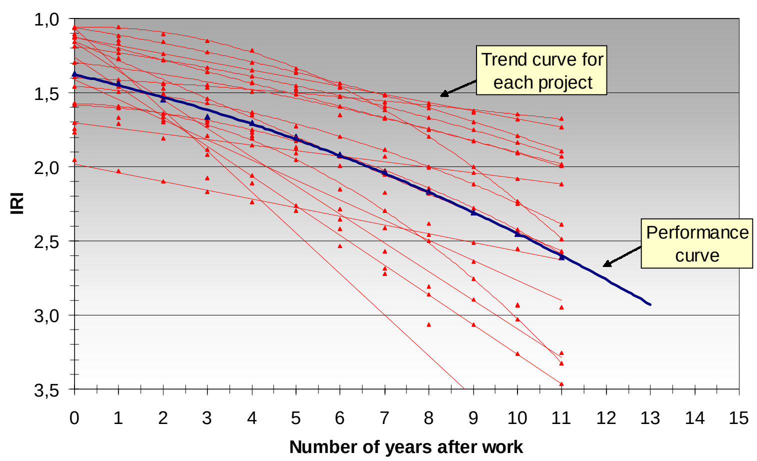


Figure 4: Sample performance curve: CIR, national road

The performance curves thus established are presented in Figure 5, and the respective service lives retained for purposes of analyzing each of the rehabilitation operations for each road category, are summarized in Table 5.

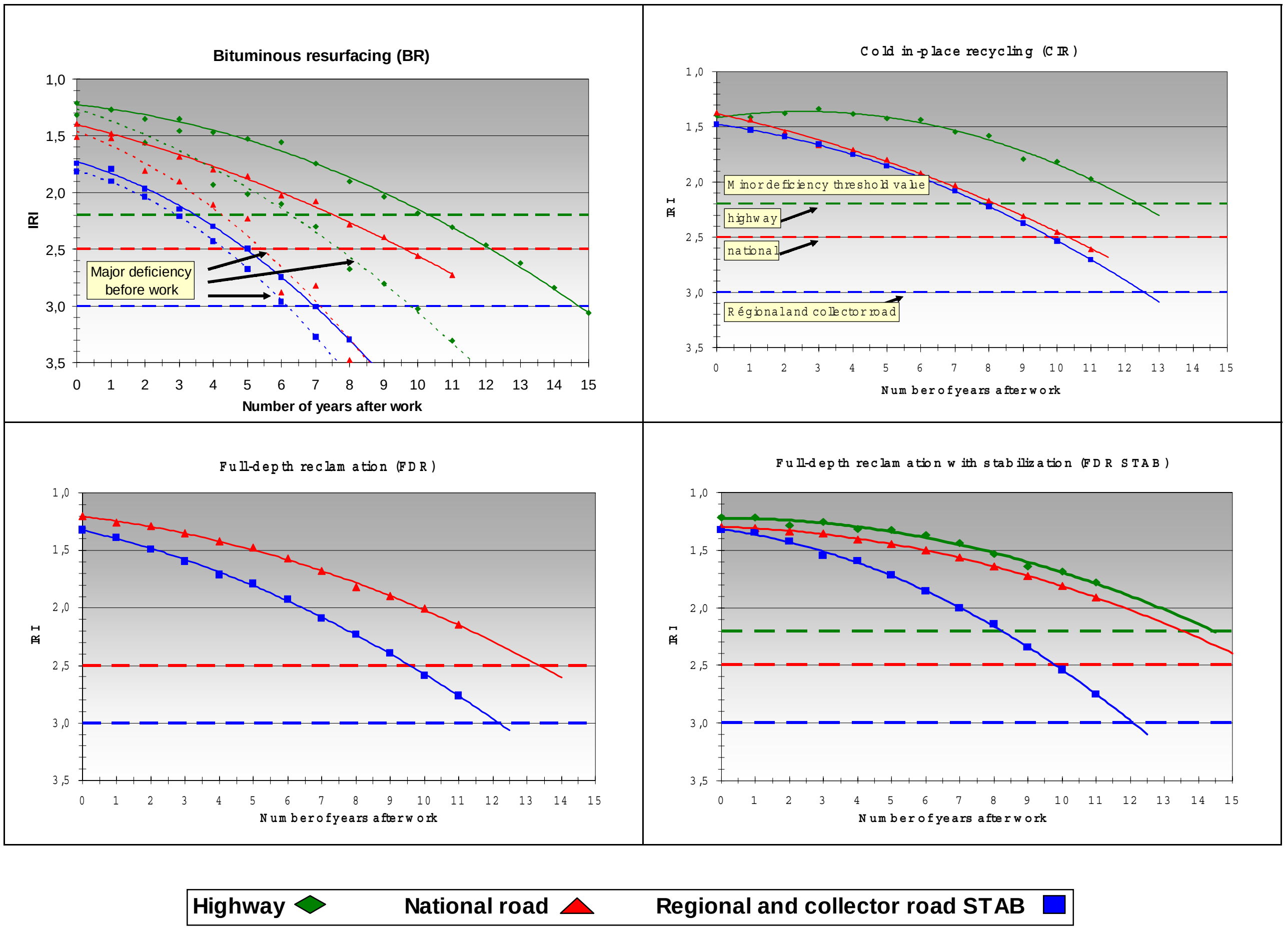


Figure 5: Performance curves

<table>
<tr><th rowspan="3"></th><th colspan="6">Performance life (years)</th></tr>
<tr><th colspan="3">MINOR
Deficiency threshold value</th><th colspan="3">MAJOR
Deficiency threshold value</th></tr>
<tr><th>H</th><th>N</th><th>R</th><th>H</th><th>N</th><th>R</th></tr>
<tr><td>FDR STABILIZATION</td><td>15</td><td>15</td><td>12</td><td colspan="3">20</td></tr>
<tr><td>FDR WITHOUT stabilization</td><td>-</td><td colspan="2">12</td><td>-</td><td colspan="2">20</td></tr>
<tr><td>CIR</td><td>12</td><td>11</td><td>11</td><td colspan="3">18</td></tr>
<tr><td>BR</td><td>11</td><td>9</td><td>8</td><td>17</td><td>15</td><td>14</td></tr>
<tr><td>BR (major deficiency prior to work)</td><td colspan="3">7</td><td colspan="3">11</td></tr>
</table>

Note: A: highway, N: national road, R: regional and collector road

Table 5: Performance life of rehabilitation operations (number of years)

A distinction was made concerning the progression in the performance of the BRs, according to the pavement condition prior to work. When the pavement exhibits a major deficiency and is generally very cracked, the BR translates into a fast progression in distresses, which in turn have an impact on the IRI. In such a context, we observe an average decrease of 1 to 6 years in performance life.

Progression in Rutting

Rut-depth surveys are essential in levels 1 and 2 performance monitoring. The values of and progression in this indicator are highly significant when assessing pavement behaviour, but also when evaluating the safety factor associated with the fact that the risk of aquaplaning increases with rut depth.

The materials developed using recycling techniques are found in the granular base material in the case of a full depth reclamation (FDR), or in the base course in the case of CIR. In both instances, these materials are located directly beneath the wearing course and are subjected to repeated stresses transmitted when vehicles pass; they are therefore susceptible to surface-rut formation. This aspect of pavement behaviour is treated in the structural design phase by ensuring that the stresses induced in the recycled materials are compatible with their mechanical properties, so as to prevent the appearance and fast progression in ruts.

For all the sites (Table 4), only the values measured from the year 2000 and beyond using the multifunction vehicle were retained for purposes of this analysis.

Figure 6 summarizes all the results obtained for the various recycling techniques. First, we observe that the rate of progression in rut depth is somewhat slow and varies from 0.30 mm/yr to 0.47 mm/yr, and that it is similar for the FDR, FDR Stab and CIR techniques. The maximum and minimum values presented in Figure 6, which include 80% of the results observed (confidence level), show that the dispersion of the pavement behaviour values in terms of the progression in rutting is similar for the three techniques. Based on this approach, we deduce that a small percentage of pavements, somewhere in the order of 10%, exhibit an average rutting-depth rate greater than 1.1 mm/yr over a 10-year period.

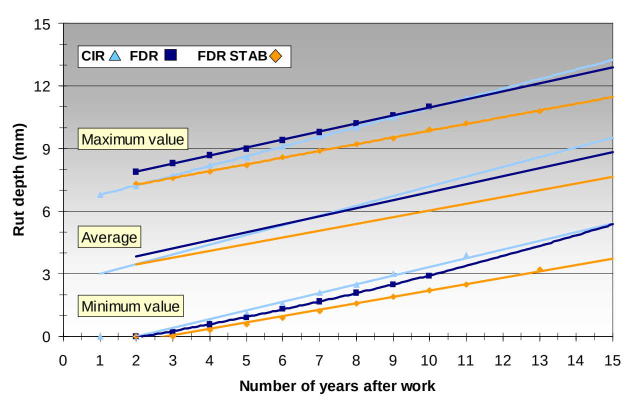


Figure 6: Progression in rut depth

Also, we observe (*Figure* 6**)** that small-depth rutting (2 to 3 mm) is present commencing with placement (compacting), i.e. at year 0. In fact, these results reflect instead the quick appearance of mild-severity rutting shortly after rehabilitation work is completed, possibly due to a post-compacting phenomenon involving the materials treated. This phenomenon tends to stabilize after the first year. Thereafter, rutting increases at a similar, if not lower, rate (mm/yr) than the rates observed in pavements having undergone conventional treatments. Apart from this particularity, which underscores the fact that certain improvements could be made to placement (compacting) methods, the results as a whole indicate that the use of recycling techniques poses no additional risk in terms of the rutting problem, provided that there is adequate prior structural designing.

Cost-benefit Analysis

The data as a whole clearly indicate that recycling treatments have a longer performance life than does conventional bituminous resurfacing (BR), based on the progression in the IRI (Table 6). When the use of recycling techniques is incorporated into a maintenance scenario, it translates into an improved long-term service level. Over the analysis period, set at 40 years, the maintenance scenarios including at least one recycling operation exhibit a total performance value that is (Pt) higher than that of reference scenario A (Table 6). On highways and national roads, scenarios B and E including FDR with stabilization and CIR result in major performance gains reaching as much as 47.9%, whereas the performance gains are less significant on regional roads, except for scenario B, where we see a 26.3% performance gain.

Scenario	**Performance gain: 100*(P_{ti} - P_a)/ P_a (%)**		
	Highway	**National**	**Regional**
B (FDR STAB)	38.8	47.9	26.3
C (CIR)	24.5	34.6	9.9
D (FDR)	-	38.4	10.4
E (FDR + CIR)	42.5	44.7	15.9

Table 6: Performance gains (%) compared to reference scenario A

These initial results highlight the fact that eliminating the cracking pattern during FDR work has beneficial effects on pavement behaviour, which in turn translates into maintaining a higher service level than is associated with a scenario involving only successive BRs.

Another finding derived from all the observations was that the performance lives of the different operations concur with those predicted by the MTQ's design method, which was based on an adaptation of the AASHTO 1993 (12). Current structural design practice predicts performance lives of 15 to 20 years, depending on the road category, when a pavement undergoes CIR or FDR. The ride comfort index reached at the end of performance life, corresponding to the major deficiency threshold values (Table 1), is similar to the expected present serviceability index (PSI_{final}) (13). This finding indicates that all the inputs – modulus, ESAL, etc. – recommended for design purposes (12) make it possible to predict a service level representative of those observed on the various pavement sections examined in this study.

The performance of the maintenance scenarios according to the BCR ratio approach is summarized in Table 7.

First, we note that all the scenarios including a recycling technique exhibit a BCR higher than 1, indicating a better performance than that associated with reference scenario A. For highways, we note similar BCR for the three scenarios B, C and E, which reflects the fact that the additional costs associated with this work increases the user service level in similar proportions. Regarding national roads, we observe a clearer trend in which scenario C (CIR) exhibits better performance, despite the fact that scenarios B and E ensure a very sizeable performance gain, in the order of 45% compared to that for reference scenario A. When the difference in costs **(ΔNPV)** between a given scenario and reference scenario A is small, i.e. less than 4%, the value of the BCR tends to increase significantly. This particular case constitutes a limitation on this approach, and in such a case, the value of the BCR must be interpreted with caution. So it is for scenario C, where we note a small difference in cost, reflected in a very high BCR (>20). In fact, scenario C represents an appreciable performance gain (10%), mainly on regional roads, whereas the NPV, evaluated for a 40-year period, does not differ significantly from that for reference scenario A.

Scenario	**Additional cost (ΔNPV%) = 100*(NPVi - NPVa)/ NPVa and benefit/cost ratio (BCR)**					
	Highway		**National**		**Regional**	
	ΔNPV%	**BCR**	**ΔNPV%**	**BCR**	**ΔNPV%**	**BCR**
B (FDR STAB)	45	4	33	7	23	11
C (CIR)	13	8	12	14	<4	>20
D (FDR)	-		26	7	18	5
E (FDR + CIR)	34	5	41	5	18	8

Table 7: Additional percentage of the* ΔNPV *compared to reference scenario A* and *benefit/cost ratio (BCR) of maintenance scenarios compared to reference scenario A

It is important to remember that the cost of the work is contingent upon a multitude of factors related to pavement design, geographic context (work site) and specific economic factors arising from the workings of the industries (markets) concerned (price of asphalt, competition, etc.). In this study, the costs used reflect those currently observed in industry practice for each road category. It is clear that a more detailed analysis allowing for integration of the costs of different types of maintenance scenarios for several traffic contexts, together with the respective performance curves, would further elucidate the findings of this study.

For all the maintenance scenarios (Table 3), the economic impacts related to the delays imposed on users (user-delay costs) for the types of pavements considered (Table 2) represent approximately 10% to 13% of the NPV for highways and national roads, and in the order of 7% for regional and collector roads. On the other hand, we note, that for any given road category, the user-delay costs are similar from one scenario to another over a long analysis period. When one considers the impacts of the different types of maintenance work associated with each scenario (in terms of the number of days where traffic flow will be disrupted), however, the estimated differences between the various scenarios may be significant, depending on the context. For example, reference scenario A, which involves frequent short-term work, will result in a disruption of 16d/km over a 40-year period. For the other scenarios, we estimate the disruption time at between 12 d/km to 14d/km, which represents a reduction in impacts (such as the loss of economic activity for businesses adjacent to the worksite) for both users and local residents and for other activity sectors affected by the work.

Another point that must be taken into account is that this analysis, which was based solely on the progression in the summer ride comfort index (RCI), does not allow for a representative assessment of the effects of cracking on pavement behaviours over a full year. Hence, the fast reflective cracking that occurs following bituminous resurfacing (BR) increases the risks of water infiltration. In the presence of freeze/thaw cycles, this promotes crack formation, which in turn impacts significantly on pavement service level during the winter. The propensity for such a phenomenon to occur after BR is much smaller if one considers the fact that this type of rehabilitation operation translates into a consistently low rate of cracking.

The empirical approach taken in this study to describe the performance of recycled pavements at the very most provides a general assessment of the performance of these techniques, without being able to specify or explain the causes for the dispersion in the data observed. Clearly, paying greater attention to the application of criteria for selecting these techniques, to project preparation, to structural design (traffic) and to the execution of the actual work would enhance the performance of these rehabilitation operations. However, the methodology followed in this study does not allow us to quantify the degree to which the attention paid to these preparatory activities would help improve performance. That said, the results as a whole, which reflect current practices in this field, indicate that the use of recycling techniques on distressed pavements (major deficiencies) is both a high-performance and cost-effective approach from a long-term perspective.

Conclusion

Several sections of pavement in Quebec, totalling over 400 kilometres, have undergone full-depth reclamation (FDR) with or without stabilization and cold in-place recycling (CIR) over the past 12 years or more. This work was evaluated in terms of the progression in ride comfort (IRI) and rutting. Based on the results, it was possible to quantify performance and complete a benefit/cost analysis of four maintenance scenarios involving FDR and CIR, compared to a conventional maintenance approach using only bituminous resurfacing (BR).

Overall, the results indicate that over a 40-year analysis period, the application of all the scenarios involving the use of a recycling technique is reflected in a performance gain ranging from 10% to 48% compared to that associated with the reference scenario (bituminous resurfacing). Furthermore, even though the scenarios that include recycling work are more costly in terms of net present value (NPV), all these scenarios offer superior performance (benefit/cost ratios; BCR).

The main results of this study are currently being integrated into the MTQ's pavement management system, notably by refining the performance curves used to evaluate the behaviour of recycled pavements. Thus, the more widespread use of these techniques may be worth considering in a context of seeking to optimize network-based operations.

This study constitutes the first phase of a more detailed analysis that will examine the use of these techniques in various contexts in order to further clarify their cost-effectiveness, and ultimately lead to recommendations concerning their use.

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