

Non-Destructive Testing for Optimizing Concrete Pavement Rehabilitation

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ABSTRACT

Visual inspection is the state-of-practice in deciding the type and location of repairs in road rehabilitation projects. Field non-destructive testing (NDT) can provide information on pavements performance to help make such decisions. NDT was carried out on City of Winnipeg's regional roads. The projects included two rigid pavements and one composite structure and they were scheduled for rehabilitation in 2017.

Falling Weight Deflectometer (FWD) testing was performed prior to and after milling and full-depth repairs to evaluate the effect of the asphalt overlay on load transfer efficiency, as well as the improvement in joint performance achieved by full-depth repairs. Real Time Kinematic (RTK) surveying equipment was used to capture coordinates of test locations for retesting after milling or full-depth repairs. This study also evaluates how pavement deflection measurements can be incorporated at the design stage to facilitate the decision making process and to optimize rehabilitation costs with the availability of joint performance information.

Hundred fifty joints were tested in total and their performance was evaluated through their load transfer efficiency, peak deflection and differential deflection between the approach and leave slabs at the joint. It was found that load transfer efficiency measurement experienced a considerable reduction once the asphalt overlay was milled. This means that testing concrete joints performance before milling overestimates their performance and could lead to different repair decisions. Joints generally achieved over 90% load transfer efficiency following a full-depth repair. In cases where the load transfer efficiency was low after a full-depth repair, the peak and differential deflections were found to be small. This highlights the importance of including peak and differential deflection criteria in evaluating performance. Moreover, it was found that in one project approximately 22% of tested joints were under-performing in terms of load transfer efficiency, while 50% of them received full-depth repair. The cost of such repair could have been optimized with the availability of such information. This study sheds light on the benefits of FWD information in the decision making process of joint repairs.

INTRODUCTION

The predominant state-of-practice in road rehabilitation projects is to conduct visual inspection on concrete and composite structures to decide the type and location of repairs. Non-destructive testing (NDT) can provide insights into pavement performance to assist such decisions.

NDT can be utilized in rehabilitation projects as a decision making tool to engineers. It provides easily accessible information about the condition of the roads so that the projects' budgets can be better distributed and the appropriate treatment methods can be selected. The speed at which NDT can be conducted and its lower cost compared to the conventional laboratory testing has made it a popular method to evaluate roads.

One of the commonly used NDT is deflection testing and the Falling Weight Deflectometer (FWD) has become the main testing device of choice for many agencies. Hveem (1995) demonstrated how pavement deflections can provide information about the pavements structural capacity to provide the service level it was intended to. FWD testing can be a relatively quick and cost-effective method to determine pavement layers stiffness to compare the strength and the subgrade support condition along a project section. Moreover, it can evaluate the performance of joints in jointed concrete pavements (JCP) and identify possible voids under joints. FWD testing may be conducted prior to the project's commencement to collect performance data. This means that joint testing is performed on the asphalt overlay that is predominately present in City of Winnipeg roads, and is bound to influence the results of the joint load transfer efficiency (LTE). This study examines the affect of asphalt overlays on LTE measurements, joint performance improvement achieve by full-depth repairs (FDRs) and evaluates the current visual-based decision making process in selecting the treatment type and location.

OBJECTIVES

The goal of this study is to evaluate the benefits of incorporating FWD information at the design stage to assist the engineers in the decision making process. The aims of the study are as follows

- Evaluate the effect of the asphalt overlay on load transfer efficiency measurements
- Study the joint performance achieved by full-depth repairs
- Examine how FWD information can be incorporated at the design stage to facilitate the decision making process and to optimize rehabilitation costs

BACKGROUND

Deterioration of Concrete Pavement Joints

Deterioration of rigid pavement joints is a principal distress that can affect the serviceability of JCPs. It can also lead to further deterioration due to the ingress of water into the subsurface layers of the pavement structure. JCPs undergo loss of integrity at the joints due to the loss of shear force transfer across the joint via dowels. Due to repeated heavy traffic or construction method/quality, installed dowels may become loose or suffer from concrete delamination underneath them. This, in turn, disrupts the load transfer capacity of joints. Loss of load transfer across joints results in increased deflections at the approach and leave side of the joints which may lead to cracking (Snyder, 2011). Moreover, after repeated load cycles and the loss of load transfer, base and subgrade materials are pumped and eroded which leads to the development of voids under slab corners (National Highway Institute, 1994).

Falling Weight Deflectometer Joint Testing

FWD simulates the load of a moving vehicle by applying an impulse load on a 150 cm radius circular plate resting on the pavements surface. Geophones arranged in fixed distances from the loading plate record the pavements response to the applied load. For further detail on the FWD equipment, reference can be made to (NCHRP, 2009). FWD deflection testing can be performed to evaluate the performance of joints through their load transfer efficiency (Smith et al, 2017). LTE testing is carried out by applying FWD load on one side of the joint and recording the deflection values on the loaded and unloaded side of the joints. **Figure 1** shows the FWD arrangement for the testing of the approach and leave sides of concrete pavement joints.

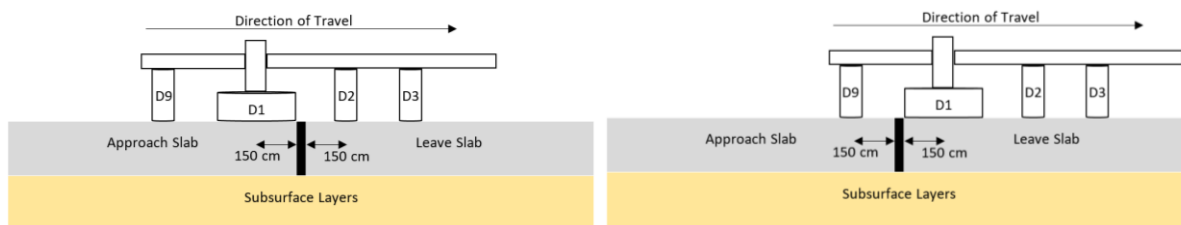


Figure 1: FWD Testing for a) Approach and b) Leave Side of Jointed Concrete Pavement Joints.

Snyder (2011) states that load transfer efficiency should be considered along with other parameters such as peak deflections and differential deflections of joints. Since LTE is merely a ratio, high LTE values indicating good performance can be obtained while joints experience high deflections that lead to pumping and cracking. Similarly, low LTE values signalling bad performance can be computed when joints deflections are too low to cause any deterioration. Therefore, this study examines the peak deflection of the joint and the differential deflection between the approach and leave sides of the joint in evaluating joint performance. **Table 1** summarizes the equations for computing LTE and peak and differential deflections.

Table 1: LTE, Peak Deflection and Differential Deflection Equations.

Parameter	Approach Side of Joint	Leave Side of Joint
LTE (%)	$\frac{D1}{D2}$	$\frac{D1}{D9}$
Peak Deflection (μm)	$D1$	$D1$
Differential Deflection (μm)	$D1 - D2$	$D1 - D9$

Threshold Values of Joint Performance

Low joint performance can be due to low shear force transfer across the joint, weak support and dowel looseness. Joints' capacity to transfer shear forces across joints is evaluated through LTE, the ratio of deflections on the loaded and unloaded sides of a joint. Peak deflection under the applied load, $D1$, is considered to provide information on the condition of the support under the JCP at the joint. Differential deflection provides information on dowel looseness and possible concrete delamination under the dowel.

It is suggested that joints with differential deflections exceeding $130 \mu\text{m}$ would perform unsatisfactorily in the long term (Larson and Smith, 2005). Pennsylvania DOT specification stipulates filling the voids under the concrete slab joints when corner deflections exceed $500 \mu\text{m}$ and LTE exceeds 65% (PennDOT, 2016). Other literature sources have used LTE values ranging between 70% and 75% (Vandenbossche, 2007 and Smith et al, 2017). The criteria for acceptable joints performance in this study were assigned as follows

- LTE > 70 %
- Peak Deflection < $500 \mu\text{m}$ (20 mils)
- Differential Deflection < $130 \mu\text{m}$ (5 mils)

FWD TESTING PLAN

Non-destructive FWD testing was carried out on City of Winnipeg's regional roads prior to and after rehabilitation. The projects were scheduled for rehabilitation in 2017 and consisted of two rigid and one composite (asphalt over concrete) sections. In this process, the scheduled work was not interrupted or interfered with. To be able to perform NDT prior to and after milling or full-depth repair, Real Time Kinematic (RTK) surveying equipment was used to capture coordinates of joint tests locations.

FWD testing was conducted at the joints of 15 adjacent slabs for each lane of a test section. More or less joint testing was performed according to the available time. For the composite section, joints locations were determined based on reflection cracks and were later confirmed after milling during rehabilitation. Every joint was tested at four different load levels – 25 kN, 40 kN, 55 kN and 70 kN. However, the results presented are for the 40 kN load level.

FWD JOINT PERFORMANCE RESULTS

FWD joint testing was carried out in this study on 2 rigid and 1 composite structures prior to and after rehabilitation. The joints of the composite pavement were tested before and after milling to evaluate the effect of the asphalt overlay on computed load transfer efficiency. Testing of the rigid pavement was carried out to investigate the joint performance offered by full-depth repairs (FDR) as well as how pavement deflection measurements can be utilized to assist the decision making process of road repairs. The testing was conducted concurrently with the rehabilitation, without interference with the type and location of repairs planned.

Effect of Asphalt Overlay

The approach and leave sides of 40 joints were tested prior to and after asphalt overlay milling to evaluate the effect of asphalt overlay on computed load transfer efficiencies, peak deflections and differential deflections. Khazanovich and Gotlif (2003) showed that for a large sample size, the approach and leave deflection data are statically different. However, a statistical student t-test of the leave and approach sides of the 40 joints tested shows that LTEs, peak deflections and differential deflections are statically similar, as shown in Table 2. Consequently, the results shown **Figure 2** through **Figure 6** are for approach deflection tests.

Table 2: Results of t-test for LTE, Peak Deflections and Differential Deflections between Approach and Leave Deflection Testing Prior to Asphalt Overlay Milling.

Parameter	Mean Approach	Mean Leave	p-value ¹	Statistically Similar
LTE, %	85.6	85.7	0.1205	Yes
Peak Deflections, μm (mils)	210 (8.3)	213 (8.4)	0.1136	Yes
Differential Deflections, μm (mils)	44 (1.7)	46 (1.8)	0.1501	Yes

¹ Statistically different if p-value was less than or equal to 0.05 for 95% confidence interval.

Figure 2 shows the distribution of LTEs before and after asphalt overlay milling. As can be seen, the LTE distribution prior to milling had a mean of approximately 85% with a standard deviation of 4%. After milling, the mean dropped to 78% with a standard deviation of 7%. It is believed that this is attributed to the way the asphalt overlay distributes forces and stresses across its depth to the surface of the concrete structure. **Figure 3** demonstrates how an effective force is applied on the unloaded side of the joint when the FWD load is distributed across the depth of the asphalt overlay layer. This effective force causes an increased deflection in the unloaded side of the joint, driving the computed LTE to be higher than when the asphalt overlay, and the effective force consequentially, are not present.

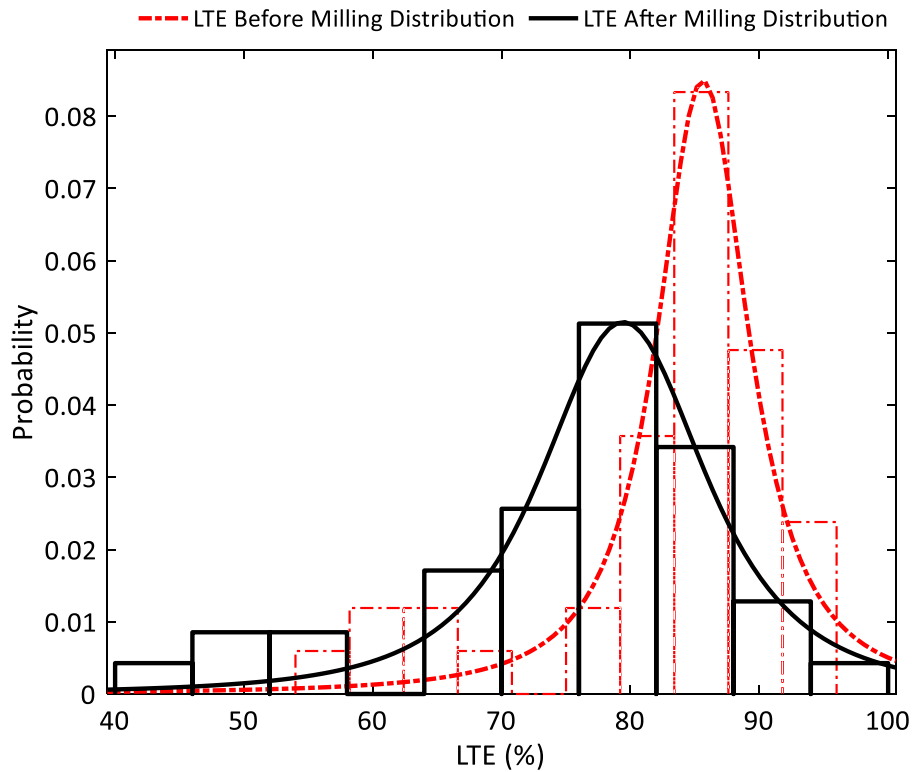


Figure 2: Distribution of Joint LTE Before and After Asphalt Overlay Milling.

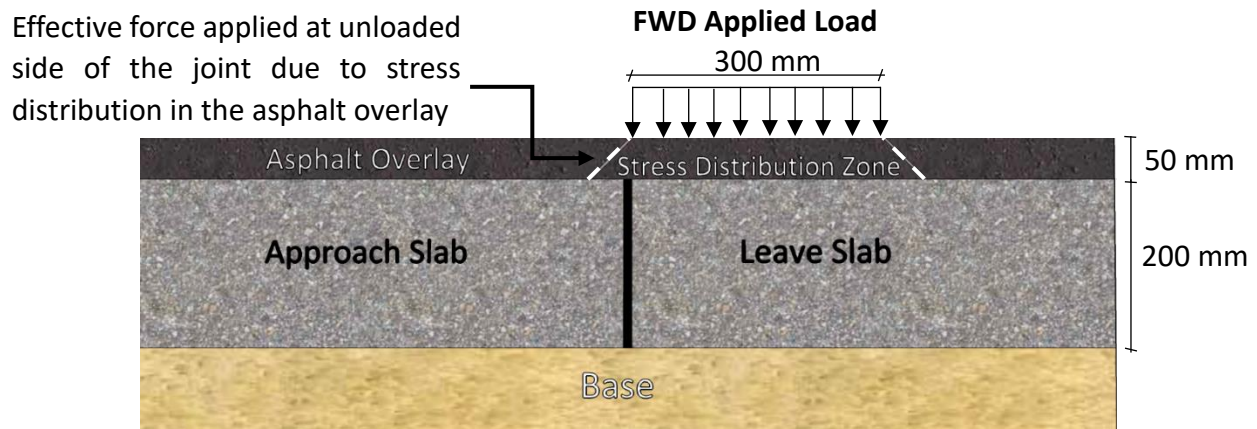


Figure 3: Stress Distribution across Asphalt Overlay Causing Overestimated Computed LTE.

This information can be used in two ways. Firstly, it highlights the improvement asphalt overlays offer JCPs in terms of load transfer efficiency. As observed, the improvement in LTE offered by asphalt overlays may not be significant enough to rely on in rehabilitation projects. FDRs or dowel bar retrofits should, therefore, be carried out to improve JCP joints performance prior to placing the asphalt overlay. Secondly, LTE measurements on the surface of asphalt overlays may underestimate the number of joints requiring rehabilitation which affects project planning and budgeting. As the asphalt overlay overestimates the performance of joints, this could lead to different repair decisions. **Figure 2** shows that after milling, there were joints with LTEs as low as 40% to 55% - a band of LTE values that did not exist prior to milling. The cumulative distribution of the LTE values before and after milling, in **Figure 4**, shows that before milling only 4% of the tested joints fell below the 70% LTE threshold. However, the percentage was tripled to 15% of joints after milling.

Figure 5 and Figure 6 show that joints peak and differential deflection measurements increase upon milling the asphalt overlay layer. Mean peak deflection and differential deflection increased by approximately 45 μm and 30 μm , respectively, after the removal of the asphalt overlay with some increasing by 200 μm such as joint 40. This is anticipated as the removal of the asphalt overlay is weakening the overall pavement structure, leading to increased deflections. Moreover, as shown in Figure 3, the differential deflection is increased after milling as the absence of the effective force on the unloaded side of the joint reduces deflections there. In addition, less pressure of the applied load arrives to the concrete structure on the loaded side of the joint when it is applied on the asphalt overlay, causing a lower peak deflection prior to milling.

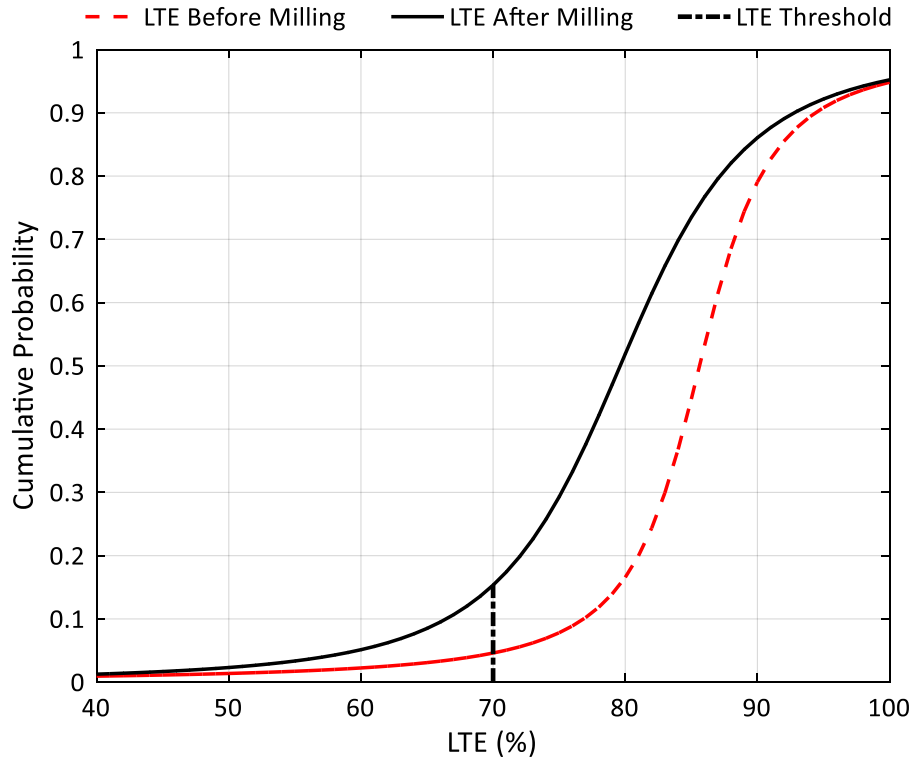


Figure 4: Cumulative Distribution of LTE Values Before and After Milling.

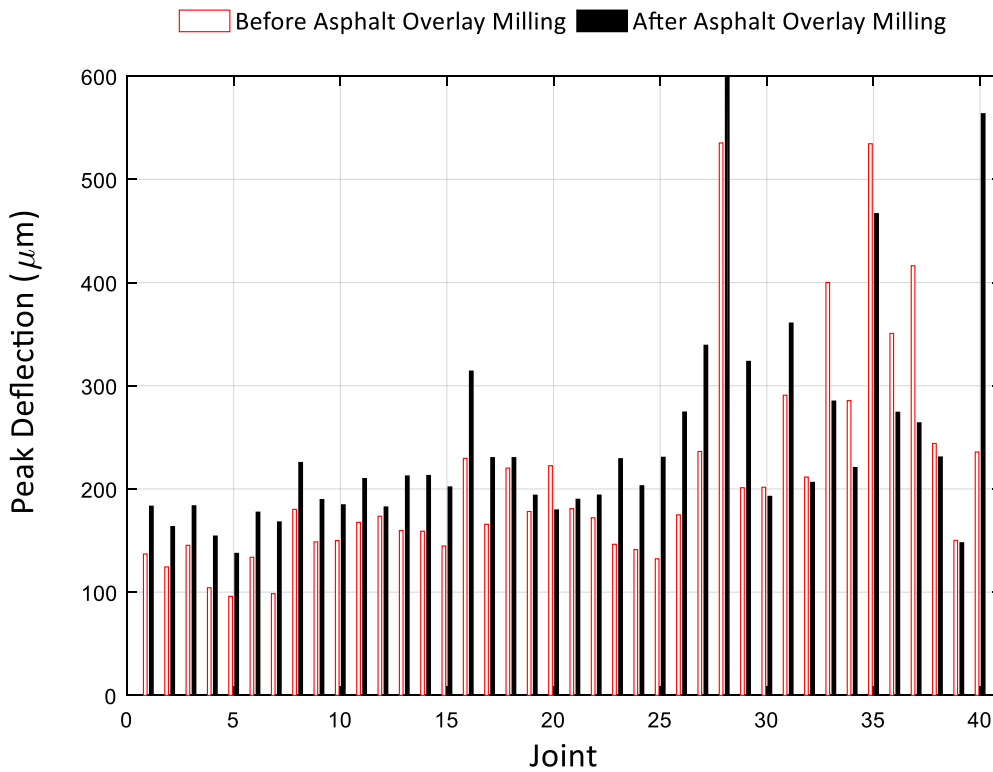


Figure 5: Joints Peak Deflections Before and After Asphalt Overlay Milling.

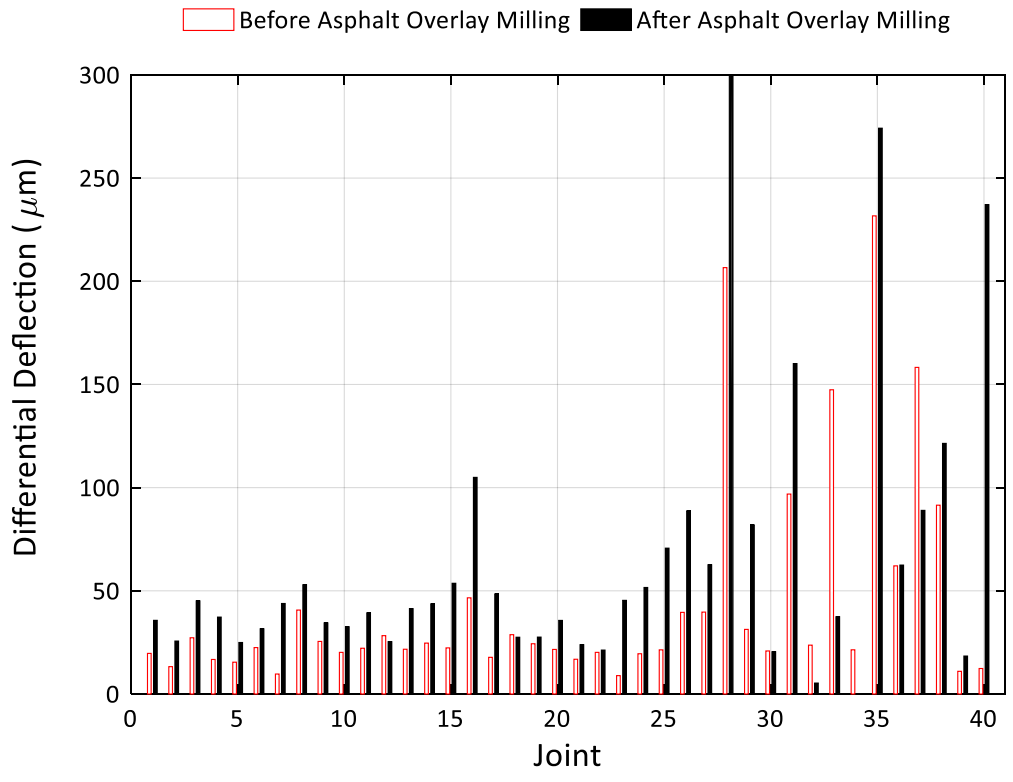


Figure 6: Joints Differential Deflections Before and After Asphalt Overlay Milling.

Joint Performance Achieved By Full-Depth Repairs

Part of this study aimed at evaluating the joint performance, in terms of LTE, peak deflection and differential deflections, achieved by FDRs. In this light, the performance of joints prior to FDRs are not presented as the aim is to investigate whether FDRs are providing well-performing joints. **Figure 7** summarises the computed LTE, Peak and Differential Deflections for 49 joints receiving FDR.

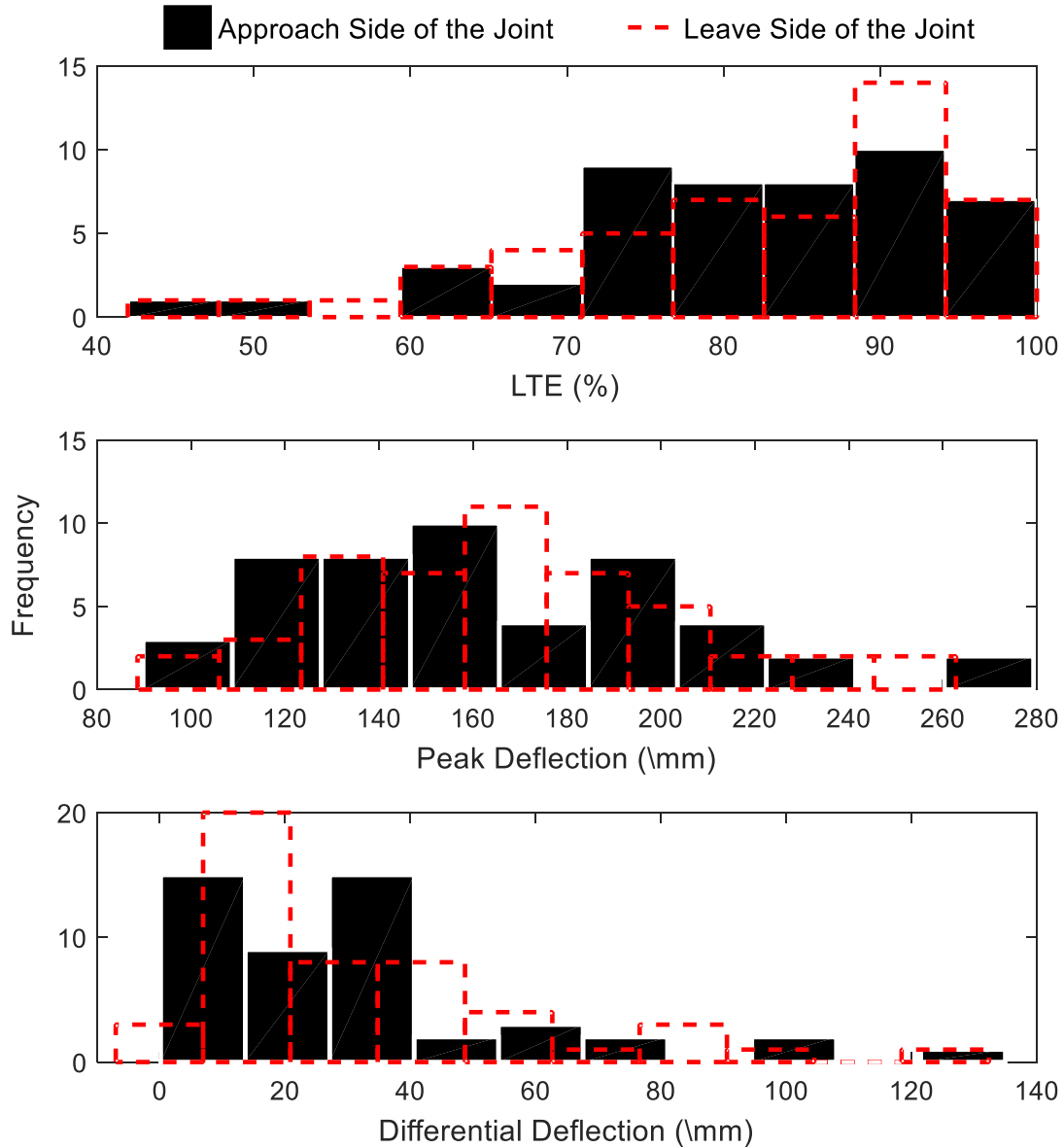


Figure 7: Histograms of Load Transfer Efficiency, Peak Deflection and Differential Deflection of Joints After Full-Depth Repair.

Six joints on the approach and 10 joints on the leave side of the joints, **Figure 7**, have load transfer efficiency lower than the threshold value of 70%. However, none of the joints receiving FDR exhibited peak and differential deflections higher than the 500 μm , indicating good support condition. One joint with 42% LTE experienced differential deflections of 135 μm and 132 μm and peak deflections of 233 μm and 228 μm for the approach and leave sides, respectively. This joint indicates good support condition but possibly loose dowels. 57% of joints receiving FDRs had LTE values over 80% and the average peak deflection for these joints was 155 μm while their average differential deflection was 16 μm . Joints not meeting LTE criteria had average peak and differential deflections of 212 μm and 88 μm , respectively. It is clear that there is a correlation between LTE values computed and differential deflections. This is anticipated as differential deflection is typically computed to provide information about dowel looseness. Moreover, these results highlight the significance of having peak and differential deflections as parameters to evaluate joints performance along with LTE.

The variation in FDRs performance is thought to be attributed to construction method and quality. Differential deflections were generally very low, indicating similar deflection levels across the joint and well anchored dowels. Only few joints showed higher differential deflections. It is believed that this is because the grout injected in the dowel hole may have oozed out of the hole or that not enough time was given for the grout to cure. Furthermore, for joints with LTE less than 70%, their peak deflections were comparable to those with LTE values over 80%. This indicates that, generally, support condition may not be as alarming as dowel looseness and grouting for new FDRs. The joints with higher peak and differential deflections are expected to deteriorate earlier than the other joints and call for maintenance work in the near future. Only two joints had peak and differential deflections higher than 250 μm , indicating weaker support than the other joints. FDRs have displayed their capability to achieve load transfer efficiency and low peak and differential deflections across joints.

Incorporation of Joint Performance at Design Stage

Visual inspection is the predominant state-of-practice in deciding the areas and types of repairs in rehabilitation projects. However, the performance of joints with surface distresses, or patches, may prove hard to predict in the field. **Figure 8** below shows an example of two joints but with the first having 65% LTE, 280 μm and 99 μm peak and differential deflections, respectively. The second joint, **Figure 8b**, has 95% LTE, 235 μm and 11 μm peak and differential deflections, respectively. It appears that the first joint is experiencing lower performance than the second even if it may appear unpatched and well saw-cut. With visual inspection as the only decision making tool, both joints may have received full-depth repair, either one or none – potentially incurring the cost of an additional FDR or missing the chance to repair the low-performing joint which offsets early deterioration in the rehabilitated structure. With the availability of FWD joint information, the joint in **Figure 8a** would have received an FDR while that in **Figure 8b** would have either received no treatment or a partial-depth repair if seen warranted by the project engineer.

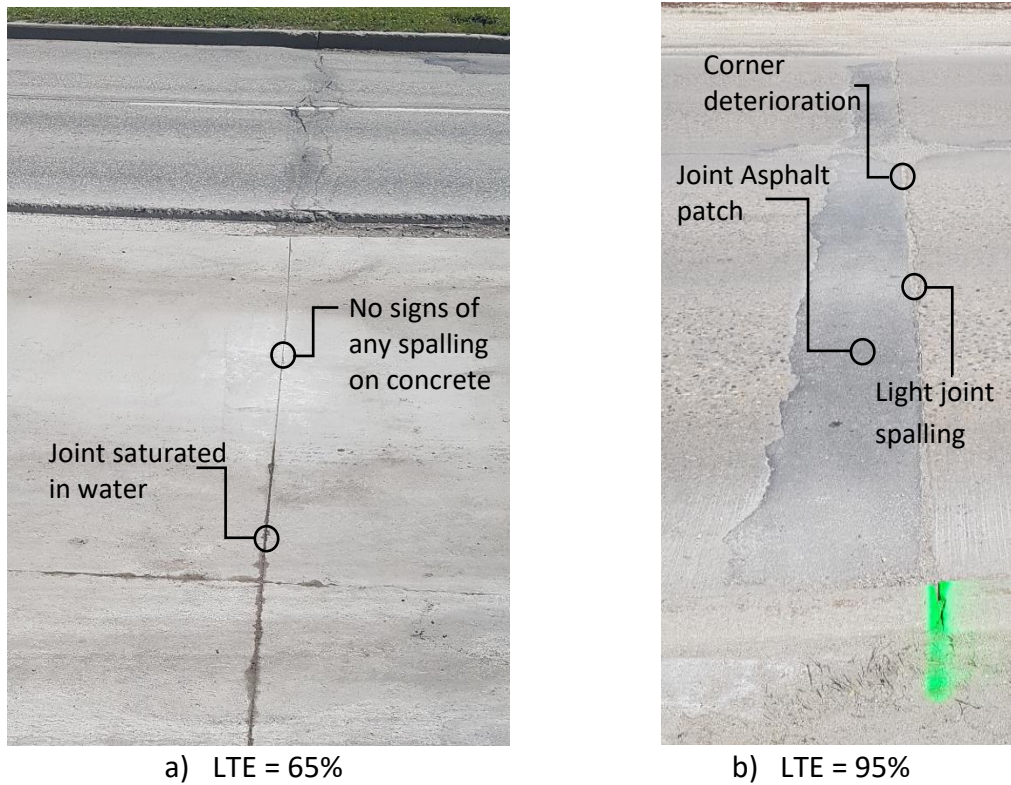


Figure 8: Joints with different visual with a) LTE = 65% and b) LTE = 95%.

To optimize the project cost, the budget should be allocated appropriately to the areas it is needed. FWD performance information can supplement visual inspection in the decision making process to improve the selection of the type of repair for better use of the available rehabilitation budget. In this study, FWD testing was carried out concurrently with the rehabilitation work to investigate the effectiveness of the current, visual decision making process. **Table 3** summarises the number of joints tested for two projects, the percentage of joints not meeting the set performance criteria, percentage of joints receiving full-depth repairs and the subsequent percentage of the success rate in applying FDRs where they are needed without the availability of FWD joint performance information.

Table 3: Summary of Joint Performance Tests without Interfering in Construction Decisions and Their Respective Field Visual-Based Decisions across Two Projects.

Lane	Number of Joints Tested	% Joints Not Meeting Performance Criteria*	% Joints Receiving FDR	Success Rate of Applying FDR Where Performance Was Not Met
Median	40	10 %	23 %	100 %
Center	25	8 %	12 %	0 %
Curb	48	17 %	25 %	13 %

*Performance criteria: LTE > 70%, peak deflection < 500 μm , and differential deflection < 130 μm

It can be observed that field decisions constantly lead to more repairs than what appears to be needed. In the median lane, 13% of the full-depth repairs conducted were for joints meeting performance criteria and so their cost may have been able to be reduced had the FWD information been available prior to rehabilitation. Similarly, the 12% joints repaired could have been reduced to 8% and applied where they are needed. Without FWD information prior to rehabilitation, cost was increased and not allocated to repairs that would maximize performance and minimize cost. Across the two projects, a total of 24 FDRs were carried out within the tested sections only 5 of which were where they are needed in terms of the set criteria. This means that the cost of 20 FDRs could have been reduced, or eliminated, with the availability of joint performance information. Moreover, which required joint performance improvement will continue to deteriorate to cause further damage to the existing concrete and the newly laid asphalt layers, leading to the reduction of the rehabilitation’s lifespan.

Performance information can be used not only to help decide which joints receive treatment, but also the type of treatment. **Table 4** shows the performance parameters for the joints not meeting the set criteria over two projects. It is clear that joints 2, 4, 5, 8, 9 and 10 have very weak support compared to, say, joints 1,3 and 6. Therefore, it would be ideal to conduct FDR with base compaction for those joints. Joint 7 has marginal LTE with differential deflections approaching the limit and considerable indication of loss of support. Therefore, slab stabilization may reduce peak deflections and consequently improve LTE and differential deflections. Joint 11 may have loose dowels, or concrete cracking under the dowel, and so dowel bar retrofit may be the selected treatment.

Table 4: LTE, Peak and Differential Deflections of Joints Not Meeting Set Performance Criteria and Corresponding Potential Performance-Based Repair Decisions.

Joint	LTE (%)	Peak Deflection (μm) at 40 kN	Differential Deflection (μm) at 40 kN	Potential Repair Decision
1	67.31	285.59	93.36	Dowel Bar Retrofit
2	60.10	566.67	226.10	Full-Depth Repair
3	68.81	280.53	87.50	Dowel Bar Retrofit
4	62.11	423.02	160.30	Full-Depth Repair
5	57.90	457.82	192.75	Full-Depth Repair
6	58.30	259.19	108.07	Dowel Bar Retrofit
7	70.56	355.52	104.65	Slab Stabilization
8	62.27	536.52	202.43	Full-Depth Repair
9	64.07	401.69	144.33	Full-Depth Repair
10	61.66	472.10	181.00	Full-Depth Repair
11	62.35	338.18	127.33	Dowel Bar Retrofit

The current visual inspection method provides inputs related to surface distresses and drainage conditions, but it should be supplemented with performance information about the load transfer capacity of joints, dowel looseness and support condition, when possible. With the availability of such information at the design stage, improved construction planning and allocated budget can be achieved.

CONCLUSIONS

FWD Joint testing was conducted to evaluate the benefits in assessing dowel and joint conditions and the quality of support in urban rehabilitation projects. Currently, decisions are largely made based on visual inspection of surface deterioration whilst FWD joint performance could be utilized to improve the decision making process on the type and location of repairs in rehabilitation projects. This would ultimately optimize the performance of the repairs and enable better cost allocation for the projects' budgets. This study set out threshold values for joint performance parameters, namely LTE, peak deflection and differential deflection. The set performance parameters were used to evaluate the effect of asphalt overlays on joint performance, performance achieved by full-depth repairs, and how the information can be used at the design stage to improve planning. The findings can be summarized as follows

- Testing concrete joints in the presence of overlays overestimates joints performance and may lead to different repair decisions. The percentage of joints failing the set performance criteria tripled after the asphalt overlay was removed.
- Asphalt overlays do not increase the load transferring capability of rigid pavements by a considerable amount. Full-depth repairs should, therefore, be carried out prior to overlaying.

- Full-depth repairs achieved high LTE and low peak and differential deflections generally, restoring the performance of joints in JCPs. However, a number of FDRs have low LTEs below the set threshold and differential deflections close to the 130 μm threshold value. It is believed to be due to construction method and quality.
- FWD testing showed that field visual-based repair decisions do not have a high success rate in applying repairs where performance criteria were not met. The cost of such repairs could be controlled and better allocated with FWD testing prior to rehabilitation.
- Not only can FWD information help engineers decide on the location of testing, but examining the deflections may aid in deciding on the type of rehabilitation – such as full-depth repair, partial-depth repair and dowel bar retrofit.

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