INTERLOCKING CONCRETE PAVEMENTS IN NORTH AMERICA: A PERFORMANCE EVALUATION STUDY

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The use of interlocking concrete pavements in North America is a rather new development when compared to conventional asphalt and concrete. Little information on performance is available for interlocking concrete pavements. Availability of this information in North America would allow existing design methods to be verified or calibrated or new ones developed. Furthermore, performance information would accelerate the acceptance of concrete pavers by the engineering community. Towards overcoming this limitation, the performance of interlocking concrete pavements at three sites were evaluated. Record searches along with field investigations -- deflection testing, visual condition surveys, and transverse profile surveys -- were conducted as part of this effort. This paper provides a brief description of each site and summarizes the field and office data obtained, along with the interpretation of these data. Emphasis is on structural performance in terms of structural capacity, distresses, and rut depths. Other performance indicators for interlocking concrete pavements are also discussed.

INTRODUCTION

The concept of tightly fitted paving units or pavers set on a flexible aggregate base is as old as the roads of the Roman Empire. The modern version, interlocking concrete pavements, originated in The Netherlands in the late 1940's 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. The pavement system was a logical development from centuries of use of segmental paving systems in Europe. Concrete pavers came to North America in the mid-1970's and have been successfully used in many pavement applications.

Because numerous research studies throughout the world have shown that the load distribution and failure modes of an interlocking concrete pavement are very similar to those of any other flexible (or asphaltic concrete) pavement system, most existing design methods rely on modified flexible pavement design procedures. There is, however, a lack of performance data on concrete pavers in North America to verify or calibrate existing design methods or to develop new ones, a study was undertaken to document the performance of streets in North America constructed with concrete pavers. Three projects were selected to 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 in order to assess the functional and structural condition of the pavements. They included: (1) nondestructive deflection testing; (2) visual condition surveys; and (3) transverse profile or rut depth surveys. The results of the field investigations, with available construction, traffic and climatic data, served as the basis for this study. This paper provides a description of each site and summarize the field and office data obtained, along with the interpretation of these data. Other performance considerations for interlocking concrete pavements are discussed in a later section. Finally, the major findings and conclusions are presented in the last section.

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 13,935 m^2, including sidewalks, and extends along 1,006 m of Main Street; see Figure 1. The first section -- Sherbrooke to Wyld -

was opened to traffic in later July 1983, but had to be closed due to a substantial number of corner "pop-offs" caused by the incorrect gradation of the joint sand. The damaged pavers were replaced, the surfaced resanded, and the section successfully reopened to traffic. The last section -- Algonquin to Cassells -- was opened to traffic in early November 1983.

Figure 1 also shows a schematic diagram of the pavement cross section and laying pattern. The pavement consists of 80 mm concrete pavers over 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 150 mm granular base and 200 mm aggregate 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 catch basins and storm sewer outlets. Subdrains were not installed in this project due to the free-draining subgrade material.

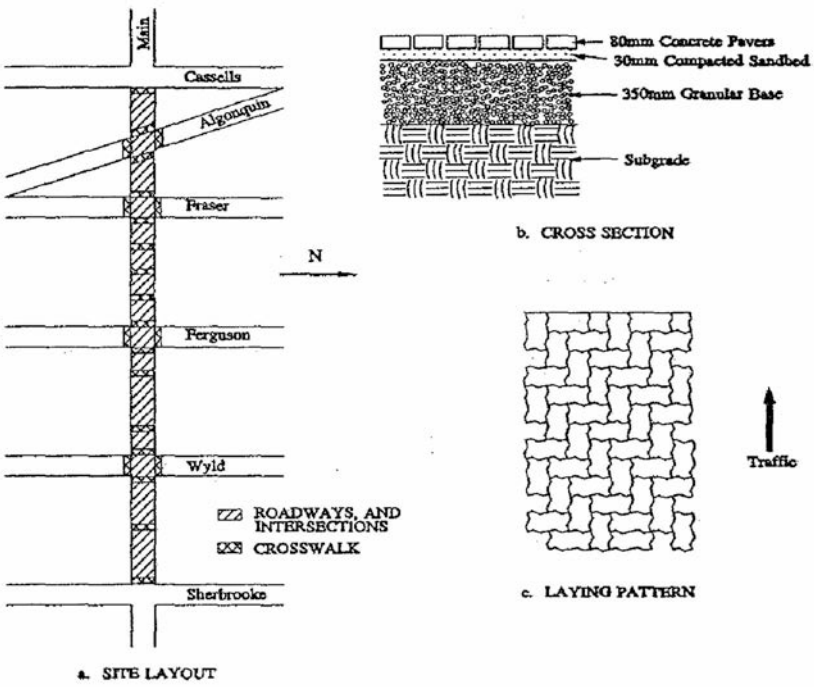

FIGURE 1. NORTH BAY, ONTARIO

Two-way traffic along Main Street is approximately 8,000 vehicles per day, with 13,300 vehicles per day at the intersection of Algonquin and Main Streets. Although no division 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% delivery trucks and buses. The pavements are also subjected to very severe weather conditions. Temperatures range from -40°C to 35°C, with an average daily temperature of 3°C. North Bay also receives an average of 990 mm of precipitation each year, which consists of both rain and snow.

Center City of Timmins, Ontario

Timmins, a city in northern Ontario, underwent a downtown renovation program that utilized over 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 2 shows the layout of the study area (Third, Cedar, and Pine Streets).

The pavements consist of 80 mm concrete pavers over a 30 mm bedding sand layer. The pavers are laid in a herringbone pattern and are supported by a 150 mm aggregate base and a granular subgrade. Both the pavement cross section and laying pattern of the pavers are also illustrated in Figure 2. Storm sewers and drains provide outlet for surface water off the interlocking concrete pavement.

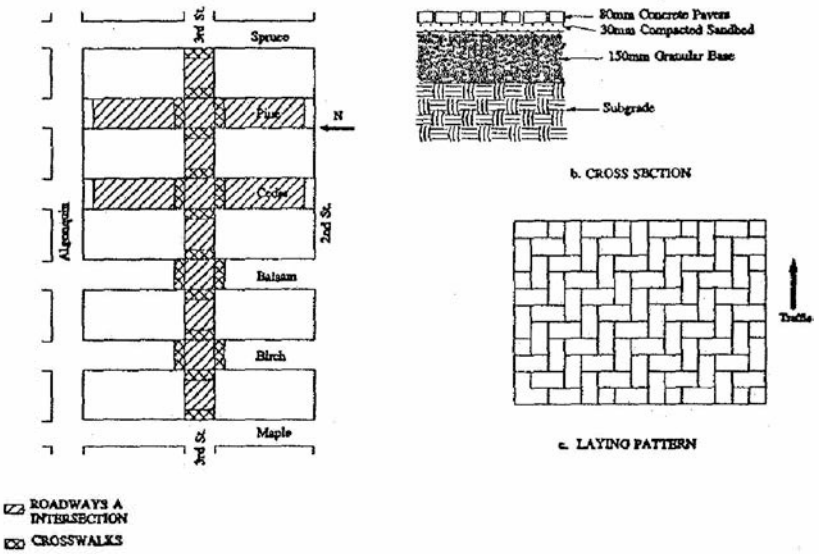

FIGURE 2. TIMMINS, ONTARIO

Two-way traffic on Third Street has been estimated to be 6,000 vehicles per day and includes automobiles, buses, and trucks. While 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% buses and delivery trucks. Like at North Bay, the climate at this site is also very severe. Temperatures range from -43°C to 38°C, with an average daily temperature of 1°C. Timmins also receives an average of 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 as part of center city revitalization. The mall is trafficked by buses that transport citizens to and from the many shops that line Hay Street. The mall covers an area of 3,850 m^2, not including sidewalks; see Figure 3.

The pavements were constructed in the summer of 1984 and opened to traffic in May 1985. Figure 3 also shows the pavement cross section and laying pattern used. The pavement consists of 80 mm concrete paver over 38 mm of bedding sand. A 51 mm asphalt concrete layer over 200 mm of unbound aggregate base provide 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 due to the discovery of archeological artifacts. Storm sewers and drains provide outlets for surface water from the interlocking concrete pavement.

The mall is intended for bus access only. Buses typically have a weight of 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. Unlike at the two previous sites, the climate in Fayetteville is considerably milder. While temperatures range from -34°C to 43°C, the average daily temperature is 16°C. The average annual precipitation is 480 mm, with very little snowfall.

PERFORMANCE EVALUATION

Pavement Structural Capacity

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 22 to 40 kN force.

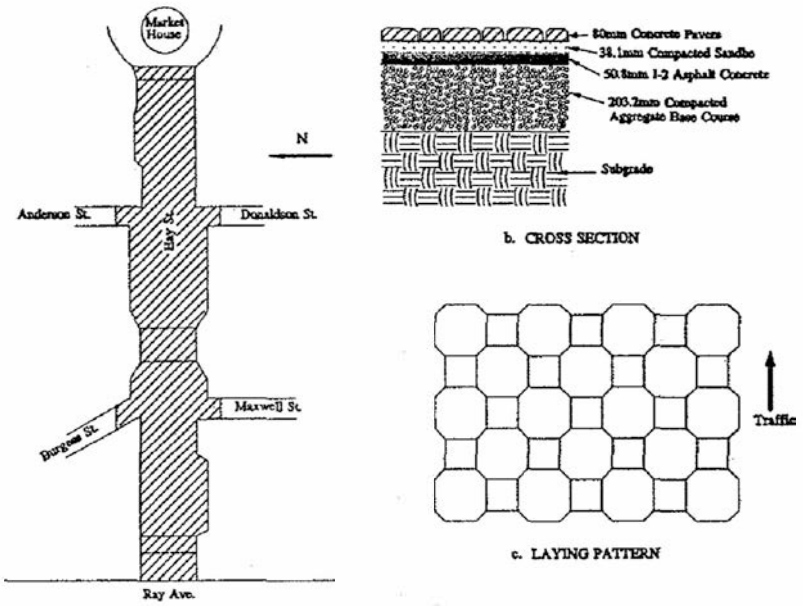

FIGURE 3. FAYETTEVILLE, NORTH CAROLINA

The response of the pavements to these loads was measured by means of deflection sensors located at 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 partial statistical summary of the measured deflections at each site.

Table 1 - Surface Deflections

Project Site	Pavement Category	Number of Points	Parameters	Sensor		
				r=0.0	r=61.0	r=122.9
North Bay	Roadways	95	Average Std. Dev.	392 54	106 21	53 13
	Intersections	14	Average Std. Dev.	379 41	109 28	52 15
	Others	6	Average Std. Dev.	1245 465	209 78	89 22
Timmins	Roadways	89	Average Std. Dev.	397 49	121 20	63 10
	Intersections	24	Average Std. Dev.	395 49	122 19	64 12
Fayetteville	Roadways	44	Average Std. Dev.	488 81	103 13	51 6
	Others	36	Average Std. Dev.	520 66	102 12	52 6

Notes: (1) Deflections shown correspond to a 40 kN load, measurements were also taken at a nominal 22 kN load but are now shown here.

(2) Deflections at 20.3, 30.5, 45.8, and 91.4 not shown due to space limitations.

To analyze the measured deflections, a multi-layer elastic solution was used because of its simplicity and general acceptance 5); both pavers and bedding sand are modeled as a composite layer. In particular, in-situ pavement layer moduli were backcalculated using a program called MODULUS (10). This program utilizes a forward calculation scheme (elastic solution), 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 concrete pavers and bedding sand surface layer, an unbound aggregate base layer, and the subgrade soil. In the evaluation of the Fayetteville pavements, a two-layer structure was used since preliminary analysis of the deflection data yielded very similar moduli for both the base and subgrade layers (no attempt was made to backcalculate the modulus of the thin asphalt concrete layer below the bedding sand).

The results of the moduli backcalculation analysis are summarized in Table 2. These results have been grouped into roadways, intersections, and others (parking lanes, sidewalks, bus stops). 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, as traffic across the Hay Street intersections is not allowed.

Table 2 - Backcalculated Layer Moduli

Project Site	Pavement Category	Number of Points	Layer Type	Layer Modulus	
				Mean (MPa)	Std. Dev. (MPa)
North Bay	Roadways	190	Pavers/Sand Granular Base Subgrade	2598 272 103	1132 74 32
	Intersections	28	Pavers/Sand Granular Base Subgrade	3858 198 123	1322 49 18
	Others	12	Pavers/Sand Granular Base Subgrade	815 100 54	127 12 32
Timmins	Roadways	178	Pavers/Sand Granular Base Subgrade	2069 595 122	712 163 21
	Intersections	48	Pavers/Sand Granular Base Subgrade	2898 442 132	1018 178 27
Fayetteville	Roadways	88	Pavers/Sand Base/Subgrade	2374 86	857 12
	Others	72	Pavers/Sand Base/Subgrade	1423 83	469 14

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 pavers 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 2,856 MPa to 3,808 MPa for the intersections; 2,067 to 2,598 MPa for the roadways; and 813 to 1,426 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 several countries, are summarized in Table 3. While 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 pavers initially act as individual units and gradually lock together and share the load. This has been called "progressive stiffening" or "lock up."

Table 3 - Moduli for Composite Block and Sand Layer (from Literature Review)

Country	Modulus (ksi)	Reference
United Kingdom	899 1,998	(1)
Japan	1,680 4,326	(4)
New Zealand	415	(7)
Australia	350 3,197	(3)
Netherlands	639 2,770	(2)
United States	3,101	(6)

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. Values generally ranging from 5,000 to 100,000 equivalent 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 were estimated on the basis of field estimates and information provided by the responsible agencies to be in the 100,000 to 120,000 range. This similarity, coupled with the fact that data from earlier years is not available, prohibited the authors from shedding further light on this issue.

A comparison of the values presented in Tables 2 and 3 also reveals that there is excellent agreement between the composite moduli derived in this study (813 to 3,858 MPa) and those found in literature (345 to 4,327 MPa). In addition, the moduli are very similar to those of asphalt concrete, particularly for high traffic areas (intersections), where in all likelihood full lock-up has already occurred. This finding illustrates that the load distribution of interlocking concrete pavements is similar to that of flexible pavements.

Pavement Distress

Because a well established and generally accepted procedure for carrying out visual distress surveys on interlocking concrete pavement does not presently exist in North America, information regarding distress types and their measurement were extracted from various sources in the literature in order to develop an interim condition survey procedure; the primary sources of information included References 15 and 17. Sampling plans for evaluation of the interlocking concrete pavements under investigation were then developed.

The pavements were first subdivided into sample units (223 m^2 per unit). Individual sample units were then selected at random for use in the field surveys -- 24 sample units covering 5,184 m^2 in North Bay, 18 sample units covering 3,888 m^2 in Timmins, and 12 sample units covering 2,441 m^2 in Fayetteville. In all cases, the sample unit coverage exceeded 50% 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 pavers. Depressions were found over 4.17% of the area surveyed, but this is somewhat misleading in that 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 in order to access underground utilities. Subsequent reinstatement of the pavement was carried out with less than satisfactory results. Corner and edge spalling of

Table 4 - Summary of Visual Distress Survey Results

Distress Type	Severity Level			Density (%)			Total Density (%)
	Low	Medium	High	Low	Medium	High	
North Bay (Area Surveyed: 5,184 m²)							
Surface Irregularities							
Depression (m²)	---	216.0	---	---	4.17%	---	4.17%
Transition to Utility (m²)	2.3	1.4	---	0.04%	0.03%	---	0.07%
Transition to Curb (m²)	4.5	---	---	0.09%	---	---	0.09%
Block Distress							
Corner or Edge Spalling (%)	3.47%	0.12%	---	3.47%	0.12%	---	3.59%
Cracked Blocks (%)	0.12%	---	---	0.12%	---	---	0.12%
Joint Distress							
Deformed Joints (m²)	3.6	---	---	0.07%	---	---	0.07%
Timmins (Area Surveyed: 3,888 m²)							
Surface Irregularities							
Rutting (m²)	---	24.3	---	---	0.63%	---	0.63%
Swell/Heave (m²)	---	14.4	---	---	0.37%	---	0.37%
Transition to Curb (m²)	---	0.4	---	---	0.01%	---	0.01%
Block Distress							
Corner or Edge Spalling (%)	2.61%	0.21%	---	2.61%	0.21%	---	2.82%
Cracked Blocks (%)	0.27%	0.04%	---	0.27%	0.04%	---	0.31%
Miscellaneous							
Snow Plow Damage (m²)	719.1	12.6	---	---	---	---	18.82%
Fayetteville (Area Surveyed: 2,441 m²)							
Surface Irregularities							
Swell/Heave (m²)	72.0	---	---	2.95%	---	---	2.95%
Depression (m²)	18.0	12.6	---	0.74%	0.52%	---	1.25%
Transition to Utility (m²)	3.1	2.0	---	0.13%	0.08%	---	0.21%
Transition to Curb (m²)	---	0.5	---	---	0.02%	---	0.02%
Block Distress							
Corner or Edge Spalling (%)	<0.01%	---	---	<0.01%	---	---	<0.01%
Stained Surface (m²)(*)	73.8	---	---	3.02%	---	---	3.02%
Joint Distress							
Deformed Joints (m²)	5.4	---	--	0.22%	---	---	0.22%

the pavers were found to be a problem in 3.59% of the area surveyed. It appears that two factors are contributing to this small, localized distress: (1) inferior quality pavers supplied by one of the manufacturers, as evidenced by their frequent replacement over the last 5 years, and (2) a combination of harsh winter conditions and snow removal operations.

At Timmins, the predominant pavement distress types are snow plow damage and block spalling, which were found over 18.82% and 2.82% of the area surveyed. Damage refers to scratch marks on the surface of the pavers resulting from snow plows. Spalling appears to be related to the same two factors as in North Bay; i.e., quality of some of the pavers as well as winter conditions and snow removal operations.

In the case of the Fayetteville pavements, the predominant distress types are surface staining, swell/heave and depressions. These distresses were found over 3.02%, 2.95%, and 1.25% 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 are of low severity and are likely due to 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 pavers.

With the exception of small, 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, it can be observed from Table 4 that surface deformation, which is the primary failure mode in interlocking concrete pavements, occurs in less than 1.5% of the pavement areas surveyed. Besides localized pavement deformations, distresses on individual pavers are the only other visible wear (3 to 4% by total area at each site).

Pavement Rut Depths

Transverse profile surveys were conducted with a Dipstick Auto-Read Profiler at multiple locations within each site to determine rut depths. This device measures the relative elevation of two points which are 0.30 m apart. Measurements were taken at 0.3 m intervals from the edge of the pavement to the centerline. From these data, rut depths were determined using commercially available software and an assumed 1.83 m straight edge. Table 5 summarizes the results of the rut depth analysis. The following observations were made from these data.

Table 5 - Rut Depth Measurements

Project Site	Number of Lines	Statistic	Rut Depth Measurements (mm) Wheel Path:		
			Left	Right	Average
North Bay	21	Mean	5.3	5.8	5.6
		Std. Dev.	4.5	3.8	4.1
		Minimum	1.2	0.3	0.7
		Maximum	23.5	16.8	20.2
Timmins	18	Mean	6.1	10.8	8.5
		Std. Dev.	3.7	4.1	3.9
		Minimum	0.0	0.4	0.2
		Maximum	11.4	17.9	14.0
Fayetteville	22	Mean	2.3	3.4	2.8
		Std. Dev.	1.6	1.8	1.7
		Minimum	0.4	0.2	0.3
		Maximum	6.4	8.0	7.2

At all three sites, rut depths in the right wheel-path are larger than those in the left wheel path. These differences are small for the North Bay and Fayetteville pavements, but quite significant in Timmins: 5.1 mm on average. It is hypothesized that they are due to the lower degree of block confinement, and hence lock-up, achieved at the pavement edge (right wheel-path) during the construction process. This is likely related to the construction of the edge restraints as well as the placement and compaction of the base, sand, and pavers at the pavement edge.

Table 5 also shows large rut depths for the North Bay and Timmins pavements: 11.4 mm 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 23.5 mm reading in North Bay was taken in the repair area referenced earlier.

The results in Table 5 clearly show the excellent performance of the interlocking concrete pavements. After 6 to 8 years in service, average pavement rut depths range from 2.8 mm in Fayetteville, to 5.6 mm in North Bay, and 8.5 mm in Timmins. These are well below the 12.7 to 19.1 mm level typically considered as a failure by most highway agencies.

OTHER CONSIDERATIONS

Data reported in the literature indicate that the performance of interlocking concrete pavements depends on the interlocking pattern and thickness, paver and the interlocking shape of the individual units. Paver shape has more of an effect on mechanical behavior; a uniform cross section will not crack as easily as a variable cross section. Paver thickness affects the mechanical behavior, and an increase in thickness also produces an increase in structural capacity. The performance of the herringbone laying pattern has been shown to have greater structural capacity than stretcher or basketweave patterns. They tend to creep in the direction of traffic movement and adversely affect the interlocking of the pavers.

Rectangular concrete pavers were laid at the two Ontario sites in a herringbone pattern, while detailed pavers blocks were used at the North Carolina site, also laid in a herringbone pattern. However, the results do not clearly indicate that one shape is performing better than the other. In addition, because the pavements under investigation were all constructed with 80 mm pavers and 31 to 38 mm of bedding sand, the impact of these factors on the performance of the pavements could not be assessed.

Furthermore, since 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 forecast about their long term performance. Future monitoring will be required to document their long term performance. Additional sites with varying factors -- e.g., paver shape and thickness, thickness of bedding sand, laying pattern, etc. -- should also be monitored over long periods of time, preferably since the time of initial construction, in order to better ascertain the influence of these factors upon performance.

CONCLUSIONS

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 pavers 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 pavement 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% of the areas surveyed.
- Rut depths along the right wheel-path are larger than those in the left wheel-path; this difference is likely to be related to the construction of the edge restraints or the placement and compaction of the base, pavers, and sand of the pavers and sand at the pavement edge.

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