Performance of Interlocking Concrete Pavements in North America

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When compared with use in other parts of the world, the use of interlocking concrete pavements in North America is a rather new development. As a result, little information about their performance is available to verify or calibrate existing design methods or develop new ones. Toward overcoming this limitation, the performance of interlocking concrete pavements at three sites was evaluated. Record searches along with field investigations—deflection testing, visual condition surveys, and transverse profile surveys—were conducted as part of this effort. A brief description of each site is provided and the field and office data obtained, along with the interpretation of these data, are summarized. Particular emphasis is placed on the performance of these pavements in terms of structural capacity, distresses, and rut depths. However, other performance considerations for interlocking concrete pavements are also discussed.

The concept of tightly fitted paving units or pavers set on a flexible granular base is as old as the roads of the Roman Empire. The modern version, interlocking concrete pavements, originated in The Netherlands in the late 1940s as a replacement for clay brick streets. This technology quickly spread to Germany and Western Europe as a practical and attractive method useful for both pedestrian and vehicular pavement. Concrete pavers were introduced in the United States in the mid-1970s and have been successfully used in many pavement applications. To date, over 100 million m^2 of interlocking concrete pavements has been placed in this country, at an average cost of \$9 to \$18/m^2 (pavers only).

A typical pavement cross section is shown in Figure 1*a*. In this pavement structure, both the base and subbase are composed of unbound granular material. Granular base and subbase layers stabilized with asphalt or cement also can be used, as shown in Figure 1*b*. Restraints are required along the edges of interlocking concrete pavements to prevent the outward migration of blocks from the force of traffic, which would result in the opening of joints and loss of interlock between the paver blocks. These restraints can be developed from any construction that prevents the lateral movement of the blocks along the periphery of the paved area.

Typical block laying patterns are illustrated in Figure 2. Regardless of the pattern used, concrete pavers are first placed, mechanically or manually, on a bedding sand layer and vibrated with a high-frequency plate vibrator. Sand is then spread and swept into the joints and the pavers are again vibrated until the joints are full of sand so that the interlocking of blocks (full shear transfer), so critical to the performance of interlocking concrete pavements, is obtained.

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Research studies have shown that the load distribution and failure modes of an interlocking concrete pavement are very similar to those of any other flexible pavement system (i.e., the main failure mode is increasing roughness due to repetitive shear deformations). Understandably, most existing interlocking concrete pavement design methods rely on modified flexible (or asphaltic concrete) pavement design procedures.

Because the use of concrete pavers in pavement construction is a rather new development in North America, little information about their performance is presently available to verify or calibrate existing design methods or to develop new ones. Toward overcoming this limitation, a study was undertaken to document the performance of streets in North America constructed with concrete pavers.

Three projects were selected for use in this study—Main Street in North Bay, Ontario; Third, Pine, and Cedar Streets in Timmins, Ontario; and Hay Street in Fayetteville, North Carolina. At each site, extensive field investigations were conducted to assess the functional and structural condition of the pavements. They included (a) nondestructive deflection testing, (b) visual condition surveys, and (c) transverse profile or rut depth surveys.

The results of the field investigations, coupled with available construction, traffic, and climatic data, served as the basis for this study. First a description of each site and a summary of the field and office data obtained are provided, along with the interpretation of these data. Then other performance considerations for interlocking concrete pavements are discussed. Finally, the major findings and conclusions are presented.

PROJECT SITES

Center City of North Bay, Ontario

The reconstruction of Main Street with an interlocking concrete pavement was part of a complete renovation plan for the North Bay city center. The project covers an area of approximately 150,000 ft^2 (13,935 m^2), including sidewalks, and extends along 3,300 ft (1,006 m) of Main Street (see Figure 3). The first block—Sherbrooke to Wyld—was opened to traffic in late July 1983, but had to be closed because of a substantial number of corner "pop-offs" caused by the wrong gradation of the joint sand. The damaged pavers were replaced, the surface was resanded, and the block was successfully reopened to traffic. The last block—Algonquin to Cassells—was opened to traffic in early November 1983.

A schematic diagram of the pavement cross section and laying pattern is also given in Figure 3. The pavement consists

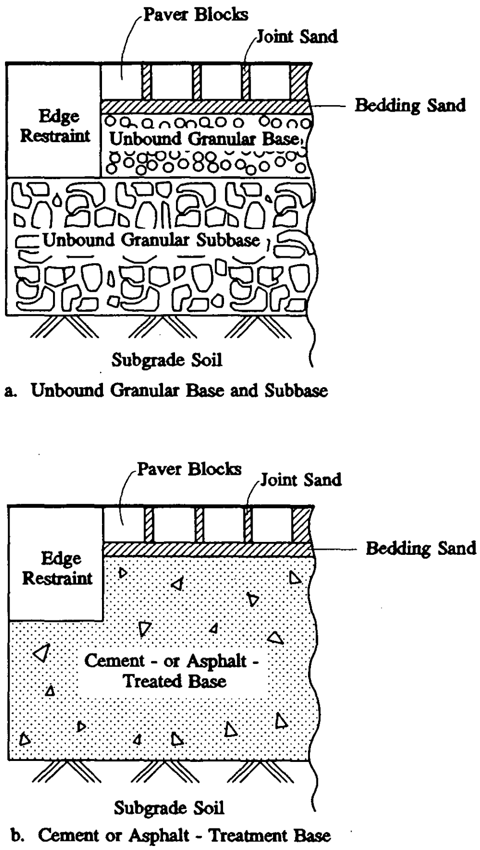

FIGURE 1 Typical interlocking concrete pavement cross sections.

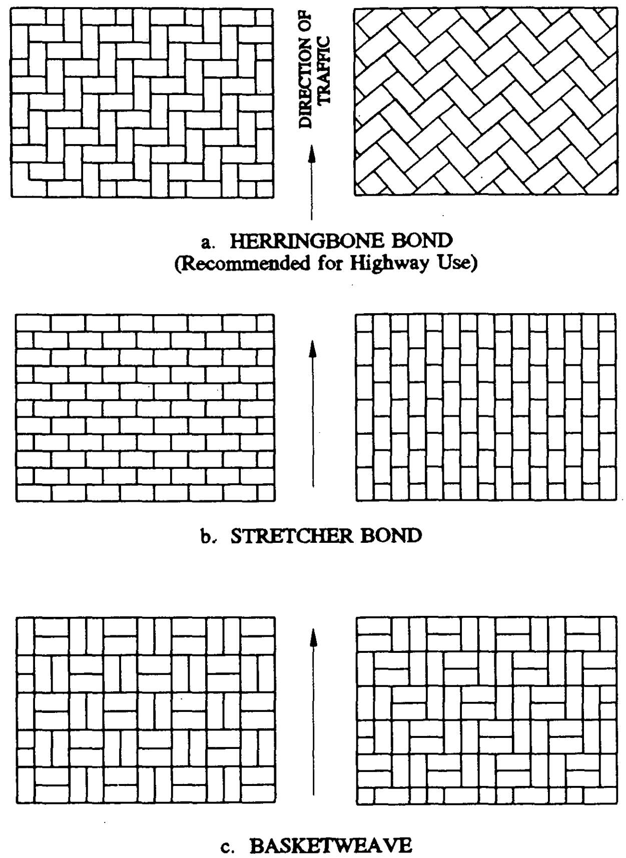

FIGURE 2 Typical block laying patterns.

of 3.2-in. (80-mm) concrete pavers over 1.2 in. (30 mm) of bedding sand. Except for the crosswalks, where a stretcher bond pattern was used, the concrete pavers are laid in a herringbone pattern. A 5.9-in. (150-mm) granular base and 7.9-in. (200-mm) granular subbase provide support for the concrete pavers and bedding sand layer. The pavement structure rests on a sandy subgrade, with shattered rock or bedrock at shallow depths. Surface water is directed to a catch basin and storm sewer outlet. Subdrains were not installed in this project because of the free-draining subbase material.

Two-way traffic along Main Street consists of approximately 8,000 vehicles per day, with 13,300 vehicles per day at the intersection of Algonquin and Main Streets. Although no breakdown by weight class is available, traffic includes automobiles, buses, and trucks. It has been estimated from field observations that most of the traffic consists of automobiles, with approximately 4 to 5 percent delivery trucks and buses.

In addition to traffic, the pavements are subjected to very severe weather conditions. Temperatures range from −40°F (−40°C) to 96°F (35°C), with an average daily temperature of 38°F (3°C). North Bay also receives an average of 39 in. (990 mm) of precipitation each year, which consists of both rain and snow.

Center City of Timmins, Ontario

Timmins, a city in the northern reaches of Ontario, underwent a downtown renovation program that utilized over 120,000 ft^2 (11,120 m^2) of pavers. The phased project, beginning in 1984, included the reconstruction of 10 streets in the city center with interlocking concrete pavements. Figure 4 shows the layout of the study area (Third, Cedar, and Pine streets).

The pavements consist of 3.2-in. (80-mm) concrete pavers over a 1.2-in. (30-mm) bedding sand layer. The pavers are laid in a herringbone pattern and are supported by a 5.9-in. (150-mm) gravel base and a granular subgrade. Both the pavement cross section and laying pattern of the pavers are also illustrated in Figure 4. Storm sewers and drains provide an outlet for surface water off the interlocking concrete pavement.

Two-way traffic on Third Street has been estimated to be 6,000 vehicles per day and includes automobiles, buses, and trucks. Although a breakdown by weight class is not available, it is estimated from field observations that most of the traffic consists of automobiles, with approximately 4 to 5 percent buses and delivery trucks.

As at North Bay, the climate at this site is very severe. Temperatures range from −46°F (−43°C) to 100°F (38°C), with an average daily temperature of 34°F (1°C). Timmins

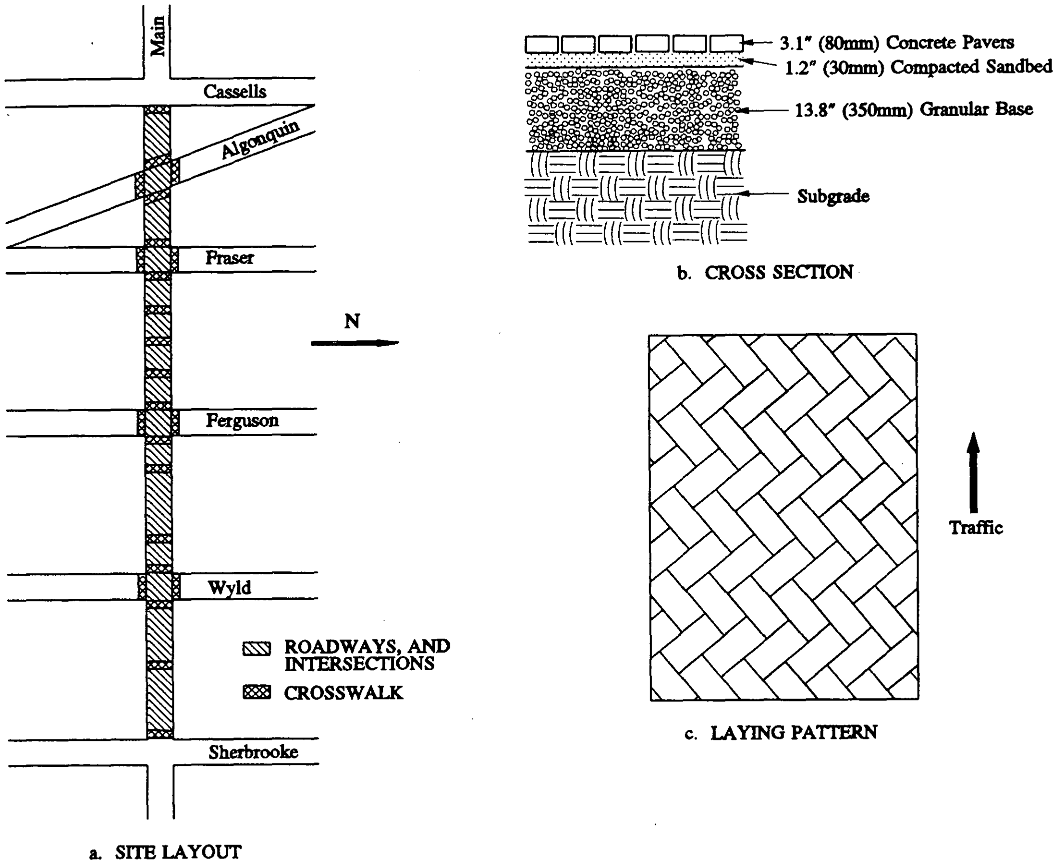

FIGURE 3 Timmins, Ontario: site layout, pavement cross section, and laying pattern.

also receives an average of 34 in. (860 mm) of precipitation each year, which consists of both rain and snow.

Transit Mall in Fayetteville, North Carolina

The Transit Mall in Fayetteville, North Carolina, is located on Hay Street between Ray Avenue and Market House Circle. Hay Street was reconstructed as an interlocking concrete pavement in an effort to revitalize the downtown district. The mall is intended for city bus access to transport citizens to and from the many shops that line Hay Street. The mall is three blocks long, 24 ft (7.3 m) wide, and covers an area of 41,400 ft^2 (3,850 m^2), not including sidewalks (see Figure 5).

The Transit Mall pavements were constructed in summer 1984 and opened to traffic in May 1985. Figure 5 shows the pavement cross section and laying pattern used. The pavement system consists of 3.2-in. (80-mm) concrete paver blocks over 1.5 in. (38 mm) of bedding sand. A 2-in. (51-mm) asphalt concrete layer over 8 in. (200 mm) of unbound granular base provides support for the concrete pavers and bedding sand layer. The top of the subgrade was removed and replaced with select fill during the excavation process because of the discovery of archeological artifacts. Storm sewers and drains provide an outlet for surface water off the interlocking concrete pavement.

The mall is intended for bus access only. Buses typically have a curb weight of 24,680 lb (110 kN) and ride on two axles. Weekly bus schedules result in traffic counts as follows: 348 buses per day during weekdays, 152 buses per day on Saturdays, and no buses on Sundays.

Compared with the climate of the two previous sites, the climate in Fayetteville is considerably milder. Although temperatures range from −29°F (−34°C) to 110°F (43°C), the average daily temperature is 61°F (16°C). The average annual precipitation is 19 in. (480 mm), with very little snowfall.

PERFORMANCE EVALUATION

Pavement Structural Capacity

Several procedures are presently available for use in pavement structural evaluation. They range from destructive procedures such as borings and cores to nondestructive testing methods such as static-creep (e.g., Benkelman beam), steady-state (e.g., Dynaflect), and impulse [falling weight deflectometer (FWD)] deflection devices. In this study, a Dynatest model 8002 FWD device was used to assess the structural capacity of the interlocking concrete pavements. Deflection basin tests were conducted using nominal impulse loads of 5,000 and 9,000 lbf (22 to 40 kN). The response of the pavements to these loads was

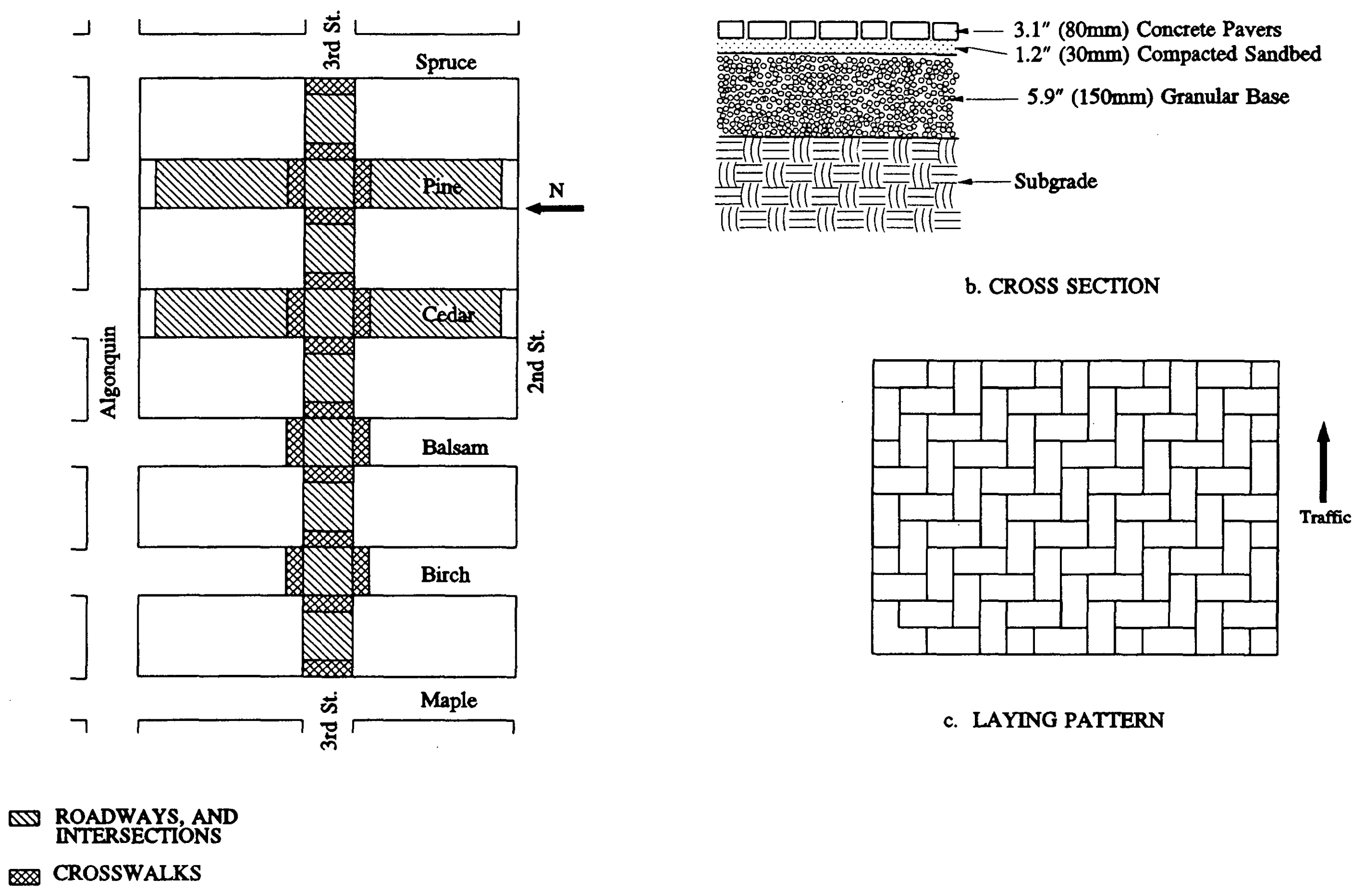

FIGURE 4 Fayetteville, North Carolina: site layout, pavement cross section, and laying pattern.

measured by means of deflection sensors located at 0, 8, 12, 18, 24, 36, and 48 in. (0, 20.3, 30.5, 45.8, 61.0, 91.4, and 121.9 cm) from the load center. A total of 652 deflection tests were performed, 242 in North Bay, 232 in Timmins, and 178 in Fayetteville. Table 1 is a statistical summary of the measured deflections at each site.

To analyze the measured deflections, a multilayer elastic solution was used because of its simplicity and general acceptance [finite element methods produce a better fit, but their complexity is a major limitation (*1*)]; both paver blocks and bedding sand are modeled as a composite layer. In particular, in situ pavement layer moduli were backcalculated using a program called MODULUS (*2*). The MODULUS program, developed by the Texas Transportation Institute, utilizes a forward calculation scheme, WESLEA [elastic solution (*3*)], to build a deflection basin data base for a given pavement. A pattern search technique is then used to determine the set of layer moduli that best fits the measured basin.

The North Bay and Timmins pavements were modeled as three-layer structures: a composite layer of concrete pavers and bedding sand surface, a layer of unbound granular base, and the subgrade soil. In the evaluation of the Fayetteville pavements, a two-layer structure was used because preliminary analysis of the deflection data yielded very similar moduli for both the base and subgrade layers. No attempt to backcalculate the modulus of the thin asphalt concrete layer below the bedding sand was made because current technology is not sufficiently advanced to accurately and consistently do otherwise.

The results of the moduli backcalculation analysis are summarized in Table 2. These results have been grouped into three major categories—roadways, intersections, and others (parking lanes, sidewalks, bus stops)—on the basis of traffic. In the case of the Transit Mall in Fayetteville, North Carolina, the moduli backcalculated at the intersections have been grouped with those corresponding to the roadways, because cut-through traffic across the Hay Street intersections is not allowed. Table 2 also shows the layer moduli obtained for asphaltic concrete pavements adjacent to the project sites.

Several major conclusions can be drawn from the results presented in Table 2. First, there is a clear relationship between the amount of traffic the interlocking concrete pavement receives and the modulus of the composite paver blocks and bedding sand layer. In all cases, the modulus of this composite layer decreases as one goes from the high ("intersections") to the low ("other") traffic areas; average modulus values range from 420 to 560 ksi for the intersections; 300 to 377 ksi (2067 to 2598 MPa) for the roadways; and 118 to 207 ksi (813 to 1426 MPa) for the low traffic areas.

This finding is consistent with the results from other similar studies found in the literature. Modulus values for the composite paver and sand layer, developed by researchers in sev-

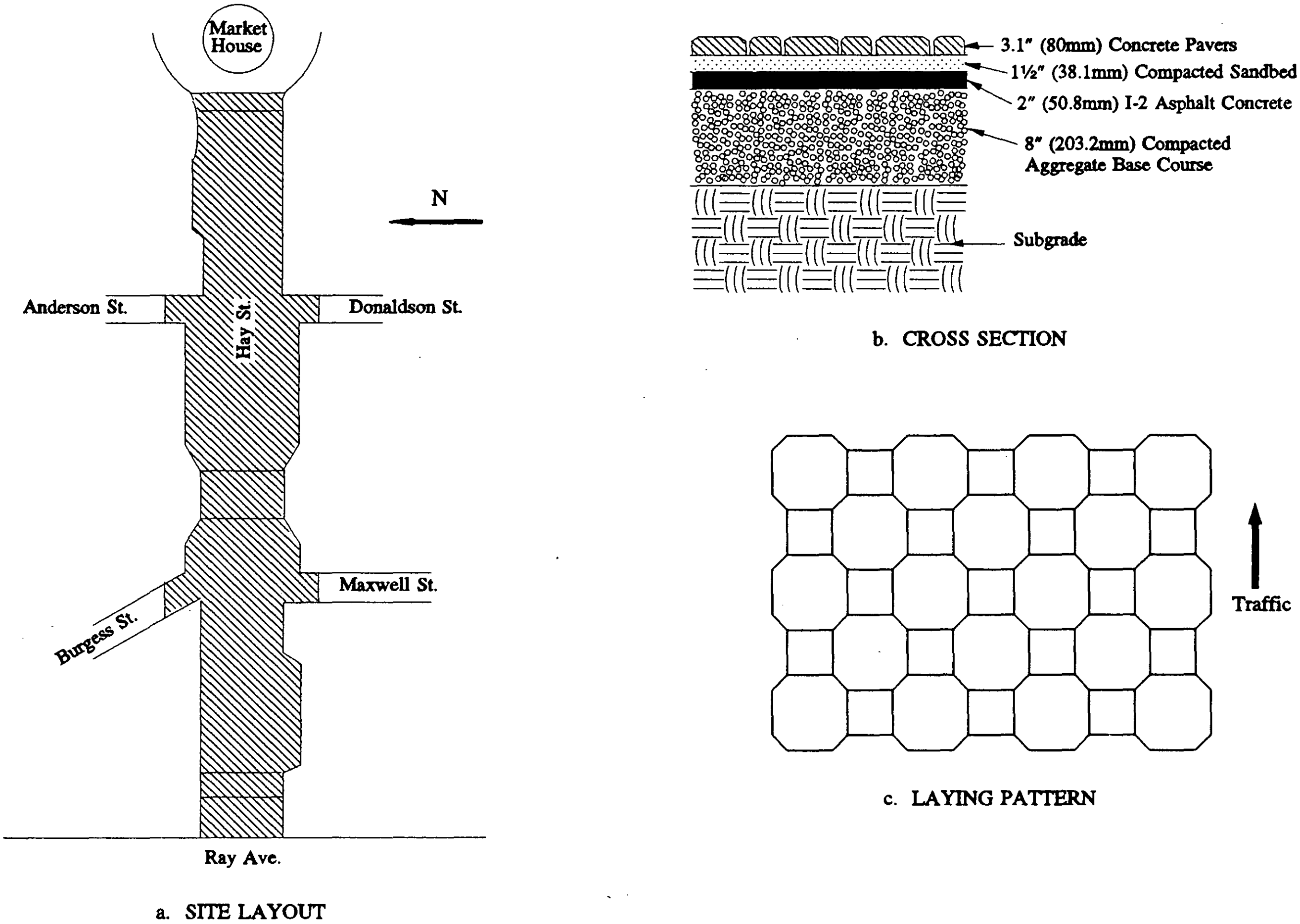

FIGURE 5 North Bay, Ontario: site layout, pavement cross section, and laying pattern.

eral countries, are summarized below (1 ksi = 6.89 MPa):

Country	*Modulus (ksi)*	*Reference*
United Kingdom	130.5	(*7*)
	290.0	
Japan	243.9	(*13*)
	627.9	
New Zealand	60.2	(*15*)
Australia	50.8	(*11*)
	464.0	
Netherlands	92.7	(*10*)
	402.1	
United States	450.0	(*14*)

Although a wide range of values is reported, it is apparent that initial modulus values are significantly lower than those measured after many traffic repetitions, revealing a time/traffic dependence of the layer strength. Thus, the paver blocks initially act as individual units and gradually lock together and share the load.

Although the concept of progressive stiffening is widely accepted, significant differences exist in the literature as to when full lock-up of the pavers occurs (*4*). Values generally ranging from 5,000 to 100,000 equivalent 18-kip (80-kN) axle loads (EALs), but as high as 1,000,000 EALs, have been suggested. For the sites investigated, the number of EALs since construction was determined on the basis of field estimates and information provided by the responsible agencies to be in the 100,000 to 120,000 range (i.e., very similar for all three sites). This similarity, coupled with the fact that data from earlier years are not available, prohibited the authors from shedding further light on this issue.

A comparison of the values presented in Table 2 and those from other researchers also reveals that there is excellent agreement between the composite moduli derived in this study [118 to 560 ksi (813 to 3858 MPa)] and those found in the literature [50 to 628 ksi (345 to 4327 MPa)]. Because the use of interlocking concrete pavements in North America is a relatively new development when compared with countries such as The Netherlands and Australia, where they have been used for several decades, these results are encouraging.

Table 2 also shows that the moduli of the composite block and sand layer are similar to those of asphalt concrete (AC). This is particularly true for the high traffic areas (intersections), where in all likelihood full lock-up has already occurred. Modulus values range from 420 to 560 ksi (2894 to 3858 MPa) for the pavers and sand layer versus 408 to 568 ksi (2811 to 3914 MPa) for the AC layer. More importantly,

TABLE 1 Measured Deflections

Project Site	Pavement Category	Number of Points	Parameter	Sensor r=0"	r=8"	r=12"	r=18"	r=24"	r=36"	r=48"
North Bay	Roadways	95	Average (mils)	15.44	11.45	8.68	5.70	4.19	2.82	2.08
			Std. Dev. (mils)	2.13	1.43	1.11	0.96	0.83	0.65	0.52
			C.O.V. (%)	13.79	12.49	12.74	16.91	19.69	23.24	25.07
	Intersections	14	Average (mils)	14.93	11.16	8.60	5.86	4.28	2.81	2.05
			Std. Dev. (mils)	1.60	1.68	1.56	1.36	1.11	0.79	0.58
			C.O.V. (%)	10.69	15.03	18.13	23.17	25.98	28.27	28.10
	Others	6	Average (mils)	49.00	34.38	21.80	12.02	8.23	5.08	3.52
			Std. Dev. (mils)	18.30	12.64	9.19	4.71	3.09	1.46	0.87
			C.O.V. (%)	37.35	36.76	42.14	39.17	37.47	28.79	24.82
	AC Pavements	6	Average (mils)	7.77	6.17	5.10	3.72	2.83	1.73	1.18
			Std. Dev. (mils)	0.93	0.71	0.60	0.48	0.39	0.27	0.22
			C.O.V. (%)	11.93	11.59	11.70	12.89	13.88	15.34	18.83
Timmins	Roadways	89	Average (mils)	15.62	11.73	8.97	6.20	4.78	3.29	2.49
			Std. Dev. (mils)	1.93	1.58	1.25	0.94	0.77	0.54	0.41
			C.O.V. (%)	12.38	13.49	13.90	15.22	16.04	16.52	16.31
	Intersections	24	Average (mils)	15.57	11.78	9.14	6.28	4.80	3.33	2.50
			Std. Dev. (mils)	1.91	1.55	1.25	0.94	0.73	0.54	0.46
			C.O.V. (%)	12.29	13.13	13.66	14.96	15.10	16.17	18.41
	AC Pavements	3	Average (mils)	19.10	15.50	13.70	11.37	9.17	6.40	4.20
			Std. Dev. (mils)	6.76	4.52	3.44	2.16	1.17	0.53	0.17
			C.O.V. (%)	35.40	29.17	25.11	18.98	12.74	8.27	4.12
Fayetteville	Roadways	44	Average (mils)	19.23	13.89	9.88	5.95	4.05	2.67	2.00
			Std. Dev. (mils)	3.18	2.12	1.48	0.82	0.52	0.30	0.24
			C.O.V. (%)	16.53	15.27	14.97	13.74	12.77	11.06	12.03
	Others	36	Average (mils)	20.49	14.24	9.58	5.68	4.00	2.73	2.05
			Std. Dev. (mils)	2.59	2.07	1.62	0.73	0.47	0.32	0.25
			C.O.V. (%)	12.66	14.56	16.96	12.89	11.65	11.67	11.99
	AC Pavements	5	Average (mils)	16.68	13.10	10.88	8.28	6.16	3.76	2.62
			Std. Dev. (mils)	2.09	1.93	1.40	0.89	0.61	0.38	0.29
			C.O.V. (%)	12.55	14.72	12.86	10.71	9.85	10.06	11.26

Notes: (1) 1 inch = 25.4 mm; 1 mil = 25.4 micron
(2) Deflections shown correspond to a 9,000 lb. load, measurements were also taken at a nominal 5,000 lb. load but are not shown here.

TABLE 2 Backcalculated Layer Moduli

Project Site	Pavement Category	Number of Points	Layer Type	Layer Thickness (in.)	Layer Modulus Mean (ksi)	Std. Dev. (ksi)	C.V. (%)
North Bay	Roadways	190	Pavers/Sand	4.3	377.0	164.3	44.2
			Granular Base	13.8	39.5	10.7	27.7
			Subgrade	Variable	14.9	4.6	30.6
	Intersections	28	Pavers/Sand	4.3	559.9	191.9	35.0
			Granular Base	13.8	28.7	7.1	24.7
			Subgrade	Variable	17.9	2.6	14.2
	Others	12	Pavers/Sand	4.3	118.3	18.5	11.8
			Granular Base	13.8	14.5	1.8	13.6
			Subgrade	Variable	7.8	4.6	45.4
	AC Pavements	12	Asph. Conc.(*)	5.5	567.8	184.5	31.8
			Granular Base	14.8	34.3	4.6	14.0
			Subgrade	Variable	13.8	2.1	15.3
Timmins	Roadways	178	Pavers/Sand	4.3	300.3	103.4	35.0
			Granular Base	5.9	86.3	23.6	30.3
			Subgrade	Variable	17.7	3.1	17.9
	Intersections	48	Pavers/Sand	4.3	420.6	147.8	35.7
			Granular Base	5.9	64.2	25.9	43.6
			Subgrade	Variable	19.1	3.9	20.1
	AC Pavements	6	Asph. Conc.(*)	3.5	566.0	233.0	39.0
			Granular Base	6.0	91.9	39.8	43.3
			Subgrade	Variable	9.5	0.6	6.1
Fayetteville	Roadways	88	Pavers/Sand	4.6	344.5	124.4	35.1
			Base/Subgrade	Variable	12.5	1.7	13.7
	Others	72	Pavers/Sand	4.6	206.6	68.0	30.2
			Base/Subgrade	Variable	12.1	2.0	15.2
	AC Pavements	10	Asph. Conc.(*)	5.0	408.0	151.0	37.0
			Granular Base	8.0	42.6	26.7	62.6
			Subgrade	Variable	11.1	1.3	11.1

Notes: (1) 1 inch = 25.4 mm; 1 ksi = 6.89 MPa
(2) Modulus of this layer has not been tempearture corrected as surface gradient temperature data were not available

this finding illustrates that the load distribution of interlocking concrete pavements is similar to that of flexible pavements.

Pavement Distress

Because not all pavement distress is traceable to structural mechanisms, accurate condition surveys that assess a pavement's physical distress are vital to the performance evaluation effort. Condition survey results not only provide a measure of pavement condition, but also assist in defining probable causes of the distress. To accomplish this, however, the condition survey must provide for certain minimum information requirements: (a) identification of the distress types existing in the pavement, (b) measure of the severity level for each distress type present, and (c) measure of area affected by each combination of distress type and severity.

Because interlocking concrete pavements are a relatively new development, a well-established and generally accepted procedure for carrying out visual distress surveys does not presently exist. In view of this, information regarding distress types and their measurement was extracted from various sources in the literature to develop an interim condition survey procedure. The primary sources of information were Shahin and Kohn (*5*) and a Dutch Study (*6*), as well as unpublished information provided by the Concrete Paver Institute. Table 3 shows the final list of distress types selected for interlocking concrete pavement evaluation along with their units of measure and possible severity levels.

Sampling plans for evaluation of the interlocking concrete pavements under investigation were then developed. The pavements were first subdivided into sample units according to area [2,400 ft^2 (223 m^2) per sample unit]. Individual sample units were then selected at random for use in the field surveys—24 sample units covering 57,600 ft^2 (5351 m^2) in North Bay, 18 sample units covering 43,200 ft^2 (4013 m^2) in Timmins, and 12 sample units covering 27,120 ft^2 (2520 m^2) in Fayetteville (in all cases, the sample unit coverage exceeded 50 percent of the total pavement area). Finally, for each sample unit selected, the pavement distress types present as well as their severity and extent were determined. Table 4 summarizes the results of these visual condition surveys on a site-by-site basis. From these data, the following observations were made.

The predominant pavement distress types at North Bay are depressions and corner or edge spalling of the blocks. Depressions were found over 4.17 percent of the area surveyed, but this is somewhat misleading because they are very localized; all occur within one sample unit. Furthermore, these depressions are over an area where excavation of the pavement surface was necessary to gain access to underground utilities, and the subsequent pavement repairs were carried out with less than satisfactory results. Corner and edge spalling of the blocks was found to be a problem in 3.59 percent of the area surveyed. It appears that two factors are contributing to this distress: (a) inferior-quality pavers supplied by one of the manufacturers, as evidenced by their frequent replacement over the last 5 years, and (b) a combination of harsh winter conditions and snow removal operations.

At Timmins, the predominant pavement distress types are snowplow damage and block spalling, which were found over 18.82 and 2.82 percent of the area surveyed. Snowplow damage refers to scratch marks on the surface of the paver blocks resulting from snow removal operations using plows. Block spalling appears to be related to the same two factors as in North Bay, that is, quality of some of the pavers as well as winter conditions and snow removal operations.

In the case of the Fayetteville interlocking concrete pavements, the predominant distress types are surface staining, swell/heave, and depressions. These distresses were found over 3.02, 2.95, and 1.25 percent of the area surveyed, respectively. The first distress type is primarily associated with oil spillage from buses, which account for most of the traffic at this site. The other two distress types—swell/heave and depression—are of low severity and are likely caused by a combination of bus loadings and wet soil. Furthermore, the swell and heave distress is very localized (i.e., within one sample unit). In this area a water main broke, requiring removal and replacement of the paver blocks.

Overall, it was concluded that with the exception of localized areas, the interlocking concrete pavements at the three North American sites are providing excellent performance. After 6 to 8 years, the pavements are still in very good to excellent condition. If localized distresses are not included in the analysis, surface deformation, which is the primary failure mode in interlocking concrete pavements, occurs in less than

TABLE 3 Interlocking Concrete Pavement Distress Types

Distress Type	Unit of Measure	Severity Levels
Surface Irregularities:		
Rutting	square feet	Low, Medium, High
Swell and Heave	square feet	Low, Medium, High
Depression	square feet	Low, Medium, High
Transition to Utility	square feet	Low, Medium, High
Transition to Curb	square feet	Low, Medium, High
Block Distress:		
Corner or Edge Spalling	percent	Low, Medium, High
Cracked Blocks	percent	Low, Medium, High
Polished Aggregate	square feet	not applicable
Stained or Contaminated Surface	square feet	not applicable
Horizontal Creeping	square feet	Low, Medium, High
Joint Distress:		
Deformed Joint (Joint Width)	square feet	Low, Medium, High
Loss of Sand in Joint	square feet	Low, Medium, High
Miscellaneous:		
Snow Plow Damage	square feet	not applicable
Others	not applicable	not applicable

Note: 1 square foot = 0.09 square meter

TABLE 4 Visual Distress Survey Results

A. North Bay (Area surveyed: 57,600 s.f.)

Distress Type	Severity Level			Density (%)			Total
	Low	Medium	High	Low	Medium	High	Dens. (%)
Surface Irregularities							
Rutting (s.f.)	---	---	---	---	---	---	---
Swell/Heave (s.f.)	---	---	---	---	---	---	---
Depression (s.f.)(**)	---	2400	---	---	4.17%	---	4.17%
Transition to Utility (s.f.)	25	15	---	0.04%	0.03%	---	0.07%
Transition to Curb (s.f.)	50	---	---	0.09%		---	0.09%
Block Distress							
Corner or Egde Spalling (%)	3.47%	0.12%	---	3.47%	0.12%	---	3.59%
Cracked Blocks (%)	0.12%	---	---	0.12%	---	---	0.12%
Stained Surface (s.f.)(*)	---	---	---	---	---	---	---
Joint Distress							
Deformed Joints (s.f.)	40	---	---	0.07%	---	---	0.07%
Miscellaneous							
Snow Plow Damage (s.f.)	---	---	---	---	---	---	---

B. Timmins (Area Surveyed: 43,200 s.f.)

Distress Type	Severity Level			Density (%)			Total
	Low	Medium	High	Low	Medium	High	Dens. (%)
Surface Irregularities							
Rutting (s.f.)	---	270	---	---	0.63%	---	0.63%
Swell/Heave (s.f.)	---	160	---	---	0.37%	---	0.37%
Depression (s.f.)	---	---	---	---	---	---	---
Transition to Utility (s.f.)	---	---	---	---	---	---	---
Transition to Curb (s.f.)	---	4	---	---	0.01%	---	0.01%
Block Distress							
Corner or Egde Spalling (%)	2.61%	0.21%	---	2.61%	0.21%	---	2.82%
Cracked Blocks (%)	0.27%	0.04%	---	0.27%	0.04%	---	0.31%
Stained Surface (s.f.)(*)	---	---	---	---	---	---	---
Joint Distress							
Deformed Joints (s.f.)	---	---	---	---	---	---	---
Miscellaneous							
Snow Plow Damage (s.f.)	7990	140	---	#####	0.32%	---	18.82%

C. Fayetteville (Area surveyed: 27,120 s.f.)

Distress Type	Severity Level			Density (%)			Total
	Low	Medium	High	Low	Medium	High	Dens. (%)
Surface Irregularities							
Rutting (s.f.)	---	---	---	---	---	---	---
Swell/Heave (s.f.) (**)	800	---	---	2.95%	---	---	2.95%
Depression (s.f.)	200	140	---	0.74%	0.52%	---	1.25%
Transition to Utility (s.f.)	34	22	---	0.13%	0.08%	---	0.21%
Transition to Curb (s.f.)	---	6	---	---	0.02%	---	0.02%
Block Distress							
Corner or Egde Spalling (%)	<0.01%	---	---	<0.01%	---	---	<0.01%
Cracked Blocks (%)	---	---	---	---	---	---	---
Stained Surface (s.f.)(*)	820	---	---	3.02%	---	---	3.02%
Joint Distress							
Deformed Joints (s.f.)	60	---	---	0.22%	---	---	0.22%
Miscellaneous							
Snow Plow Damage (s.f.)	---	---	---	---	---	---	---

Note: 1 square foot (s.f.) = 0.09 square meter

(*) No severity level associated with this distress type
(**) Only identified in one sample unit

1.5 percent of the pavement areas surveyed (see Table 4). Besides localized pavement deformations, distresses associated with individual paver blocks are the next major problem at the sites. This problem is largely one of aesthetics and can be easily resolved by the replacement of the affected blocks (3 to 4 percent by total area at each site).

Pavement Rut Depths

The primary failure mode in interlocking concrete pavements is increasing roughness as a result of repetitive shear deformations. The results of the visual condition surveys provided some insight about the extent and severity of this distress type, but not an accurate measurement of their magnitude. Accordingly, transverse profile surveys were conducted at multiple locations within each site to determine rut depths.

A Dipstick Auto-Read Profiler was used in this effort. This device measures the relative elevation of two points that are 1 ft (0.30 m) apart. Measurements were taken at 1-ft intervals from the edge of the pavement to the centerline. From these data, rut depths were determined using commercially available software and an assumed 6-ft (1.83-m) straight edge. Table 5 summarizes the results of the rut depth analysis. The following observations were made from these data.

At all three sites, rut depths in the right wheelpath are larger than those in the left wheelpath. These differences are

TABLE 5 Rut Depth Measurements

Project Site	Number of Lines	Statistic	Rut Depth Measurements (inches) Wheel Path: Left	Right	Average
North Bay	21	Mean	0.210	0.230	0.220
		Std. Dev.	0.176	0.148	0.118
		Minimum	0.047	0.010	0.061
		Maximum	0.927	0.662	0.569
Timmins	18	Mean	0.242	0.426	0.334
		Std. Dev.	0.145	0.162	0.142
		Minimum	0.000	0.014	0.007
		Maximum	0.449	0.706	0.551
Fayetteville	22	Mean	0.090	0.133	0.112
		Std. Dev.	0.062	0.072	0.048
		Minimum	0.014	0.008	0.034
		Maximum	0.253	0.313	0.208

Note: 1 inch = 25.4 mm

small for the North Bay and Fayetteville pavements but quite significant in Timmins: 0.20 in. (5.1 mm) on average. It is hypothesized that these differences are caused by the lower degree of block confinement, and hence lock-up, achieved at the pavement edge (right wheelpath) during the construction process (i.e., related to the construction of the edge restraints as well as the placement and vibration of the pavers and sand at the pavement edge).

Table 5 also shows large rut depths for the North Bay and Timmins pavements: 0.45 to 0.93 in. (11.4 to 23.5 mm). These large measurements occur in just a few localized areas, which correspond with those few distressed areas identified from the visual condition surveys. For example, the 0.93-in. (23.5-mm) reading in North Bay was taken in the repair area alluded to earlier.

Overall, however, the results in Table 5 clearly indicate the excellent performance of the interlocking concrete pavements. After 6 to 8 years in service, average pavement rut depths range from 0.11 in. (2.8 mm) in Fayetteville to 0.22 in. (5.6 mm) in North Bay and 0.33 in. (8.5 mm) in Timmins. These are well below the 0.50 to 0.75-in. (12.7- to 19.1-mm) level typically considered as a failure by most highway agencies.

OTHER CONSIDERATIONS

Data reported in the literature (*1,4,7–19*) indicate that the performance of concrete paver pavements depends on the interlocking of the individual units and, to a lesser degree, on the shape and thickness of the block. The interlocking of the paver blocks is in turn influenced by laying pattern and thickness of the bedding sand.

Block shape has more of an effect on the mechanical behavior of concrete blocks (i.e., a uniform cross section will not crack as easily as a variable cross section). Block thickness primarily affects the mechanical behavior, but an increase in thickness also produces an increase in structural capacity. The performance of the herringbone laying pattern is much better than that of the stretcher or basketweave patterns, which tend to creep in the direction of traffic movement and adversely affect the interlocking of the pavers. Also, as thickness of the bedding sand layer decreases, the overall performance improves. Very thin layers [less than 1 in. (25.4 mm) after compaction], however, will not produce the locking-up action obtained by sand migration upward into the joints during the initial vibration phase in construction.

Because the pavements under investigation were all constructed with 3.2-in. (80-mm) paver blocks and 1.2 to 1.5 in. (30.5 to 38.1 mm) of bedding sand, the impact of these factors on the performance of the pavements could not be assessed. With regard to block shape and laying pattern, rectangular concrete pavers were laid at the two Ontario sites in a herringbone pattern, whereas irregular-shaped blocks were used at the North Carolina site, also laid in a herringbone pattern. However, the results do not clearly indicate that one is performing better than the other. The pavements at all three sites are structurally sound, have similar moduli for the composite paver block and sand layer, show little distress (mostly localized), and have small rut depths.

Furthermore, because these pavements were constructed at around the same time (1983 to 1985) and pavement condition data other than those collected in this study are not available, little can be said about the long-term performance of these pavements. Although they are presently in excellent condition, future monitoring will be required to establish their long-term performance. Additional sites with varying factors —for example, block shape and thickness, thickness of bedding sand, and laying pattern—must also be monitored over long periods of time, preferably since the time of initial construction, to better ascertain the influence of these factors on the performance of interlocking concrete pavements.

CONCLUSIONS

When compared with use in other parts of the world, the use of interlocking concrete pavements in North America is a relatively new development. As a result, little information about their performance is available to verify or calibrate existing design methods or develop new ones. Toward overcoming this limitation, the performance of interlocking concrete pavements at three sites was evaluated. Record searches along with field investigations—deflection testing, visual condition surveys, and transverse profile surveys—were conducted as part of this effort.

From the analysis and interpretation of the data collected, the following observations and conclusions were made:

- A definite relationship exists between the amount of traffic the pavement receives and the modulus of the composite paver blocks and bedding sand layer; as traffic increases, the modulus also increases.
- There is excellent agreement between the backcalculated composite moduli and those found in the literature for other parts of the world where these pavements have been used for several decades.
- The backcalculated composite moduli are very similar to those of asphalt concrete, thus confirming that the load distribution of interlocking concrete pavements is very similar to that of flexible pavements once lock-up has occurred.
- After 6 to 8 years in service, the pavements at the three sites are in excellent condition. All are structurally sound, very little distress is present (mostly localized areas), and very small rut depths were measured.
- If localized distresses are not included in the analysis, then surface deformation, which is the primary failure mode in interlocking concrete pavements, occurs in less than 1.5 percent of the areas surveyed.
- Rut depths along the right wheelpath are larger than those in the left wheelpath; this difference is likely to be related to the construction of the edge restraints or the placement and vibration of the pavers and sand at the pavement edge.

Finally, although much valuable information was obtained from this initial study, additional effort is still required to better define the performance of interlocking concrete pavements. Additional sites, covering a wider range of factors such as laying patterns, bedding sand thickness, block thickness, traffic, subgrade, and environment must be evaluated. Only through such monitoring studies will the influence of these factors on the performance of the pavement be adequately established.

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