BEST PRACTICE DESIGN FOR CONCRETE PAVERS FOR CANADIAN MUNICIPAL APPLICATIONS

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SUMMARY

Interlocking concrete block pavements combine the advantages of concrete pavements with those of asphalt concrete pavements. Individual concrete blocks have a high stiffness and resistance to spills and deicing chemicals while the pavement system is flexible and is not susceptible to thermal cracking as with asphalt concrete pavements. While there has been extensive use of interlocking concrete block pavements for pedestrian and recreational areas in North America, their use for residential and municipal roadways significantly lags behind compared to their use in Europe and South Asia. This paper outlines the structural design of interlocking concrete block pavements for roadway design using an adaptation of the 1993 AASHTO Guide for the Design of Pavement Structures. Example pavement structures for a variety of subgrade, traffic and base conditions are provided along with their sensitivity to changes in design inputs. Finally, the use of the presented design matrices is shown through a series of case studies.

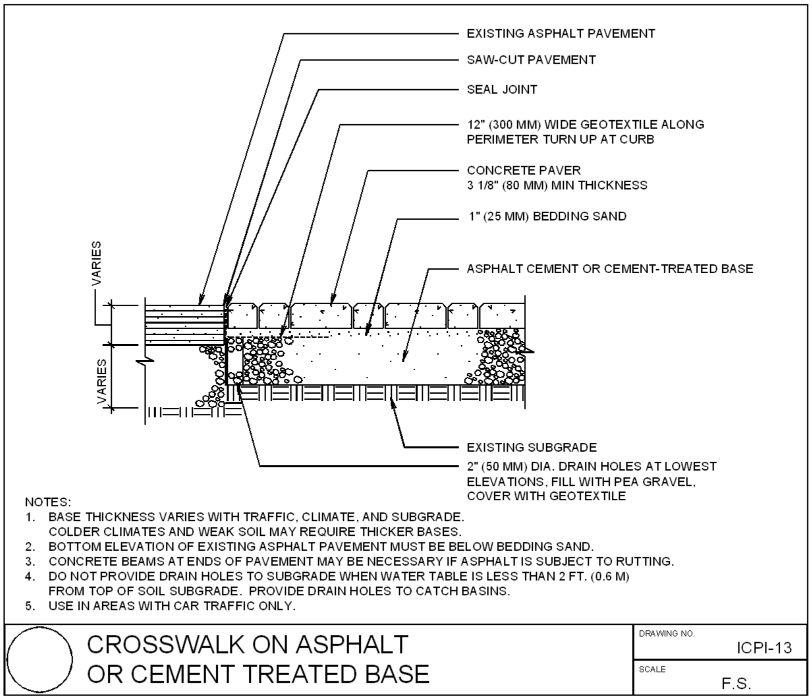
1. BACKGROUND

The Roman Empire was one of the first to use the concept of interlocking concrete pavements for the road system. The Romans first built pavements by tightly fitting paving units or pavers on a compacted flexible granular base [ICPI, 2004]. The basic paving stone concept was later revised and introduced in the Netherlands in the late 1940's as a replacement for clay brick streets. Interlocking concrete pavements later spread to Germany in the 1960's, and, in the 1970's, began to emerge in the United Kingdom, Australia, South Africa, and North America. Currently, there are approximately 60 million square metres and 300 million square metres of concrete pavers are produced annually in North America and Europe, respectively [Tighe, "Interlocking Concrete Pavements"]. Concrete pavers have been successfully used in many pavement applications such as driveways, recreational areas, parking lots, city streets, sidewalks, ports and container terminals, and airports.

Interlocking concrete block pavements provide high resistance to freeze-thaw and deicing salts, high abrasion and skid resistance, and protection from petroleum products or deformation/indentations due to high ambient temperatures. Joint sand between the individual concrete pavers facilitates vehicle wheel load transfer and controlled crack locations in order to minimize stress cracking and surface degradation. Concrete pavers are set in bedding sand, which is placed over a base material that can consist of untreated aggregate base, bituminous or cement treated base, or even Portland cement concrete. The spaces between the individual paving units is filled with clean high quality joint sand. A typical interlocking concrete block pavement design for a crosswalk application is shown in Figure 1 [ICPI, 2003]. When used over an untreated aggregate base, the pavers and base material can be locally removed to gain access to underground utilities. Upon completion of any underground utility repairs, the individual concrete pavers can be reused, thus reducing waste materials [ICPI, 2004].

2. INTRODUCTION

Load distribution in an interlocking concrete block pavement is similar to a flexible asphalt concrete pavement. Vehicle wheel loads are distributed through the concrete pavers over a large area in the base and subbase layers. A properly constructed interlocking concrete block pavement will resist vertical, rotational, and horizontal movements. Vertical interlock of the individual concrete blocks is accomplished by shear transfer through the joint sand, which also transfers vertical loads to the surrounding concrete pavers. Interlock is necessary to prevent differential settlement of individual concrete pavers, and can be achieved by proper paver thickness selection, consistent spacing between the individual pavers, and the provision of adequate horizontal restraint from a stationary edge or curb. A crown will further enhance rotational interlock and will also facilitate drainage, tightening of the units through loading and minor settlement, and increased structural capacity. Horizontal interlock of the individual concrete blocks is achieved through the laying patterns and is required to disperse horizontal forces resulting from braking, turning, and accelerating tires. Typically, the Herringbone pattern is the most effective laying pattern and offers improved system structural capacity [ICPI, 2004].



NOTES:
1. BASE THICKNESS VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE. COLDER CLIMATES AND WEAK SOIL MAY REQUIRE THICKER BASES.
2. BOTTOM ELEVATION OF EXISTING ASPHALT PAVEMENT MUST BE BELOW BEDDING SAND.
3. CONCRETE BEAMS AT ENDS OF PAVEMENT MAY BE NECESSARY IF ASPHALT IS SUBJECT TO RUTTING.
4. DO NOT PROVIDE DRAIN HOLES TO SUBGRADE WHEN WATER TABLE IS LESS THAN 2 FT. (0.6 M) FROM TOP OF SOIL SUBGRADE. PROVIDE DRAIN HOLES TO CATCH BASINS.
5. USE IN AREAS WITH CAR TRAFFIC ONLY.

Figure 1. Typical Interlocking Concrete Block Design Detail for a Crosswalk. [ICPI, 2003]

The typical failure mechanism of an interlocking concrete pavement is also similar to that of a flexible pavement. Failure is in the form of localized settlement or rutting of the concrete paver surface, which is the result of a deformed base or subbase layers due to insufficient structural support or compaction. To address this failure mechanism, the pavers and sand in the affected area are typically removed, the affected layers are strengthened, and the bedding sand and pavers are reinstalled [Tighe, “Construction Methods”].

With the increasing use of concrete pavers in North America and around the world, a simple and comprehensive design method is needed to assist pavement designers in the successful implementation of interlocking concrete block pavements. The Interlocking Concrete Pavement Institute (ICPI) has developed detailed design procedures for the various applications [ICPI, 2004]. Since the failure mode of interlocking concrete pavements is similar to that of a flexible asphalt pavement, the design procedure outlined in this paper was based on the American Association of State Highway and Transportation Officials (AASHTO) 1986 and 1993 Guide for Design of Pavement Structures [AASHTO, 1993]. Through an analysis of AASHTO 1993 and Mechanistic Design Principles, typical interlocking concrete paver designs suitable for municipal type traffic have been developed. The structural design analysis examines pavement designs for typical municipal applications representing a range of roadway functional classes along with three drainage categories, six traffic categories, three base types, and various combinations of subbase thicknesses. In essence, this paper provides a best practice matrix of interlocking concrete block pavement structural designs for municipal applications.

3. METHODOLOGY

A typical interlocking concrete block pavement includes concrete pavers placed on top of a layer of bedding sand over a base and subbase layer. The base layer can be constructed using untreated aggregate, asphalt treated base, or cement treated base. If either an asphalt or cement treated base is used, a granular subbase layer may be placed underneath the treated base layer. The AASHTO 1993 flexible pavement design method can be summarized using the following equation [AASHTO, 1993]:

$$LogW = Z_R \times S_0 + 9.36 \times \log(SN+1) - 0.20 + \frac{\log\left[\dfrac{p_i - p_t}{p_i - 1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log(M_R) - 8.07 \qquad [1]$$

where:

W = design traffic load in equivalent single axle loads (ESALs)
Z_R = standard normal deviate
S_0 = standard deviation
SN = structural number of the pavement
p_i = initial serviceability
p_t = terminal serviceability
M_R = subgrade resilient modulus.

The structural number is used to describe the structural strength of the pavement, and can be summarized as: [TAC, 1997]

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \qquad [2]$$

where:

a_i = structural layer coefficient of layer i
D_i = thickness of layer i,
m_i = drainage coefficient of layer i

The factors that are taken into account by the AASHTO 1993 and mechanistic design principles can be grouped into five main categories: environment, traffic type and composition, subgrade soil strength, and pavement layer material properties. Moisture and temperature levels and their variation can influence on the performance of a pavement. Excessive moisture can decrease the load bearing capacity of the subgrade or base materials, while temperature can also contribute to a decreased load bearing capacity, particularly for asphalt stabilized layers. Moisture and freezing temperatures working together will lead to freeze-thaw cycles in the pavement structure, thus causing heaving of certain layers and reduced bearing capacity during thaw periods. In the AASHTO pavement design procedure, moisture and temperature effects are taken into account by adjusting the strength of the subgrade soil and the different pavement layers [ICPI, 2004]. For the purpose of this paper, it was assumed that proper drainage is provided for all pavement layers and the drainage coefficients in Equation 2 are set to one.

The amount of damage caused by traffic loading will depend on the number and type of vehicles that pass over the pavement section. Traffic design loading for the AASHTO design procedure is represented using the Equivalent Single Axle Load (ESAL) concept. One ESAL is represented as the impact from a single 18-kip or 80 kN axle load. The pavement design life was chosen to be 20 and 40 years, and the cumulative ESALs are estimated based on a simplified method developed by the U.S. Strategic Highway Research Program (SHRP). The method developed by SHRP estimates the cumulative ESALs based on the estimated average annual daily traffic (AADT), which is based on the functional category of the road, and the percentage of commercial traffic. In this method, it is assumed that pavement damage is caused solely by commercial traffic. The SHRP simplified method developed equations to estimate the cumulative design ESALs for one-lane roads, two-lane roads, and roads with more than two lanes. Since this paper is interested in municipal applications, the design ESALs is estimated using the equation for a two-lane road [TAC, 1997]:

$$ESAL = 182.5 \times AADT \times TP \times TF \times [1.57 - 0.083 \times \log_e(AADT/2)] \qquad [3]$$

where,

ESAL = Equivalent single axle design loads
AADT = average annual daily traffic
TP = percent of commercial vehicles
TF = truck factor (0.76 for a typical municipal flexible pavement)

Table 1 summarizes the calculated and rounded ESALs used for the different roadway functional classes and AADT.

Table 1. Calculated ESALs for Various AADT Levels.

AADT	Functional Category	Percent Commercial	Calculated ESALs	Rounded ESALs	Design ESALs (20 yrs)	Design ESALs (40 yrs)
500	Local	0.5	719	800	16,000	32,000
1000	Local	1	2,825	3,000	60,000	120,000
5000	Local	1	13,516	15,000	300,000	600,000
10000	Minor Arterial	3	79,521	80,000	1,600,000	3,200,000
15000	Major Arterial	5	196,501	200,000	4,000,000	8,000,000
20000	Principal Arterial	5	259,825	250,000	5,000,000	10,000,000

*Note the ESALs have been rounded for design purposes.

Resilient modulus is used to describe the strength of the subgrade soil, and can be determined from laboratory testing or through surrogates such as California Bearing Ratio (CBR) and R-value tests. For an accurate assessment of the subgrade soil strength, laboratory tests should be conducted on field samples to represent the various conditions that will be experienced during the design life [ICPI, 2004]. However, if it is not possible to perform laboratory tests, typical resilient modulus values are available from the AASHTO soil classification system [AASHTO, 1993]. Table 2 summarizes the resilient modulus values recommended for the AASHTO-Ontario pavement design model, which are also used to develop the best practice interlocking concrete block pavement design matrices.

The pavement material and thickness is described with the calculation of the structural number with Equation 2. Three base types are considered for the design matrices are untreated granular, asphalt treated and cement treated bases with layer coefficients of 0.14, 0.28, and 0.28 respectively. The layer coefficient for the concrete pavers and bedding layer is set to 0.44 which is typical for an asphalt concrete pavement, and the layer coefficient for the subbase was assumed to be 0.09 for all cases [ICPI, 2004]. Typical concrete pavers for vehicular applications are 80 mm thick, and the bedding sand layer is constructed to 25 mm [Tighe, “Construction Methods”]. For granular base, the minimum recommended thickness is 100 mm for traffic levels below 500,000 ESALs and 150 mm for traffic levels over 500,000 ESALs [ICPI, 2004]. If either the asphalt treated or cement treated base is used, the minimum thickness for that particular layer is 100 mm. For the treated base layers, an unbound base layer with a minimum thickness of 150 mm must be placed underneath for constructability reasons. If the subbase layer thickness required is less than 100 mm, that layer would typically be converted to additional granular base material.

Using the layer thicknesses indicated in Table 2, the additional amount of subbase that is needed to satisfy the structural number (SN) is calculated with Equation 1 for different levels of traffic and subgrade materials. The initial and terminal serviceability of the pavement are assumed to be 4.2 and 2.5 respectively, and the reliability and standard deviation are 75 percent and 0.45. Based on the design ESALs, resilient modulus, and serviceability of the pavement, the required structural capacity, expressed as a structural number, is calculated from Equation 1. Using Equation 2, the additional subbase thickness that is required to satisfy the needed structural capacity is calculated for the three different types of base materials. For the treated bases where a granular base is required, the subbase is converted to the granular base material to meet the 150 mm minimum requirement by using the granular base equivalency (GBE) ratio, which is equal to 0.67 for subbase materials in Ontario [TAC, 1997], and the remaining structural requirement is satisfied by calculating the required subbase layer thickness.

Table 2. Recommended M_R values for the AASHTO-Ontario design model [5].

Brief Description	Category No.	MTO Classification	Drainage Characteristics	Susceptibility to Frost Action	M_R for Typical Subgrade, MPa		
					Good	Fair	Poor
Rock, rock fill, shattered rock	1	Boulders/ cobbles	Excellent	None	90	80	70
Well graded gravel and sand	2	GW, SW	Excellent	Negligible	80	70	50
Poorly graded gravel and sand	3	GP, SP	Excellent to fair	Negligible to slight	70	50	35
Silty gravels and sands	4	GM, SM	Fair to semi-impervious	Slight to moderate	50	35	30
Clayey gravels and sands	5	GC, SC	Practically impervious	Negligible to slight	40	30	25
Silts and sandy silts	6	ML, MI	Typically poor	Severe	30	25	18
Low plasticity clays and silts	7	CL, MH	Practically impervious	Slight to severe	27	20	15
Medium to high plasticity clays	8	CI, CH	Generally impervious	Negligible to severe	25	20	15

4. RESULTS

Tables 3 and 4 indicate the calculated subbase thicknesses for different ESALs, untreated, asphalt treated, and cement-treated base material, subgrade category, and subgrade drainage quality. The design matrices are separated into different tables based on the design periods. For constructability purposes, if a certain pavement layer is required, the minimum thickness that will be built is set to 25 mm. Also, each layer is rounded to the nearest 5 mm for realistic design specifications. For all designs, the pavement is constructed with an 80 mm concrete paver layer, 25 mm bedding sand layer and a 150 mm layer of granular base, and the remaining required strength will be provided by one of the three subbase types considered.

Figures 2 and 3 compare subbase thicknesses for a 20-year and 40-year design period. The figures show that there is no significant difference between the subbase thicknesses required for the two design periods. Therefore, it may be possible to increase the design period of a pavement from 20 years to 40 years for a relatively small increase in the initial construction cost.

Figure 4 shows the required subbase thickness for selected subgrade types. This plot illustrates the effect that the base type would have on the subbase thickness required. Since it was assumed that the layer coefficient for both asphalt and cement treated base were equal to 0.28, the subbase thickness requirement for these two base types are the same. The main difference occurs between the granular base and the treated bases. For a granular base, a thicker subbase layer is required since the layer coefficient for the granular base is half that of the treated bases. Also, with the mandatory 150 mm base that is placed underneath the treated base layer, pavements utilizing a treated base layer will require less subbase thickness compared to a pavement with a granular base.

The calculated subbase thickness was compared with outputs from the AASHTO DARWin computer program, which is a computer program based on the AASHTO 1993 Guide for Design of Pavement Structures. The calculated design and the DARWin output correlated within a few millimeters.

Table 3. Subbase thickness (mm) for a 20 year design period for a standard 80 mm concrete paver over 25 mm bedding sand and 150 mm granular base.

Category	Drainage	ESALs					
		16,000	60,000	300,000	1,600,000	4,000,000	5,000,000
1	Good	0	0	0	25*	150	185
	Fair	0	0	0	60*	195	230
	Poor	0	0	0	105	245	280
2	Good	0	0	0	60*	195	230
	Fair	0	0	0	105	245	280
	Poor	0	0	0	220	375	415
3	Good	0	0	0	105	245	280
	Fair	0	0	0	220	375	415
	Poor	0	0	95*	360	530	570
4	Good	0	0	0	220	375	415
	Fair	0	0	95*	360	530	570
	Poor	0	0	145	425	595	640
5	Good	0	0	55*	305	470	510
	Fair	0	0	145	425	595	640
	Poor	0	0	210	500	680	725
6	Good	0	0	145	425	595	640
	Fair	0	0	210	500	680	725
	Poor	0	85*	335	650	840	890
7	Good	0	0	185	470	645	690
	Fair	0	55*	295	600	790	835
	Poor	0	145	410	735	935	985
8	Good	0	0	210	500	680	725
	Fair	0	55*	295	600	790	835
	Poor	0	145	410	735	935	985

* Typically subbase thicknesses of less than 100 mm would be converted to granular base and added to the standard 150 mm of granular base.

Table 4. Subbase thickness (mm) for a 40 year design period for a standard 80 mm concrete paver over 25 mm bedding sand and 150 mm granular base.

Category	Drainage	ESALs					
		32,000	120,000	600,000	3,200,000	8,000,000	10,000,000
1	Good	0	0	0	120	260	300
	Fair	0	0	0	160	305	345
	Poor	0	0	0	210	360	400
2	Good	0	0	0	160	305	345
	Fair	0	0	0	210	360	400
	Poor	0	0	75*	335	505	545
3	Good	0	0	0	210	360	400
	Fair	0	0	75*	335	505	545
	Poor	0	0	195	485	665	710
4	Good	0	0	75*	335	505	545
	Fair	0	0	195	485	665	710
	Poor	0	25*	255	555	735	785
5	Good	0	0	150	430	600	645
	Fair	0	25*	255	555	735	785
	Poor	0	75*	325	635	825	875
6	Good	0	25*	255	555	735	785
	Fair	0	75*	325	635	825	875
	Poor	25*	185	460	795	995	1045
7	Good	0	50*	295	600	790	835
	Fair	0	150	415	740	940	990
	Poor	60*	255	540	885	1095	1145
8	Good	0	75*	325	635	825	875
	Fair	0	150	415	740	940	990
	Poor	60*	255	540	885	1095	1145

* Typically subbase thicknesses of less than 100 mm would be converted to granular base and added to the standard 150 mm of granular base.

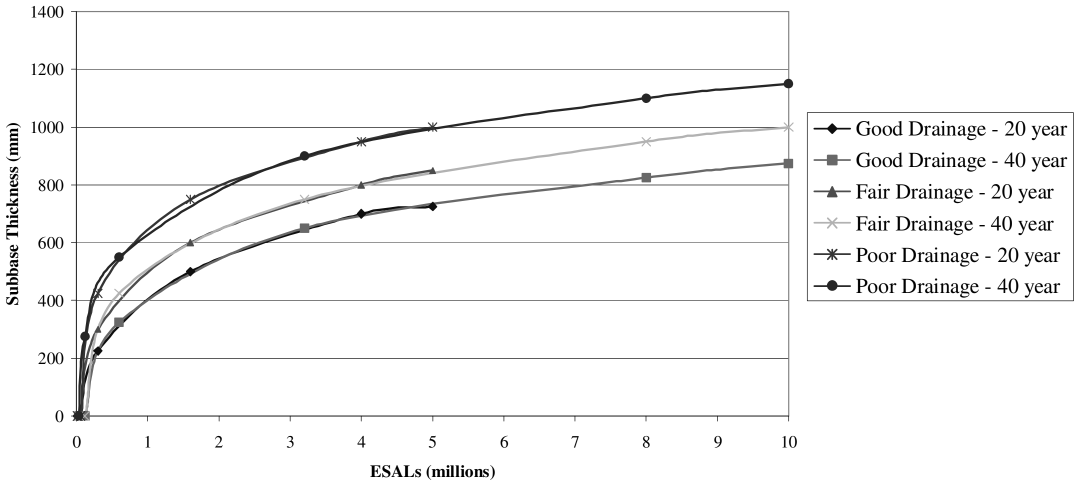


Figure 2. Granular base over inorganic clays or high plasticity, fat clays.

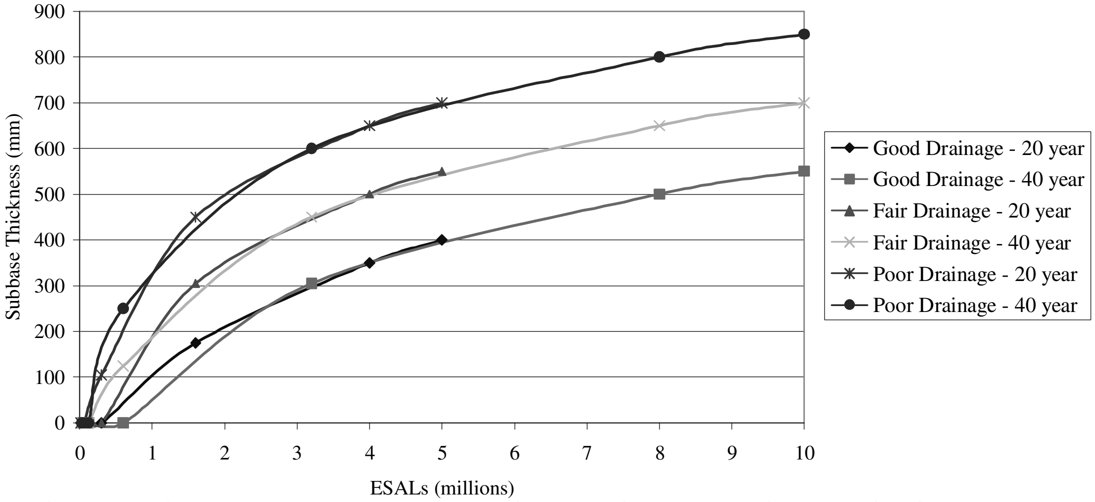


Figure 3. Asphalt treated base over inorganic clays or inorganic silts.

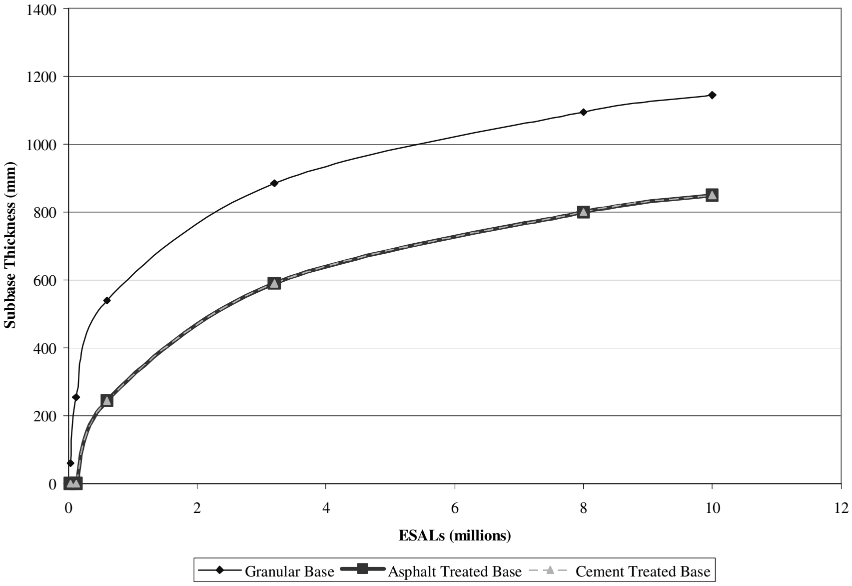


Figure 4. Inorganic clays or high plasticity, fat clays subgrade with poor drainage.

5. CONCLUSIONS

This paper presented several best practice design matrices for interlocking concrete pavements mainly for use in municipal applications. One of three bases can be used for the construction of concrete pavers: untreated granular base, asphalt treated base and cement treated base. The design matrices are categorized based on the base type and the design period. Two design periods were analyzed, namely 20 and 40 years, and each design matrix provides a best practice design for the pavement structure. The design matrices were calculated using the AASHTO 1993 and Mechanistic Design Principles, which are based on flexible pavement design. The matrices were created for road classes from local roads with an AADT of 500 to principal arterial roads with an AADT of 20,000. A pavement structure is recommended based on the cumulative ESALs, subgrade soil type, and the drainage quality of the subgrade soil.

The design matrices developed for use in this paper are only applicable for municipal type applications where there are relatively low traffic volumes and weights.

6. REFERENCES

AASHTO, 1993. “AASHTO Guide for Design of Pavement Structures.” American Association of State Highway and Transportation Officials, Washington, D.C.

ICPI, 2003. “Interlocking Concrete Pavements Detail Drawings, ICPI-13 Crosswalk on Asphalt or CTB.” Interlocking Concrete Pavement Institute.

ICPI, 2004. “Tech Spec Number 4 Structural Design of Interlocking Concrete Pavement for Roads and Parking Lots.” Interlocking Concrete Pavement Institute.

TAC, 1997. “Pavement Design and Management Guide.” Transportation Association of Canada, Ottawa, Ontario.

Tighe, Susan and Chung, Wilson, 2004. Report Title. “University Curriculum Interlocking Concrete Pavements, Module: Interlocking Concrete Pavements”. Developed for The Interlocking Concrete Pavement Institute, University of Waterloo.

Tighe, Susan and Chung, Wilson, “University Curriculum Interlocking Concrete Pavements, Module: Construction Methods”, Developed for The Interlocking Concrete Pavements Institute, University of Waterloo, 2004.