Evaluation and Treatment of Slab Stepping on a Major Runway

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Severe slab-stepping (slab-faulting) problems have been observed during the past 5 years in the takeoff areas of Runway 06R/24L, the main runway at Lester B. Pearson International Airport in Toronto. The magnitude of this slab stepping of the plain portland cement concrete pavement is such that complaints about roughness were being received and airport management was concerned that the functional service life of this critical facility was being reduced. A comprehensive field evaluation of the slab stepping was undertaken to determine its cause, extent, and severity to develop practical rehabilitation alternatives for Transport Canada to consider. This field program included the treatment, on a trial basis, of a short section of the runway using diamond grinding equipment to remove the slab stepping. In 1989 the trial grinding section was resurveyed and no significant slab stepping was observed. In 1991 a contract was let to complete full-scale precision diamond grinding of the concrete in the takeoff areas of Runways 06R and 24L and on Taxiways Bravo and Echo. Postgrinding precision profiling was completed, and pavement roughness was found to be well within commonly accepted standards.

The pavements of Runway 06R/24L at Lester B. Pearson International Airport in Toronto, Canada, were constructed in 1960 using plain portland cement concrete over untreated granular base. The 31-year-old pavement has performed satisfactorily, requiring only routine repairs such as localized slab replacement, joint sealing, and maintenance due to the cumulative effects of age and repeated heavy aircraft loadings. However, in the early 1980s the runway developed a slab-stepping (slab-faulting) problem in the areas of the runway that are subjected to repeated applications of moving, fully loaded heavy aircraft during takeoff (and that generally coincide with the "touchdown" areas of the runway). This slab-stepping problem had progressed to the stage at which most of the slabs in the traveled center portion of the Runway 06R/24L touchdown areas (each about 30.5 m wide and 300 m long) had stepped 6 to 12 mm. Some slabs had stepped as much as 25 to 38 mm; similar slab stepping was also observed on the 24L holding area and adjoining taxiways.

From an operational point of view, Runway 06R/24L is extremely critical to the airport. As the only CAT 2 runway with pavement-inset centerline lighting at that time, Runway 06R/24L was the primary runway at Canada's busiest airport. At about 2900 m, it is the shortest of the three main runways, and its surface has been transversely grooved to improve its skid resistance. The airport runway configuration is shown in Figure 1.

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At the request of Transport Canada, an investigation of the runway slab-stepping problem was completed during summer 1987 by John Emery Geotechnical Engineering Limited.

RUNWAY CONSTRUCTION HISTORY AND TRAFFIC ANALYSIS

Transport Canada provided construction history and traffic data for Runway 06R/24L for use during the investigation. This documentation included original construction records (contract documents and construction drawings), pavement construction history sheets, pavement condition survey sheets, skid resistance test results, and aircraft movement data for 1982 through 1986.

The pavement was originally constructed between 1960 and 1962 as 355 mm of plain portland cement concrete (no specified nominal compressive or flexural strength details available) over 150 mm of crushed gravel or crushed stone base and 305 mm of granular subbase. The pavement condition survey data indicated that the runway pavements exhibited moderate corner cracking, slab cracking, and joint sealant failure, and minor edge cracking and joint spalling.

The review and analysis of the aircraft movement records for 1982 through 1986 were particularly relevant to the study. The Runway 06R/24L aircraft movement data are summarized in Table 1. Aircraft movements on Runway 06R have increased by almost 90 percent; movements on Runway 24L have increased by 40 percent (Figure 2). The most significant increase in aircraft movements also occurs in the heavier weight categories—particularly, 90,000 to 136,000 kg. The Runway 24L takeoff area, which also exhibits the most severe slab-stepping problem, has been subjected to the greatest number of and largest increase in heavy aircraft loads. This finding strongly supported the opinion that the stepping problem was related to repetitions of heavy aircraft loads during takeoff and not to impact loads of much-lighter landing aircraft.

FIELD INVESTIGATION PROGRAM

To determine the probable cause of the slab-stepping problem and to assess its overall significance in terms of runway serviceability and rehabilitation, a comprehensive field investigation program was undertaken. The general pavement, subsoil, and groundwater conditions for Runway 06R/24L were determined, and detailed pavement evaluation and geotechnical work was completed in the stepped takeoff areas of the runway and in a small section in the relatively distress-free central portion.

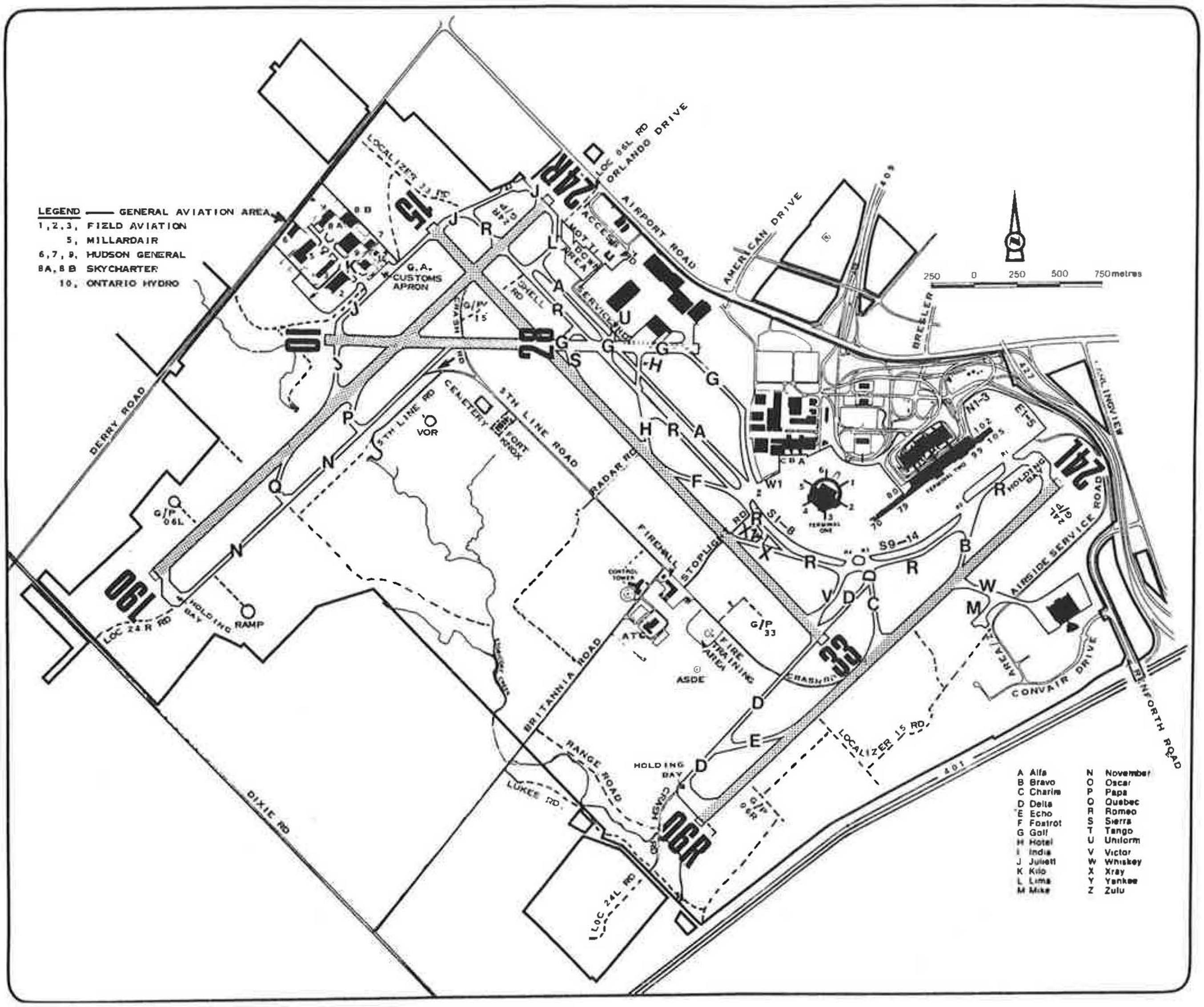

FIGURE 1 **Base map of Lester B. Pearson International Airport, 1985.**

TABLE 1 RUNWAY TRAFFIC DATA, 1982–1986

	Number of Aircraft Movements by Runway and Year									
Weight Category	1986		1985		1984*		1983		1982	
(kg)	24L	06R	24L	06R	24L	06R	24L	06R	24L	06R
0 to 2000	152	222	208	248	132	202	134	273	130	225
2001 to 4000	1086	1358	1254	1339	983	1198	991	1550	848	1274
4001 to 5670	3574	3564	4269	3098	2519	2210	1745	1984	1241	1174
5671 to 9000	135	271	159	258	209	198	203	356	389	437
9001 to 18000	313	698	211	465	168	274	244	396	214	369
18001 to 35000	4534	3923	4805	2780	2258	1624	1930	1510	2216	1302
35001 to 70000	23195	18414	23444	12800	19321	12515	16847	12487	16748	9365
70001 to 90000	13676	10442	14321	7754	13558	8789	12190	9166	11801	6427
90001 to 136000	4132	3425	3648	1976	2155	1284	949	586	4	2
136000 plus	9994	7051	10639	5272	9692	6059	8976	6034	9916	5582
Total Annual Movements	60791	49368	62955	35990	50995	37963	44209	34342	43509	26157

* Estimated average (one month of data missing)

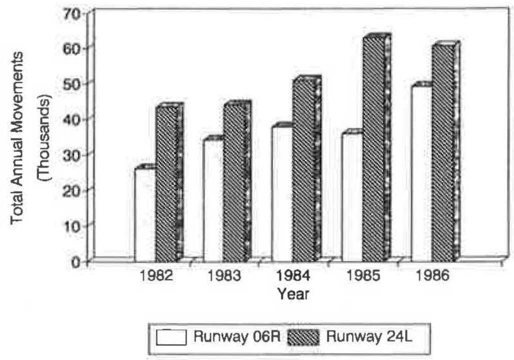

FIGURE 2 Runway traffic data.

The field investigation involved

1. Detailed visual surveying of pavement condition (distress survey);
2. Precise surveying using a precision level and Invar staves to determine the vertical slab orientation;
3. Geotechnical investigation to confirm runway soil and groundwater conditions;
4. Plate load testing of the runway subbase and subgrade;
5. Laboratory testing of the runway slab concrete (flexural strength of concrete prisms and compressive strength of concrete cores);
6. Load transfer determination using the Dynatest falling weight deflectometer (FWD); and
7. Slab deflection testing using a 50-tonne rubber-tired proof roller.

Site Geotechnical Conditions

The geotechnical investigation consisted of 15 boreholes adjacent to the runway and 3 probeholes within repair areas. Subsoil samples were recovered at regular intervals for classification and laboratory testing, and standpipes were installed to allow measurement of the groundwater level.

The principal soil type encountered was dense to very dense sand and silt till. Some compact to dense silty clay fill and sand fill overlying the till (up to 1.5 m deep) were also proven. Groundwater observations confirmed that the groundwater is generally located at depths of 3.0 m at the south end of the runway and 1.5 m at the north end.

To assess the subbase and subgrade support capabilities, nonrepetitive static plate load testing was completed in accordance with Transport Canada procedures. Tests were completed at the top of the granular base course (560 mm of granular base and subbase overlying subgrade at this location) and 150 mm above the subgrade. The testing at the top of the granular base course confirmed a subgrade bearing strength value of 518 kN; testing near the top of subgrade confirmed a bearing strength value of 148 kN.

Pavement Condition

The pavement condition survey was completed in accordance with Transport Canada distress descriptions, supplemented by the American Concrete Institute's *Guide For Making a Distress Survey of Concrete Pavements* and U.S. Army Corps of Engineers' PAVER distress guides. The results of the survey indicated that, with the exception of the slab-stepping problem, the concrete pavement was in good condition. Low-severity pop-outs and joint spalling were observed, as were occasional slab cracking and corner breaks.

The precise surveying confirmed that the joint stepping was confined almost totally to the center two slabs (one on either side of the centerline) for the length of each takeoff area. That of the 24L takeoff area appeared to be the most severe, with stepping on the order of 12 to 15 mm. The stepping had occurred so that the approach side of the joint was higher than the leave side. Stepping of about 10 mm was observed in the 06R takeoff area. The stepping in each takeoff area was noted to end abruptly; virtually no stepping was observed in the central runway area.

Concrete materials testing consisted of flexural strength testing of beams cut from the existing runway concrete slabs and compressive strength testing of 150-mm-diameter cores. The flexural strength of the concrete was determined to be about 6.95 MPa and the compressive strength was determined to be 51.3 MPa.

FWD Testing

To determine rapidly the load transfer between concrete slabs in various thermal curl states and indicate the presence of voids or soft spots for additional testing using a heavy rubber-tired proof roller, deflection testing was undertaken using the Dynatest 8000 FWD. The slab and joint testing was completed under different time and temperature conditions (early morning, very cool; midday, warm; and late evening, cool) to monitor the potential effects of slab curl and thermal expansion and contraction joint "lock up" on load transfer and voids determination. Temperatures ranged from 4°C to 21°C in the most severe testing cycle.

The FWD was used to conduct several tests. Eleven tests were taken per slab to assess representative joint-slab combinations selected on the basis of the pavement condition and precise survey data. The typical testing sequence for each joint-slab combination is illustrated in Figure 3.

Three load levels were employed: 40 kN, 75 kN, and 105 kN. The FWD velocity transducers were positioned such that one was on either side of the joint at distances of 200 and 300

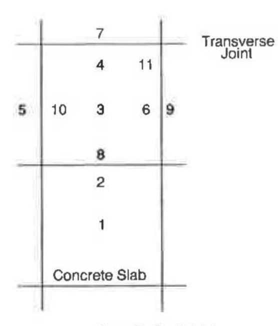

FIGURE 3 FWD testing pattern.

mm from the point of load application. Load transfer and voids detection were indicated using a simple procedure developed for concrete pavements by Shahin et al. (*1*).

The FWD test results for 12 selected joint-slab combinations are given in Table 2. These data indicate that the amount of load transfer across the joints was clearly much less when the slabs were cool because of upward slab curl and unlocking of the joints. In the worst case, the load transfer over a 12-hr period ranged from 2 percent ("unlocked") to 79 percent ("locked"). Slab-rocking potential is indicated by the calculated deflection ratios. As anticipated, there was a very strong indication of rocking in some of the slabs coinciding with the early-morning upward-curl period. However, these same slabs showed virtually no movement once the joints had locked. This strongly suggested not that significant voids were present beneath the slabs but that the "apparent" voids were associated with thermal gradient upward curling of the slabs.

Slab Deflection Testing

Though the FWD testing indicated the load transfer between concrete slabs in various thermal curl states, the relative mass of the concrete slab panels was quite large compared with the maximum FWD loadings (105 kN). Therefore, to replicate the magnitude of load of the heavy loaded aircraft, it was necessary to proof roll selected runway slab panels using a 50-tonne rubber-tired loading cart (a high-capacity FWD has subsequently been developed that simulates an aircraft wheel loading of up to 240 kN). The concrete slab panels were selected on the basis of the FWD testing and degree of slab stepping. The rubber-tired loading cart was pulled across the concrete panel at about 10 m/min using a grader. The slab deflections were continuously measured at the joint using dial gauges attached to a deflection-monitoring beam. The 9.1-m-long beam was anchored outside the influence of the loading cart. The reference frame was rigid enough to be cantilevered across the full width of the slab immediately adjacent to that being tested. Six gauges were located at the joint for each pass. The selected slabs were also measured at different time and temperature periods to monitor the effects of various thermal curl states and to differentiate between slab rocking due to thermal gradient upward curl and voids or soft spots beneath the slabs.

A typical plot of slab deflection versus the loading cart location is shown in Figure 4. Examination of the test results revealed that as the grader moved onto the slab, the leading edge of the slab deflected, causing the gauges at the trailing

TABLE 2 SUMMARY OF FWD LOAD TRANSFER AND VOIDS DETECTION ANALYSIS RESULTS

		Temperature		Load Transfer (%)				Deflection Ratio	
				Approach Slab		Leave Slab			
Slab Number	Time of Test	Ambient °C	Surface °C	Approach Joint	Leave Joint	Approach Joint	Leave Joint	d centre/ d midslab	d corner/ d midslab
32/3	5:17	18	18	95.9	90.1	96.5	85.9	2.4	8.0
	11:06	25	26	87.8	87.0	81.5	89.3	1.5	3.5
	20:55	18	22	96.2	97.8	93.5	96.1	1.5	3.7
44/5	5:35	18	18	6.2	4.9	10.4	5.6	3.5	8.9
	11:26	25	26	19.8	39.8	18.5	24.4	2.5	3.6
	21:10	18	22	68.2	83.2	54.0	65.2	3.0	8.0
50/4	6:01	18	18	3.6	2.0	11.0	6.0	3.4	5.4
	11:44	25	26	19.1	25.3	28.8	41.3	2.3	2.4
	21:25	18	22	62.2	79.4	74.0	83.6	2.7	4.7
55/6	6:17	18	18	97.0	96.1	95.7	98.0	1.6	4.8
	12:05	25	26	93.8	95.1	93.9	97.3	1.2	2.3
	00:05	15	18	72.0	91.5	95.8	95.0	1.2	3.6
75/5	6:33	18	18	22.2	28.2	15.8	18.8	3.1	4.4
	12:54	29	33	62.1	82.2	83.5	85.4	1.3	1.9
	00:23	15	18	72.0	91.5	92.3	95.0	2.0	-
85/4	6:50	18	18	16.9	10.6	14.7	9.4	3.6	7.1
	13:13	29	33	40.6	49.0	77.8	84.1	1.5	2.5
	00:39	15	18	53.2	56.3	59.1	63.9	3.4	-
100/5	7:39	18	18	25.0	14.9	12.8	13.8	2.9	5.3
	13:57	29	33	90.1	78.7	89.9	89.1	1.2	1.3
	00:56	15	18	99.3	93.4	97.7	95.6	1.9	-
110/4	8:00	26	24	17.0	20.1	28.0	31.0	3.8	5.1
	14:15	26	32	97.2	94.4	91.0	89.7	2.9	5.3
	1:14	15	18	98.3	94.2	97.2	96.3	2.7	4.4
226/5	9:48	26	24	24.5	28.1	14.9	18.2	2.1	2.7
	15:53	29	34	37.3	40.3	24.8	32.5	2.2	1.7
	00:28	12	15	26.8	16.9	12.9	28.1	5.4	8.3
234/4	9:28	27	25	12.8	14.5	12.5	13.8	3.4	4.4
	15:38	29	34	21.6	23.6	19.0	22.1	2.5	2.2
	00:13	12	15	4.1	5.8	8.2	5.5	6.5	11.0
430/3	9:05	27	25	95.4	100.0	86.5	88.2	1.4	3.3
	15:18	26	32	96.0	95.4	96.0	94.8	1.0	1.4
	1:51	10	16	94.2	98.0	96.1	93.4	1.4	3.2
440/6	8:24	26	24	94.2	94.9	96.9	94.9	1.5	4.6
	14:42	26	32	97.9	96.7	95.0	96.3	1.0	1.0
	1:35	10	16	97.7	92.8	97.8	97.3	1.4	4.5

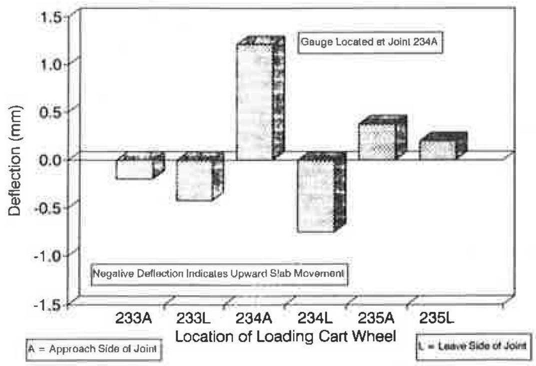

FIGURE 4 Joint deflection profile.

edge of the slab to show an upward movement of the slab. As the loading cart moved across the slab, the deflection became positive, indicating a downward movement of the slab at the joint being monitored. Once the loading cart crossed the joint, there was an abrupt downward movement of the next slab and the first slab returned to its original position. Measurements taken at other temperature conditions indicated that the slab movement (rocking) only took place when the slabs were in an upward-curl position. The loading cart analyses and findings compared quite favorably with theoretical calculations of thermally induced curl for the concrete slab dimensions and temperature gradients.

GRINDING TRIAL EVALUATION

To evaluate possible treatment measures for the slab-stepping problems, Transport Canada also required an evaluation of specialized diamond grinding equipment to restore the runway pavement to a relatively smooth condition. This trial consisted of grinding 14 slab panels (2 panels wide for a distance of 7 panels) using a Target PRM 3800 grinder obtained from Central Atlantic Contractors Inc. of Maryland (Figure 5). This equipment has a 1.0-m-wide grinding head with 60 diamond blades per 300 mm. The resulting concrete surface texture resembles corduroy, and the equipment is capable of very finely controlling the vertical depth of cut (Figure 6).

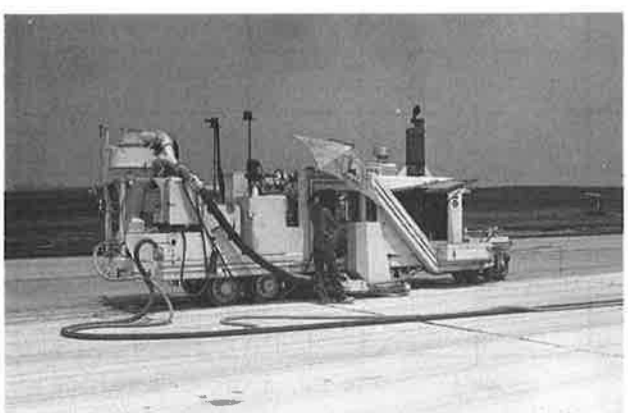

FIGURE 5 Target PRM grinder (Central Atlantic Contractors Inc.).

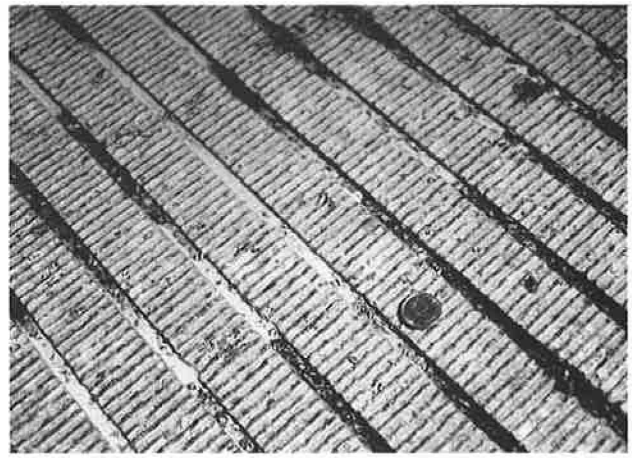

FIGURE 6 Concrete pavement surface texture after grinding.

The longitudinal profile before and after diamond grinding is shown in Figure 7. Clearly, the diamond grinding operation was able to satisfactorily remove the slab stepping and restore the runway pavement to a smooth condition.

On the basis of the results of the postgrinding evaluation, the precision grinding equipment was deemed to have the necessary longitudinal control to remove the stepping problem and produce a relatively flat surface. The grinder was observed to be able to remove only the high spots and neatly feather over the lower areas of the slab. Because of the relatively narrow width of the grinding head, transverse control is somewhat more difficult, relying heavily on the operator.

The trial grinding section was resurveyed immediately after grinding and again after 2 years. Immediately after grinding, the average slab stepping was calculated to be about 1 mm; after 2 years of service, it was about 2 mm. The long-term permanence of this repair technique was not confirmed, but because of the positive trial area performance, it was recommended that the takeoff areas of Runway 06R/24L be diamond-ground using this type of equipment or its equivalent. The apparent absence of significant voids suggested that slab stabilization was not necessary.

FULL-SCALE PAVEMENT GRINDING

In May 1991 full-scale pavement grinding was completed in the takeoff areas of Runway 06R/24L and on Taxiways Bravo

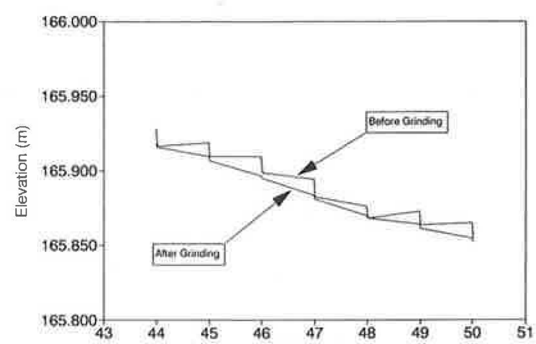

FIGURE 7 Pavement profile: trial grinding area.

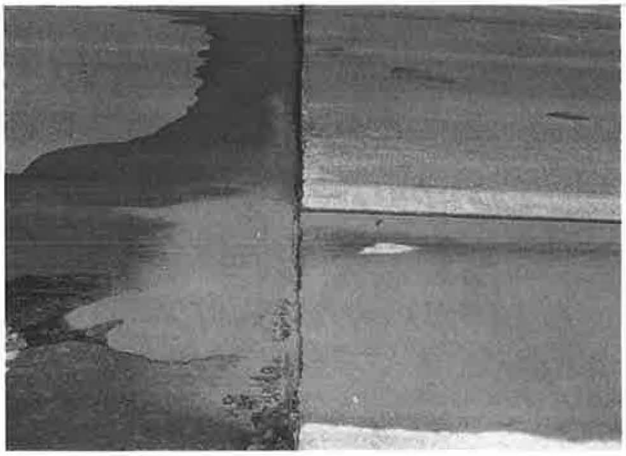

FIGURE 8 Grinding completed on Taxiway Echo.

and Echo. The precision grinding was completed by two Target PRM 3800 grinding machines subcontracted from a U.S. firm. The grinding was completed at about 200 m²/hr/machine. To restore the pavement profile, up to 15 mm of the concrete was removed (Figure 8). Note the magnitude of the stepping and depth of grinding. Upon completion of the grinding, the transverse grooving of the pavement was reinstated and all of the slab joints were resealed.

To measure and record the actual pavement profile for acceptance purposes after longitudinal grinding was completed, the finished profile was accurately measured using a Digital Incremental Profiler (*3*). The profiler is a relative elevation device that collects pavement profile elevation measurements at 300-mm increments. The data are stored by an on-board computer for later analysis.

The pavement profile was analyzed using the Runway Roughness Analysis Program (RRAP) (*4*). A plot of the postgrinding Runway 24L profile is shown in Figure 9. From the figure, it can be seen that the pavement profile after full-scale diamond grinding is relatively smooth over its entire length.

The pavement surface profiles were processed by the RRAP program to determine several pavement roughness statistics including surface profile/traveling straight edge (SP/TSE), root mean square vertical acceleration (RMSVA), and international roughness index (IRI). The SP/TSE analysis methodology is one of the simplest methods of measuring profile roughness and is the current Transport Canada procedure. The straight edge is basically a simply supported beam with a surface contact sensor at mid-length. The SP/TSE analysis simulates the movement of the straight edge in 300-mm increments with the deviation from the midpoint of the straight edge calculated with each movement. A typical profile detail and deviation plot for a 100-m section on Runway 24L are shown in Figure 10. The relatively straight line on the plots is the actual profile, and the jagged line is the profile deviation from a 3-m straight edge. The highest profile deviation measured is at the slab joints (approximately every 6 m) and measures about 1.0 to 1.5 mm. Transport Canada Publication AK-68-33-199 (*2*) defines the critical deviation (above which corrective action should be taken) as equal to 0.9 times the square root of the straight edge length (SEL) where the SEL is measured in meters and the critical deviation is measured in centimeters. For a 3-m straight edge, the critical deviation is 15.6 mm. The summary roughness statistic for the SP/TSE analysis given in Table 3 is calculated as the sum of absolute deviations per unit length.

RMSVA is defined as the root mean square difference between adjacent profile slopes. A report for the Transportation Development Center and Airports Authority Group Transport Canada (*5*) recommended using the RMSVA statistic to correlate with the current Transport Canada Riding Comfort Index (RCI) statistic. Using the RMSVA, the corresponding RCI values for the postgrinding pavements would be 7 to 8.

The IRI statistic is defined as the average rectified slope of a profile being traversed by a particular reference vehicle at

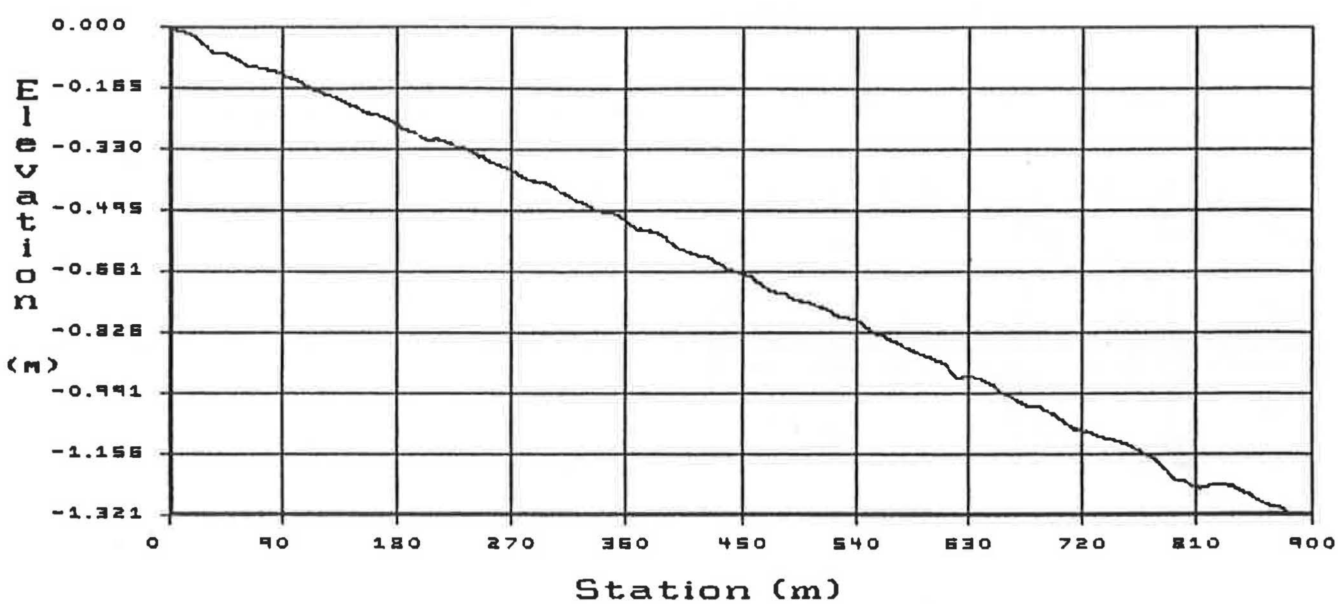

FIGURE 9 Pavement profile after grinding Runway 24L (offset: 3 mL).

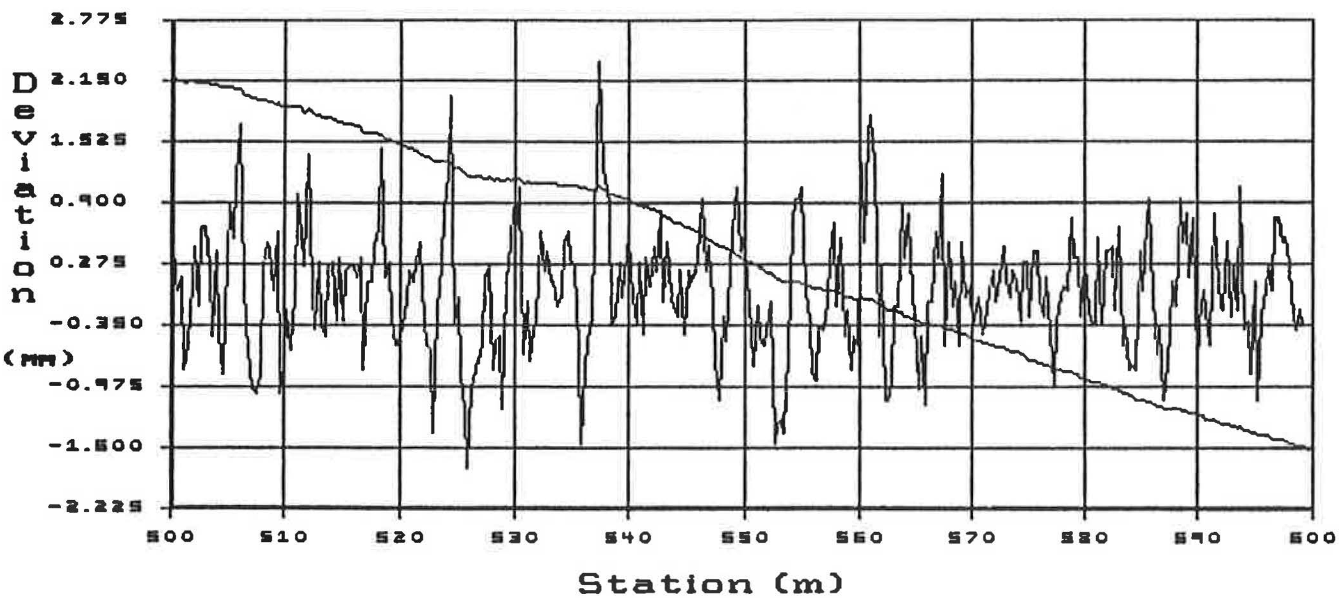

FIGURE 10 Pavement profile detail after grinding showing profile plot and deviation from a 3-m straight edge (critical deviation = 15.59 mm).

80 km/hr. For the facilities analyzed, the IRI values range from 0.93 to 1.3 mm/m. The World Bank (*6*) recommends a maximum IRI value of 2.0 mm/m for runways.

CONCLUDING COMMENTS

The postgrinding profile determination and roughness analysis confirmed the success of the full-scale grinding operation. A relatively smooth pavement surface has been restored (see Figure 11). To assess the long-term effectiveness of precision grinding as a maintenance alternative, it has been recommended that the pavements be resurveyed every 2 to 3 years.

It cannot be overemphasized that precision grinding should be considered only in instances in which the pavement is structurally adequate. Structural testing of the pavement using a high-capacity FWD or its equivalent is strongly recommended. Grinding of structurally inadequate pavements will result in further reduced structural capacity and more rapid pavement deterioration.

TABLE 3 SUMMARY OF PROFILE ANALYSES, POSTGRINDING ROUGHNESS

Facility	Root Mean Square Vertical Acceleration (mm/m2) Base Length 0.6 m	1.2 m	3.0 m	International Roughness Index (mm/m) -->	<--	Profile Deviation Per Unit Length (mm/m) Straight Edge Length 0.6 m	1.8 m	3.0 m
1. Pearson Airport Taxiway Echo OFFSET: 3.0 m R DATE: 05/28/91	2.11	0.81	0.27	0.94	0.93	0.90	1.14	1.67
2. Pearson Airport Runway 24L OFFSET: 3.0 m L DATE: 05/30/91	2.60	0.91	0.28	1.01	1.00	1.01	1.40	1.93
3. Pearson Airport Runway 06R OFFSET: 3.0 m R DATE: 05/28/91	2.86	1.12	0.36	1.15	1.16	1.11	1.65	2.38
4. Pearson Airport Taxiway Bravo OFFSET: 3.0 m L DATE: 05/28/91	3.66	1.16	0.38	1.30	1.33	1.58	1.92	2.42

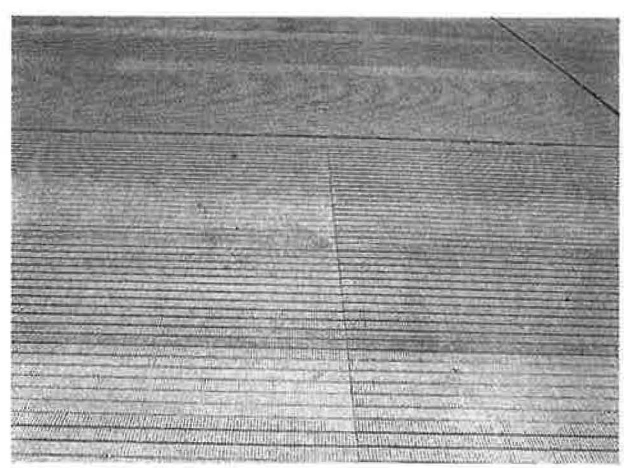

FIGURE 11 Completed pavement surface after grinding and grooving.

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The opinions and findings expressed or implied in this paper are those of the authors and not necessarily those of Transport Canada or Public Works Canada.

Publication of this paper sponsored by Committee on Pavement Maintenance.