ANALYSIS OF FALLING WEIGHT DEFLECTOMETER TESTS AT DENVER INTERNATIONAL AIRPORT

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ABSTRACT

Data collected from heavy weight deflectometers (HWD) tests at the Federal Aviation Administration (FAA) instrumented Portland cement concrete (PCC) pavement test site at Denver International Airport (DIA) are used to analyze the deflection response of the pavement. The HWD tests are conducted routinely for slabs in both the traffic and the nontraffic area. The deflection measurements show that a linear relationship exists between surface deflection and load at the center of the slabs and at the mid-points of the joints. Some of the tests were also run with the HWD weight dropped directly over multidepth deflectometers (MDDs) in the pavement. Deflections at the interior, joints, and corners of a slab measured by the HWD are compared to those measured by the MDDs at different depths. The analysis shows that the movement of an anchor at 3 meter (10 feet) below the slab surface had significant effects on the measured pavement surface deflection while the effects of movement of an anchor at 6-meter (20-feet) depth may be negligible. The analysis also indicates that a gap existed between the bottom of the PCC slab and the top of the econocrete base layer at the slab corners and at the joints. A load transfer analysis, including measurements of the strain response of the PCC slab under HWD loading, indicates that the load transfer capability of hinged joints was very stable for all the seasons, but that the load transfer capability of dummy joints varied significantly in a year. The load transfer capability of the dummy joints became very small during the winter but returned to normal (equal to even higher than is expected by the FAA design specification) in the summer.

INTRODUCTION

Heavy weight deflectometer (HWD) tests are routinely conducted at the FAA instrumented PCC pavement test site at Denver International Airport. HWD tests are conducted in two phases. In the first phase, HWD geophone sensors record vertical deflections at seven points on the pavement surface. Two series of tests are included in the first phase: *Pavement Evaluation* and *Environmental Slab*, with four and three load levels respectively. The collected data are used for pavement evaluation and environment related slab response analysis. In the second phase, the in situ pavement sensors record the pavement response while the HWD geophones record the defections on the pavement surface. These tests are conducted by placing the HWD load plate directly over the in situ deflection and strain sensors. Four series of tests are included in the second phase: *Reference, Principal, Load transfer, and Gage Verification*, with one or two load levels in each series. Table 1 lists all of the HWD tests conducted in March 1996.

One of the objectives of the HWD tests is to develop relationships between the applied load and measured deflections. The analyses in this paper include measurements made at the interior, joints, and corners of slabs within the instrumented area. A comparison is also made between the surface deflection measurements by HWD gages and the measurements by the in situ multidepth and singledepth deflectometers. Load and deflection transfer capabilities of joints are also analyzed for HWD measurements made in different seasons.

The results presented are based on the HWD test data collected in March 1996, April 1997, and August 1997. The data is available in the “Denver Database” on the FAA AAR-410 web site at http://www.airporttech.tc.faa.gov/denver (see references 1 and 2).

Table 1.
HWD tests conducted in March 1996.

Test Type	Locations	Target load kN (kip)	Number of Drops each location	Drop No. recorded by in situ sensors	Note
Principal	15	222 (50) 111 (25)	3 3	2nd	Over in situ sensors
Load Transfer	13	222 (50) 111 (25)	3 3	2nd	Over in situ sensors
Reference	4	222 (50)	3	2nd	Over in situ sensors; HWD Dropped at 22, 1, 2, 4 o'clock at each location.
Gage Verification	45	222 (50)	3	2nd	Over in situ sensors
Pavement Evaluation	15	222 (50) 178 (40) 133 (30) 89 (20)	3 1 1 1		At the center of slab along wheel-path of most commercial aircraft
Environmental Slab	26	222 (50) 178 (40) 133 (30)	4 4 4		HWD dropped at the center of slab, near transverse and longitudinal joints of slabs
Total	**118**				

RELATION BETWEEN THE LOAD AND THE DEFLECTION

Figure 1 shows the locations of the drop points for three of the environmental slab tests (B3C, B3L, and B3T) and one of the pavement evaluation slab tests (Station 270).

In the environmental slab tests, the loads are applied at the center of the slabs in lanes A and B (the top 2 rows of slabs in figure 1) and near the center of the transverse and longitudinal joints of lanes A and B. Each test consisted of drops at three load levels, 222 kN (50 Kip), 178 kN (40 Kip), and 133 kN (30 Kip), with four drops at each load (see table 1).

In the pavement evaluation tests, the loads are applied at the center of each slab in lane D (the bottom row of slabs in figure 1) along the wheel-path for most commercial aircraft. Each test consisted of drops at four load levels, 222 kN (50 Kip), 178 kN (40 Kip), 133 kN (30 Kip) and 89 kN (20 Kip), with three drops at 222 kN (50 Kip) and one drop at each of the other three loads (see table 1).

Plots of the surface deflections versus load level for all seven HWD geophones are shown in figures 2 (A) through 2 (D). In all of the plots, d_0 is the maximum pavement surface deflection at the center of the HWD load plate. The remaining plots on the figures are for the six other geophones located at increasing distances from the center of the load plate. The spacing of the geophone gages is 0.305 meter (1 foot). Linear least squares correlation curve fits are drawn for all of the deflection versus load plots.

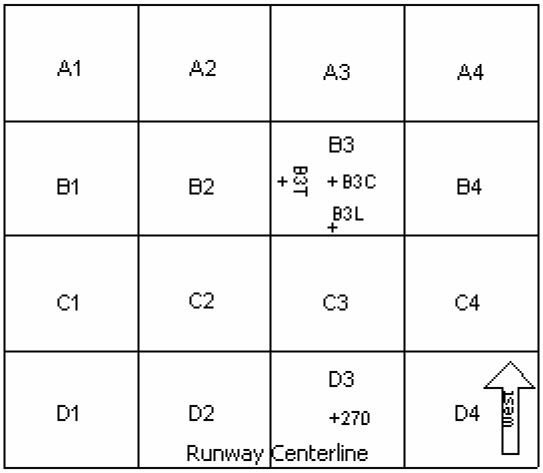

Figure 1. Location of typical test drops in the pavement evaluation and environmental test slabs.

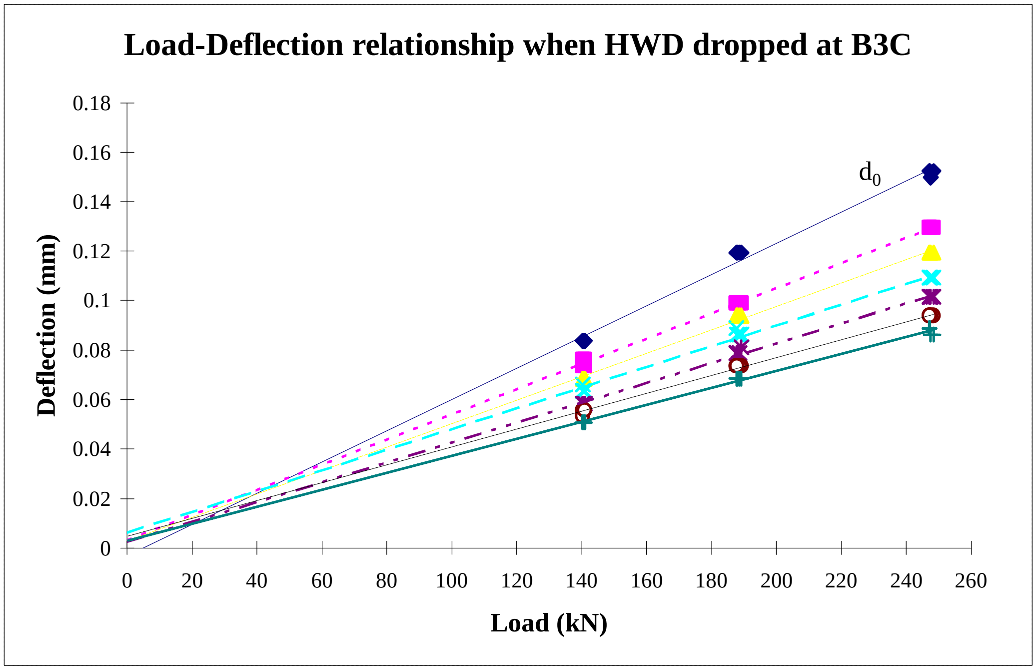

Figure 2 (A). Test location at the center of slab B3 with 3 load levels.

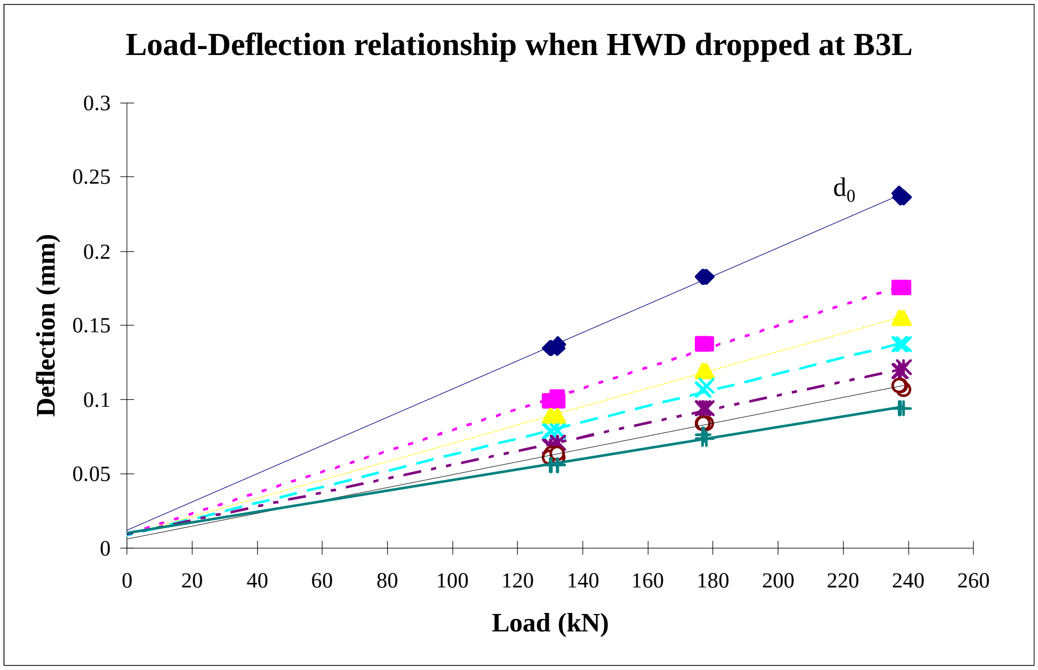

Figure 2 (B). Test location at the longitudinal doweled joint of slab B3 with 3 load levels.

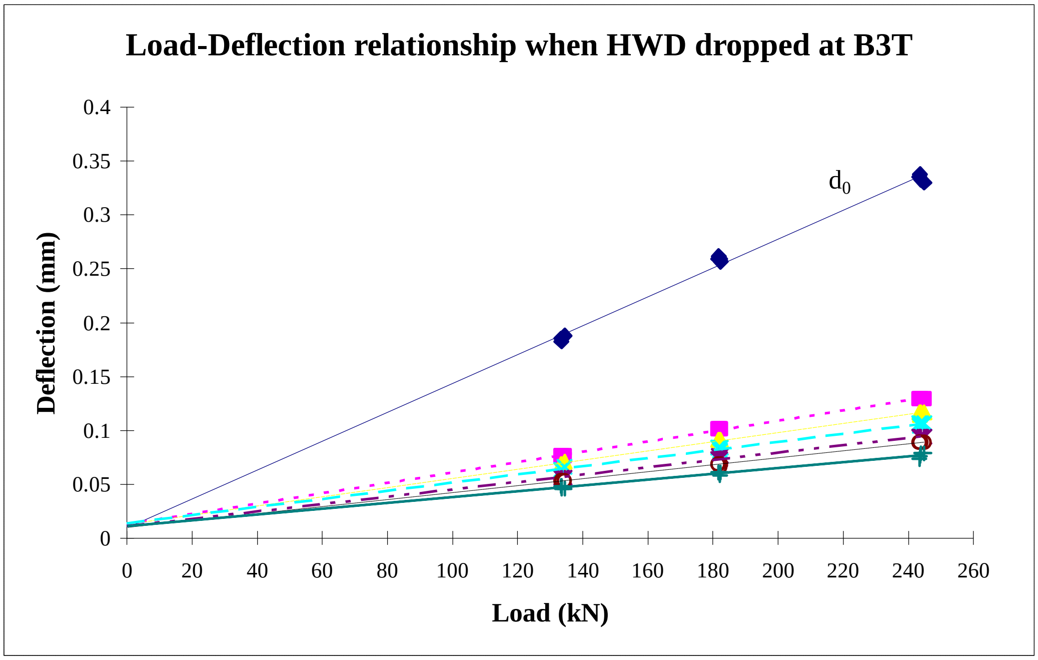

Figure 2 (C). Test location at the transverse dummy joint of slab B3 with 3 load levels.

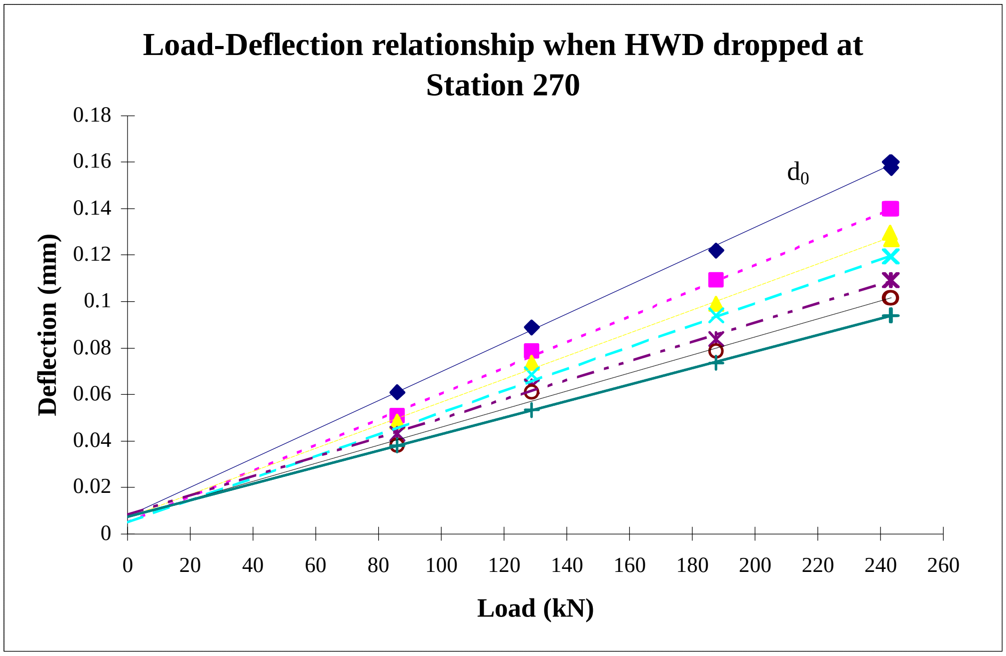

Figure 2 (D). Test location at the center of slab D3 with 4 load levels.

The figures illustrate four distinct features.

1. The multiple drops at each load level are very repeatable, both in the loads applied and the deflections measured.
2. The deflection versus load relationship is linear over the ranges of load levels and for the drop locations used in the tests.
3. With the exception of one curve in figure 2 (A), a small, but consistent, offset is shown at zero load when the linear curve fits are extrapolated back to the origin. The range of the offsets is 0.003 mm (0.1 mils) to 0.013 mm (0.5 mils), with the offset increasing as d_0 increases.
4. The deflection at the load plate (d_0) increases significantly as the drop location varies from center-slab to doweled joint to dummy joint. This is consistent with the trend of load transfer efficiency at the joints discussed later. However, the increasing trend is not uniformly repeated by the deflections at the other geophones. Table 2 shows the deflections at d_0, d_1 (next to the load plate), and d_6 (furthest from the load plate), for the largest load (nominally 222 kN (50 Kip)).

Table 2.
Geophone deflections at different locations and at the largest load.

Location	Load (kN)	d_0, mm	d_1, mm	d_1 / d_0	d_6, mm	d_6 / d_0
B3C	247	0.152	0.130	0.86	0.086	0.57
270	243	0.158	0.140	0.89	0.094	0.59
B3L	237	0.236	0.175	0.74	0.094	0.40
B3T	245	0.330	0.130	0.39	0.076	0.23

GAPS OBSERVED AT EDGE AND CORNER OF SLABS

The in situ MDDs are used to measure the pavement deflections at different depths when the HWD load plate is directly dropped over the sensors. Figure 3 (A) shows the locations of the MDDs. Figures 3 (B) and 3 (C) show the results received from the in situ MDDs when the target 222-kN (50-Kip) loads were dropped over the position of the sensors.

Four sensors are installed in each MDD. One is in the middle plane of the PCC slab (G1), one is at the bottom of the base (G2), one is at the bottom of the subbase (G3), and the fourth is located about 0.3 m above the top of the subgrade (G4), as shown in figures 3 (B) through 3 (C). The differences between the displacement measurements obtained from G1 and G2 are listed in Table 3.

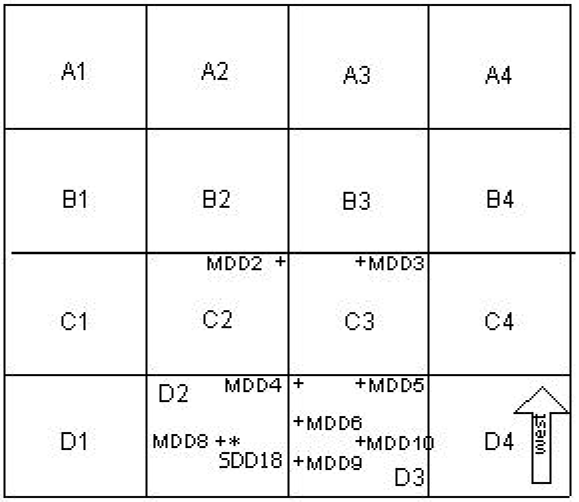

Figure 3 (A). Locations of in situ multidepth deflectometers.

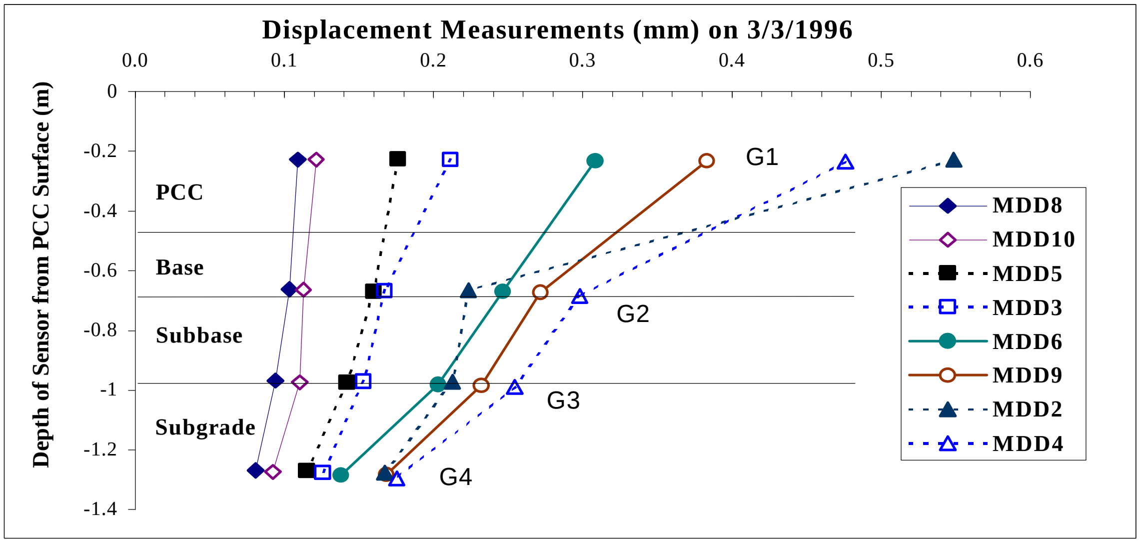

Figure 3 (B). MDD displacement measurements at different depths on 3/3/1996.

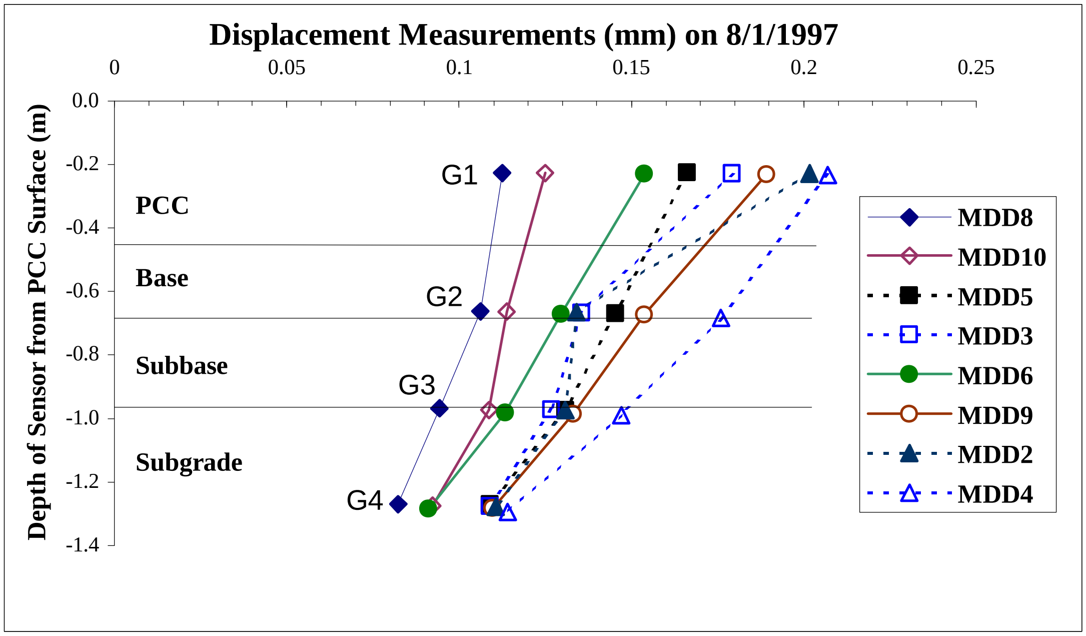

Figure 3 (C). MDD displacement measurements at different depths on 8/1/1997.

Table 3.
Difference of displacement measurements by G1 and G2 (mm).

Gages Test Date	Center		Transverse Joint		Longitudinal Joint		Corner		In situ Temperature of Slab (^oC)	
	MDD8	MDD10	MDD6	MDD9	MDD5	MDD3	MDD4	MDD2	Top	Bottom
3/3/1996	0.0058	0.0087	0.0620	0.1120	0.0164	0.0446	0.1781	0.3255	-1.7	4.4
8/1/1997	0.0064	0.0112	0.0241	0.0356	0.0208	0.0439	0.0310	0.0676	22.2	27.2

Figures 3 (B) and (C) show that slab deflections at the slab centers (MDD8 and MDD10) were almost the same (0.109 to 0.125 mm or 4.3 to 4.92 mil) on 3/3/1996 and 8/1/1997. However, the deflections were very different (0.48 to 0.55 mm on 3/3/1996 and only 0.2 to 0.21 on 8/1/1997) at the slab corners (MDD2 and MDD4). This indicates that the slab bottom always kept in contact with the base top in the slab center area but separated from the base top at the slab corners. On 3/3/1996 (the end of the winter) it separated more than on 8/1/1997 (the middle of the summer).

The above findings may also be verified by analyzing the deflection difference between the sensor readings at G1 (the middle of the slab) and G2 (at the bottom of the base layer). For MDD8 and MDD10 at the center of the slabs, the differences between the vertical displacements at G1 and G2 are less than 0.012 mm (0.47 mil). This is in the same order of the compression of the PCC slab and the base. However, the differences between G1 and G2 for MDD2 and MDD4 at the corner of the slabs are 30 to 37 times greater than the difference at the center on 3/3/1996 and 4 to 6 times on 8/1/1997. These displacement differences are far beyond the compressive deformation of the concrete and base between G1 and G2. An explanation is that gaps have developed between the bottom of the PCC slab and the top of the base layer. If this explanation is correct, the measured slab deflection contained significant contribution from the gap between the PCC and the base.

Gaps were observed at locations nearby joints, such as MDDs 3, 5, 6, and 9. The gaps in summer were less than those in winter. Also, deflections at the centers of the joints were intermediate between the deflections at the centers and the corners of the slabs. This is particularly evident in the results for 3/3/1996 in figure 3 (B), where the deflections at the tied or doweled longitudinal joints (MDD3 and MDD5) are close to the deflections at the centers of the slabs and the deflections at the aggregate interlock transverse joints (MDD6 and MDD9) are close to the deflections at the corners of the slabs.

ESTIMATION OF ANCHOR MOVEMENT

Table 4 lists the measurements of the pavement surface deflection d_0 and the middle plane deflection d_m in the PCC layer under the HWD test position. The deflection d_0 was measured by the geophone gage that is mounted at the center of the HWD load plate, but d_m was measured by the in situ MDD sensors when the HWD load plate was dropped over these sensor positions. To obtain an estimate of the compression in the PCC layer, the elastic modulus of the PCC layer was first backcalculated from the HWD measurements (see reference 3). Values were obtained in the range 41,500 to 49,500 MPa ($6.02*10^6 – 7.18*10^6$ psi). The HWD target load is 222 kN (50,000 lbs) and the radius of the load plate is 15 cm (5.9 inches). Therefore, a conservatively large estimate of the average vertical strain would be 0.074×10^{-3} ($\approx 50{,}000 / (3.1416 \times 6 \times 6) / 6{,}000{,}000$). The estimated concrete deformation between the slab surface and the mid-plane would be less than 0.016 mm (0.63 mil $\approx 0.074 \times 17 / 2$).

Table 4.
Measurements of slab deflections by HWD and MDD on 3/3/1996.

HWD location	Test target sensors	d_0 mm (mils)	d_m mm (mils)	d_0 - d_m mm (mils)
Center of slab	MDD8G1	0.168 (6.6)	0.109 (4.3)	0.059 (2.3)
	MDD10G1	0.170 (6.7)	0.122 (4.8)	0.048 (1.9)
Corner of slab	MDD2G1	0.767 (30.2)	0.549 (21.6)	0.218 (8.6)
	MDD4G1	0.620 (24.4)	0.475 (18.7)	0.145 (5.7)
Transverse joint	MDD6G1	0.381 (15.0)	0.246 (9.7)	0.135 (5.3)
	MDD9G1	0.472 (18.6)	0.384 (15.1)	0.088 (3.5)
Longitudinal joint	MDD5G1	0.249 (9.8)	0.175 (6.9)	0.074 (2.9)
	MDD3G1	0.287 (11.3)	0.211 (8.3)	0.076 (3.0)

From the last column of each row in table 4, it is clear that d_0 - d_m is significantly greater than 0.016 mm (0.63 mils).

Each MDD sensor in table 4 has a reference rod anchored at about 3 m (10 feet) below the PCC surface. The measured displacements using MDD sensors are the relative movement between the sensor and its anchor. The HWD geophones are velocity transducers and are used to measure the “absolute” vertical displacement at the measured position. As discussed previously, the slab center area was in contact with the top of the econo-concrete base. The difference between d_0 and d_m may be defined as the sum of the compressive deformation of a half thickness of the slab plus the movement of the anchor if measurement error is neglected. Based on the measured data at the center of the slab in table 4, the average anchor movement under a 222-kN (50,000-lbs) load level was about 0.037 mm (1.47 mil = (2.3+1.9)/2 – 0.63).

Some potential errors mentioned below could also exist in the measurements:

- The HWD load plate may not be positioned directly over the target sensor location in the tests. Displacement at a 1-foot offset will be approximately 10% to 20% less than at the load center when the test position is at the center of a slab. The displacement would reduce significantly more than 20% when the test position is near a dummy joint in winter.

- The peak value of the displacement may not be accurately digitized due to the anti-alias filter and sampling position; or the peak may be distorted due to signal noise. Figure 4 gives a detailed time history of MDD8G1 measurements near its peak value and two possible fitting curves for estimating the peak. It indicates that the computed peak value may vary from 0.12 to 0.15 mm (see points L and U in figure 4) depending on which curve is used. Therefore, the direct reading of 0.109 mm (see point P in figure 4) for MDD8G1 in table 3 seems to be lower than the real value of the response.

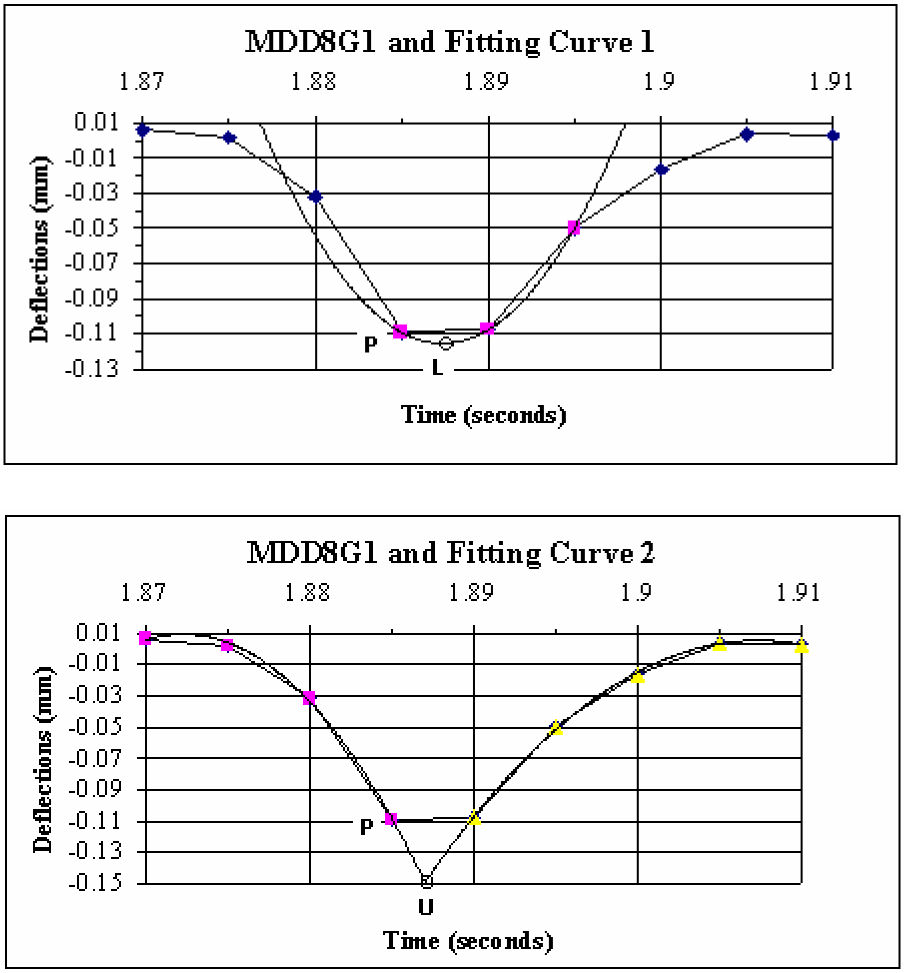

Figure 4. Estimation of MDD8G1 peak value from two different fitting curves.

Ten single-depth deflectometers (SDD) were also installed in the test pavement at Denver International Airport. Each SDD has a reference rod anchored at about 6 m (20 feet) below the PCC surface and a sensor located in the middle horizontal plane of the slab. Since the anchor depth for the MDDs is 3 m (10 ft), deflections of the SDDs due to HWD loading allows the relative effect of anchor depth to be evaluated. SDD18 in figure 3 (A) was placed 0.305 meters (1 foot) to the north of MDD8G1 in slab D2. Table 5 lists the slab deflections measured by the HWD sensor d_0 and the slab sensors in MDD8 and SDD18 when the load was dropped directly over MDD8 and SDD18. All measurements are normalized to 222 kN (50,000 lbs) for comparison.

Table 5.
Deflections measured by HWD, MDD, and SDD.

	HWD Readings (mm)		MDD Readings (mm)	SDD Readings (mm)
Load Position	MDD8	SDD18	MDD8G1	SDD18
MDD8	0.143	0.122	0.093	0.113
SDD18	0.121	0.144	0.089	0.123

As discussed previously, the slab surface deflection at the center of the HWD load plate is equal to the sum of three parts: the deflection of the pavement of the sensor location (in the middle plane of the slab) relative to the anchor, the deformation of the slab from its surface to its middle plane, and the movement of the anchor. The movement of the anchor for MDD8 may be estimated as 0.034 mm (= 0.143-0.93-0.016). And the movement of the anchor for SDD18 is 0.005 mm (= 0.144-0.123-0.016). As mentioned previously, the anchor depth for MDD8 and SDD18 were 3 and 6 m (10 and 20 feet), respectively. Therefore, the contribution of the anchor movement at 3-m depth was about 23.7% and at 6-m depth was only about 3.4% of its total surface deflection. Therefore, the effect of anchor movement at 6 meters seems negligible but that of the 3 meters depth anchor seems not.

LOAD AND DEFLECTION TRANSFER EFFICIENCY OF DIFFERENT JOINTS

The ratio between deflections on unloaded and loaded sides of a joint is defined as the Deflection Transfer Efficiency (DTE). The ratio between strain measured on the unloaded side and the sum of strains on both sides of a joint is defined as the Strain Transfer Efficiency (STE) (see references 4 and 5). Figure 5 shows the joint types and locations in the instrumented area of the pavement at Denver International Airport. Figures 6 through 8 show the measured DTE and STE values. The values are written on the loaded side. The surface temperatures measured during the HWD tests are also given in the figures.

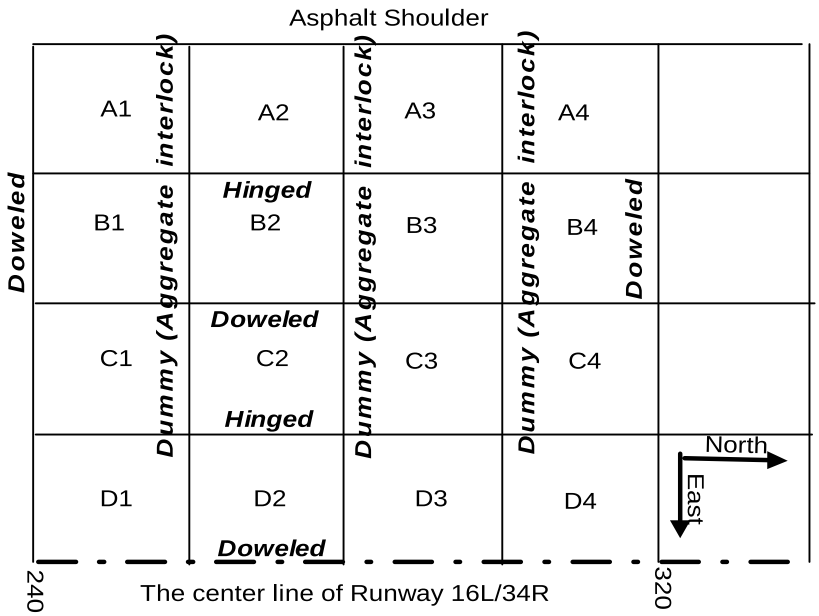

Figure 5. Slab locations and joint types.

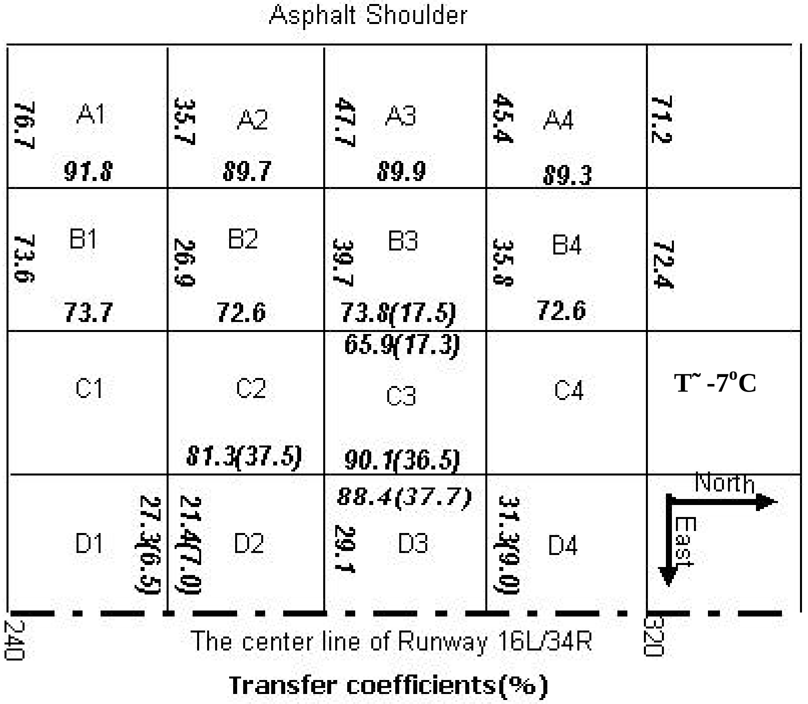

Figure 6. Deflection transfer efficiency (DTE) and strain transfer efficiency (STE). The STE measurements are in parentheses. March 1996.

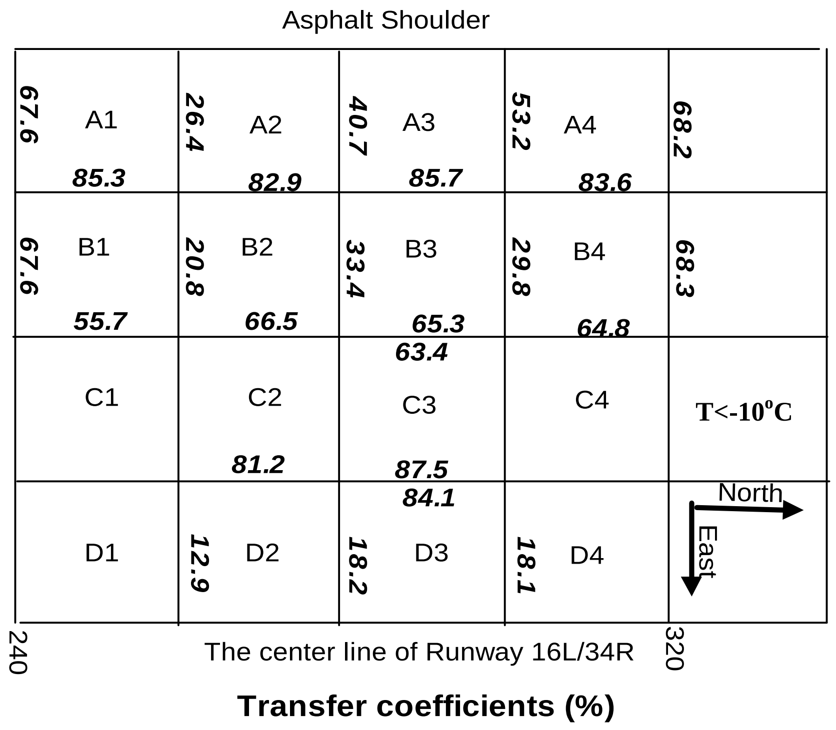

Figure 7. Deflection transfer coefficients (DTE). April 1997.

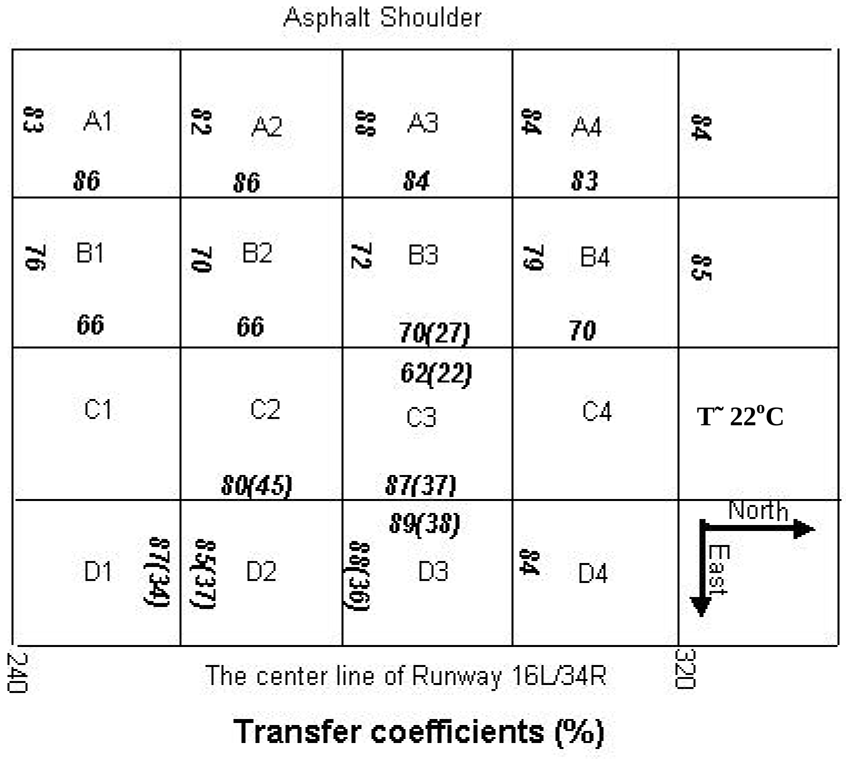

Figure 8. Deflection transfer efficiency (DTE) and strain transfer efficiency (STE). The STE measurements are in parentheses. August 1997.

In winter and early spring (see figures 6 and 7), the hinged joints received high DTE. The doweled joints received DTE less than the hinged, and the dummy joints received the lowest lowest DTE. The FAA design specification (reference 4) assumes STEs equal to 25%. Figure 6 indicates that STEs are higher than 25% at hinged joints and lower than 25% at doweled joints. Both DTE and STE of the dummy joints were extremely low at the beginning of March 1996. Also, see reference 5 for similar findings.

In the mid-summer of 1997 (figure 8), the behavior of the hinged joints was almost the same as that at the end of the winter or early spring. However, the load transfer capability of the dummy joints, from both DTE and STE, was significantly higher in the summer than the value assumed for design in reference 4.

These observations indicate that the joint stress and deflection transfer capability of the dummy joints are mainly dominated by the average temperature of the slab. When temperature is higher, slabs expand and the interlock mechanism of the dummy joints improves, leading to the higher values of DTE and STE. Since the tie bars in hinged joints hold the two slabs together, independent of the slab temperature, the measured DTE and STE values remain similar in the different seasons. The load transfer capability of the hinged joints therefore remains stable through the different seasons.

SUMMARY OF THE FINDINGS

1. The HWD deflection versus load relationship is linear over the ranges of load levels and for the drop locations used in the tests reported in this paper.
2. The slab corners and unrestrained edges were verified to curl up in winter and early spring at night by both HWD and MDD measurements.
3. The anchor movements at depths of 3 meters (10 feet) and 6 meters (20 feet) were about 23.7% and 3.4% of their surface deflections under a 222-kN (50-Kip) HWD load. Therefore, the effect of a 6-meter depth anchor movement seems negligible but that of a 3-meter anchor seems not.
4. The load transfer capability of hinged joints was stable over time. But that of dummy joints varied and was mainly dominated by the average temperature of the slabs. The performance of the doweled joints was between that of the hinged and dummy joints.

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