Port and Industrial Pavement Design Manual

Heavy duty pavements for industrial areas, bulk and container ports

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Port and Industrial Pavement Design

with

Concrete Pavers

Second Edition

by

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About the Authors

John Knapton's complete curriculum vitae is available on http://www.john-knapton.com/jkcv.htm. Highlights include ten years as a Professor of Structural Engineering at the Newcastle University in Newcastle-upon-Tyne, England. His early career included research in the 1970's that led to the publication by the British Ports Association design manual for heavy-duty pavements. He has since written three more editions. He also developed design methods for aircraft and highway pavements surfaced with concrete pavers. During the 1980's he was engaged in the design of many new and rehabilitated pavements worldwide. He has published over 70 papers in the field of pavement design and is past Chairman of the Small Element Pavement Technologists (SEPT) which perpetuates the series of international conferences on concrete block paving (see www.sept.org). Dr. Knapton is acknowledged worldwide for his technical expertise in segmental paving as well as other pavement types.

David R. Smith is Technical Director of the Interlocking Concrete Pavement Institute (ICPI) which represents the segmental concrete pavement industry in North America. He has been involved with concrete pavers since 1984 when he first contributed to the Second International Conference on Concrete Block Paving at Delft, the Netherlands. He has managed several paver projects and has been involved in the design, specifications, and construction of streets, ports, and airport projects. Mr. Smith orchestrated and contributed to much of the North American methodology on segmental concrete pavement through his work at ICPI. He is Chairman of SEPT. The authors collaborated with other authors on design and specifications for several interlocking concrete pavement projects, including the development of the world's first guide on the use of concrete pavers for aircraft pavements (also available from ICPI on www.icpi.org). They were jointly responsible for the first municipal streets in the U.S. to be surfaced with mechanically installed pavers in 1985. Mr. Smith has also written extensively on permeable interlocking concrete pavements.

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Introduction

Interlocking concrete pavements are the orthodox solution for paving ports in the United Kingdom, the Netherlands, and at many other ports in the world. The largest installation of concrete pavers is in the Port of Rotterdam, the Netherlands which contains some 20 million ft^2 (2 million m^2). Since 1981, concrete pavers have been used in an increasing number of port and industrial areas in North America. The choice of concrete pavers has been based on cost-competitiveness, low maintenance, and ability to accommodate any container or cargo handling equipment. The following lists many North American ports and industrial yards constructed with interlocking concrete pavements.

Facility	Application	Area sf (m^2)	Year built
Seagirt Terminal, Port of Baltimore, Maryland	Container yards/quay	230,000 (23,000)	1990
Seagirt Berth 4, Port of Baltimore, Maryland	Container yard	463,000 (46,300)	1997
Seagirt, Port of Baltimore, Maryland	Container yard	600,000 (60,000)	2001
Port of New Orleans, Louisiana	Container yards	1,089,000 (100,000)	1991-96
Alberta Intermodal Yard, Edmonton, Alberta	Container yard	1,000,000 (100,000)	1981
Canadian Pacific Railways, Calgary, Alberta	Container yard	1,000,000 (100,000)	1984
Pier IX, Newport News, Virginia	Coal yard	660,000 (66,000)	1983
Matson Terminal, Long Beach, California	Transtainer runway	7,000 (700)	1985
Berth 30, Port of Oakland, California	Container yard	328,000 (32,800)	1993
Berths 55-59 Port of Oakland, California	Container yard	4,700,0000 (470,000)	2000-02
Port of Fernandina, Florida	Container yard	100,000 (10,000)	1992
Port of Tampa, Florida	Container yard	495,000 (49,500)	1995
Berg Steel Pipe Company, Panama City, Florida	Interior plant	70,000 (7,000)	1980
Crothers Caterpillar Company, Ontario	Service areas	185,000 (18,500)	1979-90
Sears Warehouse, Toronto, Ontario	Truck depot	150,000 (15,000)	1989
Hemscheidt, Pittsburgh, Pennsylvania	Interior plant	20,000 (2,000)	1985
Degussa Chemical Company, Mobile, Alabama	Storage yard	60,000 (6,000)	1987
Port of Freeport, Bahamas	Container yard	1,200,000 (120,000)	1997
New London, Connecticut	Wharf	115,000 (11,500)	1997

Purpose

Port pavement design safeguards pavement from failure over a predetermined period of time. There are two types of failure associated with port pavements; structural failure and surface or functional failure. One influences the other, and failure of each or both leads to decreased operational efficiency or complete operational failure. Obviously, these failures have unfavorable economic consequences for the port operator. Therefore, a complete port pavement design must address all of the issues which might lead to structural and functional failures. In order to prevent them, port pavement design requires consideration of the following:

- structural design
- drainage design
- surface characteristics
- provision of underground services
- traffic and storage management markings, signs, and structures
- interface with other facilities and structures
- selection of appropriate construction techniques

- environmental and visual concerns

The purpose of this manual is to provide guidance on the structural design of pavements serving ports and other industries. Designers are advised, however, to consider all of the above when developing a project. Ignoring one or more of these considerations can lead to progressive reduction in pavement serviceability and performance. Ultimately structural, function, and eventually operational failure will occur. Many of these broader considerations are discussed in other publications by the Authors (1).

Executive Summary

This is the second edition of the ICPI manual, *Port and Industrial Pavement Design with Concrete Pavers*. This edition introduces a new way of analyzing pavements which is incorporated into the design method. The original research for first edition of the ICPI manual (2) was based on simplified layered elastic design from the 1970's. In those days, pavements were analyzed by programmable calculator technology (3). This meant that stresses and strains could be calculated accurately at only one or two special points in the proposed pavement structure.

The advent of high-speed personal computers has enabled structural analysis through finite element modeling. This technology enables analysis of stresses and strains at many places in the pavement structure. Locations of critical stresses and strains can be identified and structures designed to withstand them. This is a more efficient and comprehensive approach. It also enables design of the pavement structure to be separated into design of the base and design of the foundation under it. In making this separation, no accuracy is lost.

The distillation of finite element modeling has greatly simplified the design method in this manual in that only one chart is required for determining base thickness. This chart is the Equivalent Single Load as presented in Chapter 6. Table 15 in Chapter 6 can then be used to select the pavement foundation according to subgrade conditions. The resulting pavement (base and foundation) should remain serviceable throughout its life.

Chapter 1 describes loading conditions and gives information from which the design load may be established. Chapter 2 describes the choice of pavement materials available and Chapter 3 includes guidance on material specifications and a guide construction specification.

The design method uses cement-treated base (CTB) as the base material. During the last ten years, a good deal of experience has been gained in the use of Material Conversion Factors or Material Equivalence Factors. Therefore, the CTB can now be used to exchange one material for another during the design process. This means that when a design has been produced using the chart in Chapter 6, the designer can generate alternative design solutions using different materials and investigate a full range of solutions. Table 10 in Chapter 2 gives Material Conversion Factors for many commonly used base materials.

This edition differs from the first one in that Material Conversion Factors were used previously only in overlay design. An enhanced overlay section presented in Chapter 4 allows existing pavements either to be rehabilitated or strengthened. This section is based upon the cost-effective approach of evaluating the remaining structural capability of a pavement and incorporating it into rehabilitation. Examples of overlay treatment are included in Chapter 4.

Chapter 5 includes an example showing the procedure for design of new pavement. It demonstrates how cargo handling equipment operations influence pavement design and explains how the Equivalent Single Load design chart in Chapter 6 should be used. Appendices A, B and C provide further information on condition (distress) surveys, life-cycle costs, and ICPI Tech Spec technical bulletins especially relevant to port and industrial pavement bedding sand materials, mechanical installation and maintenance. Detail drawings for port and industrial pavements can be found on www.icpi.org.

Scope of the Manual

The focus of this manual is the design of interlocking concrete pavements. The manual may be used to design all types of pavements serving ports and similar cargo handling facilities. It also can be used to design highway pavements subjected to highway loads or heavier.

A particular feature of this second edition is the design method for container storage areas. In the first edition, container corner casting loads were converted to Port Area Wheel Load (PAWL) units. Because corner castings apply significantly higher levels of stress than pneumatic tires, the conversion caused some designers to experience difficulties. In this second edition, the corner casting loads have been modeled and a design curve developed specifically for such situations. This curve appears on the Single Equivalent Load design chart in Chapter 6.

Design Principles

The design procedure in this manual is based upon the principle that interlocking concrete pavements are designed to remain serviceable throughout the design life of the pavement. In terms of structural performance, failure in a heavy-duty pavement usually occurs by either excessive vertical compressive strain in the subgrade or excessive horizontal strain in the base. For pavements with stabilized bases, the tensile strain in the base is the design constraint whereas subgrade compressive strain is frequently the constraint for pavements with granular bases. Surface deformations in the order of 2 in. to 3 in. (50 mm to 75 mm) will normally exist at failure.

The manual also covers pavement overlay or inlay with concrete pavers. An existing pavement may need to be strengthened because it has deteriorated to a condition which no longer offers adequate support for the equipment, or because heavier equipment is to be introduced. Taking advantage of the existing or residual strength of pavement can sometimes lead to a cost savings. Chapter 4 demonstrates how the residual strength of a pavement can be quantified and included in overlay design.

Analysis Technique

In order to produce the charts in Chapter 6, typical heavy-duty pavements have been analyzed using a finite element model to represent all components of the pavement. Elastic properties and Poisson's ratio values were chosen to describe the behavior of each pavement component. Fatigue is considered by defining limiting stresses to which the pavement can be exposed for one load pass, and then reducing those stresses to account for multiple load repetitions.

Recent developments in pavement design procedures have separated foundation design, based on subgrade strength, from base design, which is developed from loads. This approach is introduced in the manual because it simplifies the design procedure. This procedure divides the pavement into a foundation, consisting of a subbase and capping as required, and a base. This enables thickness of the base to be proportioned to withstand the applied loads. Figure 1 on page 7 illustrates these layers typical to heavy-duty pavement. In some pavements, one or more of the layers may be absent.

The foundation can be proportioned to develop adequate support to the base and concrete pavers while accounting for subgrade soil conditions. The rationale was based on present highway pavement design procedures which include pavement foundation guidance. Specifically, highway design procedures relate subbase and capping specifications to soil subgrade strength. Therefore, the soil subgrade is always stressed to a level commensurate with its strength.

Calibration of the Design Method

All design procedures based upon mechanistic analysis require proven criteria for levels of stress or strain which define limiting permissible values. Usually, these criteria are stresses or strains existing in successful designs produced by empirical design methods. By this means, mechanistic models are effectively calibrated and designs produced by them have the same level of integrity as those produced by the design method used in calibration. This is underscored in Part IV Mechanistic-Empirical Design Procedures of the 1993 AASHTO *Guide for the Design of Pavement Structures* (4), which states, *"It is, therefore, necessary to calibrate (mechanistic) models with observations of performance, i.e., empirical correlations."*

In this manual, the limiting stresses upon which the design curves in Chapter 6 are based were determined as follows: A proven semi-empirical pavement design method was used to assess the levels of stress at critical positions in the pavement structure. The calibration method was the UK highway pavement design method modified for interlocking concrete pavers. This method is based on British Standard (BS) 7533 (5) which is derived from the UK Transport and Road Research Laboratory (TRRL) Road Note 29 (6) and original AASHTO research.

BS 7533 was used to produce a number of design examples covering a wide range of pavement design situations. These were then analyzed using a linear elastic finite element model for this manual to establish permissible stresses. The stresses which the finite element model demonstrated in pavements designed according to BS 7533 are used in this manual as the critical design stresses in pavement design.

In other words, the design charts in Chapter 6 of this manual have been produced using the same finite element model to back-analyze a range of pavements structures developed from the original AASHTO research. The experience and methodology underpinning BS 7533, i.e., AASHTO, have been transferred to this manual. Therefore, the user may deal with all pavements likely to be encountered in heavy-duty pavement design. A benefit of this analysis technique is that any inaccuracies in the finite element model should largely cancel. They will have been included in the BS 7533 back-analysis calibration in exactly the same way as they have been included in the design charts in Chapter 6.

Fifteen pavements designed according to BS 7533 were analyzed using the finite element model to determine stresses and strains at critical locations in each pavement. The pavement sections developed from BS 7533 are shown in Table 1. It shows the design thicknesses for each course when designed according to BS 7533. All of the pavement structures presented in Table 1 were analyzed using the finite element model in conjunction with a standard axle load of 18,000 lb (80 kN).

Table 1. Pavement course thicknesses used in the finite element analysis.

CBR of Subgrade	CBR 1%	CBR 2%	CBR 5%
Capping	24 in. (600 mm)	14 in. (350 mm)	Omit
Subbase	6 in. (150 mm)	6 in. (150 mm)	6 in. (150 mm)
Millions of Standard Axles (MSA)	**Base Thicknesses**		
0 to 1.5	4 in. (100 mm)	5 in. (125 mm)	5 in. (125 mm)
1.5 to 4	5 in. (125 mm)	5 in. (125 mm)	5 in. (125 mm)
4 to 8	7 in. (175 mm)	7 in. (175 mm)	7 in. (175 mm)
8 to 12	8 in. (200 mm)	8 in. (200 mm)	8 in. (200 mm)
12 to 25	9 in. (225 mm)	9 in. (225 mm)	9 in. (225 mm)

Preliminary analysis using the finite element program confirmed that the critical stresses occur at the bottom and at the top of the base layer directly beneath the applied load. Values of stresses at these critical locations are shown in Tables 2 and 3.

A check on the validity of this manual can be undertaken by comparing the tensile stresses produced by the finite element analysis with those produced by the 1993 AASHTO guide. Figure 3.9 in the *AASHTO Guide for Design of Pavement Structures* relates tensile stress in concrete pavements to pavement thickness, wheel load, and support offered to the base by the underlying materials. Table 2 below includes the AASHTO tensile stresses for comparison. In all cases, the AASHTO tensile stresses are within 7% of the finite element stresses. From Table 2, it can be concluded that BS 7533 produces pavements whose strength is in line with AASHTO guidelines.

Table 2. Maximum principal stresses (tensile) at the underside of the base course in those BS 7533 pavements back analyzed in the calibration exercise in psi (MPa). The far-right column shows stresses produced by Figure 3.9 of the AASHTO pavement design guide.

MSA	CBR 1%	CBR 2%	CBR 5%	AASHTO
0 to 1.5	345 (2.38)	356 (2.452)	324 (2.323)	320 (2.2)
1.5 to 4	263 (1.817)	271 (1.866)	253 (1.749)	265 (1.83)
4 to 8	198 (1.363)	202 (1.394)	189 (1.3)	185 (1.28)
8 to 12	152 (1.049)	155 (1.069)	144 (0.9959)	145 (1.16)
12 to 25	124 (0.8539)	126 (0.8678)	117 (0.8098)	115 (0.79)

Table 3. Minimum principal stresses (compressive) at the upper surface of the base course in those BS 7533 pavements back analyzed in the calibration exercise in psi (MPa).

MSA	CBR 1%	CBR 2%	CBR 5%
0 to 1.5	-265 (-1.829)	-269 (-1.856)	-257 (-1.772)
1.5 to 4	-232 (-1.602)	-235 (-1.621)	-224 (-1.547)
4 to 8	-198 (-1.363)	-205 (-1.412)	-197 (-1.359)
8 to 12	-184 (1.269)	-185 (-1.274)	-180 (-1.239)
12 to 25	-173 (1.191)	-173 (-1.193)	-170 (-1.169)

Tables 2 and 3 show that stresses in the base of the pavement are very similar for each subgrade CBR value, and that the stresses diminish with increasing levels of traffic. These two tables enable design stresses to be selected for all pavement types. The inclusion of higher levels of traffic broadens the applicability of the manual to pavements serving other industries as well as to highway pavements.

A small stress range in compression is expected due to the equilibrium of vertical forces through the pavement from the point of load application down to other areas. Compressive stresses at the point of load application are important in surfacing materials subject to point loads such as container corner castings, small steel wheels from specialized equipment, and stabilizing jacks on mobile cranes. These types of loads may cause localized surface distress.

In conclusion, the tensile stress at the underside of the base is frequently the limiting stress for structural design purposes in all practical pavements. Table 4 shows average values of the three tensile stresses existing in pavements designed over subgrades with CBR's of 1%, 2%, and 5% for each of the five fatigue levels (1.5 MSA to 25 MSA) used in the analysis. In this manual, the values in Table 4 are used as permissible design stresses and the design charts have been constructed using these values. It is customary to add factors of safety to stress levels in pavement design since the failure limit state is essentially one of serviceability.

Table 4. Average tensile stresses used as design stresses in psi (MPA). AASHTO stresses are also shown.

MSA	Average	AASHTO
1.5	348 (2.4)	320 (2.2)
4	261 (1.8)	265 (1.83)
8	203 (1.4)	185 (1.28)
12	145 (1.0)	145 (1.00)
25	116 (0.8)	115 (0.79)

The finite element model calculated the stresses shown in Table 4 which exist in pavements designed according to BS 7533. Therefore, it is possible to analyze a range of typical pavements in order to establish the loads which generate similar stresses for a given number of load passes. This exercise produced the curves in the design charts in Chapter 6.

The finite element model used in developing the design charts and in the calibration exercise comprises an axi-symmetric idealization. A cylindrical layered system was modeled with a diameter of 23 ft (7 m) and a depth of 8 ft (2.4 m) with 63 rectangular elements each having a node at each corner and midway along each side. Each model perimeter node was restrained horizontally, and each node at the lowest level was restrained both horizontally and vertically.

A single point load was applied at the uppermost node at the center of the model. In order to simulate the effect of a circular load accurately, an axi-symmetric load having a radius equal to that of the load was generated above the cylinder. The radius was determined by assuming the load to be applied had a pressure of 112 psi (0.8 MPa). The model was graded such that its smaller elements were concentrated near the point of load application where stress variation was steep. Larger ones were generated at greater depth and radius. The Lusas finite element package licensed to the Civil Engineering Department at Newcastle University, England, was used to generate the model (6).

Paving Materials

The material properties used in the modeling are presented in Table 5. The design charts in Chapter 6 are based upon these materials. Chapter 3 provides guide specifications for the materials. The design charts allow designs to be developed for pavements including a base comprising 1,400 psi (10 MPa) 7-day strength CTB with an assumed flexural strength of 280 psi (1.9 MPa). The surface is comprised of 3.125 in. (80 mm) thick concrete pavers on 1.25 in. (30 mm) thick bedding sand.

Experience in heavy-duty pavement design has shown that pavement surfacing materials have little influence on overall pavement strength and these can be substituted with little influence on overall structural performance. In the finite element analysis, the surface has been modeled as a homogeneous 4.3 in. (110 mm) thick layer of material having an elastic modulus of 580,000 psi (4,000 MPa) and a Poisson's Ratio of 0.15. These characteristics are similar to the properties of both concrete pavers and asphalt surfacing materials. In the case of concrete pavers, 3.125 in. (80mm) thick units placed in a herringbone pattern have been found to exhibit a high level of stability and strength.

Once a pavement section has been developed using 1,400 psi (10 MPa) CTB, it can be "exchanged" for other base materials of either greater of lesser flexural strength with the base thickness being adjusted accordingly. For example, a concrete base can be designed by replacing the CTB produced by the chart with a PCC base, using the Material Equivalence Factors in Table 9. The pavement surface selection is primarily based on functional performance such as resistance to wear rather than it structural contribution.

Table 5. Pavement material properties used in producing design charts.

Layer	Elastic Modulus, E psi (MPa)	Poisson's Ratio
Surfacing (pavers and sand)	580,000 (4,000)	0.15
Cement-treated base (1,400 psi) (10 MPa)	5,075,000 (35,000) *	0.15
Granular Subbase	43,500 (300)	0.20
Granular capping	21,750 (150)	0.25
Subgrade	1,500 X CBR (10 X CBR)	0.25

* uncracked modulus

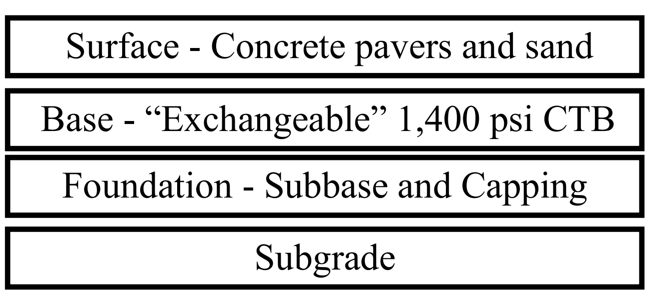


Figure 1. Pavement Components

Chapter 1 - Load Assessment

In this manual, actual loads are rationalized to a single equivalent load so that the design chart in Chapter 6 can be used to determine the base thickness. There is usually no unique load value which characterizes the operational situation. Consequently, information must be gathered about the various loads in order to derive the equivalent single load to be used with the design chart. First, information is gathered on the types of expected loads and these are modified with dynamic load factors and wheel proximities. This is followed by deriving the single equivalent pavement load from the design chart.

Wheel Load Value

The value of the design wheel load depends upon the range of container weights being handled. Design should be based upon the critical load. This is defined as the load whose value and number of repetitions leads to the most pavement damage. Relatively few repetitions of a high load value may inflict less damage than a higher number of smaller loads. The entire load profile should be expressed as a number of passes of the critical load. The evaluation of the critical load and the effective number of repetitions of that load is as follows.

Table 6 shows the distribution of container weights normally encountered in UK ports for different proportions of 20 ft (6 m) and 40 ft (12 m) containers. Where local data is available, it can be used in place of Table 6. For each of the container weights shown in Table 6, calculate the damaging effect caused when equipment is handling containers of that weight from the following equation:

$D = (W/26{,}400)^{3.75}(P/112)^{1.25}N$ [Metric: $D = (W/12{,}000)^{3.75}(P/0.8)^{1.25}N$]

Where: D = Damaging effect
W = Wheel load corresponding with specific container weight in lbs. (kg)
P = Tire Pressure in psi (MPa)
N = % figure from Table 6

The container weight leading to the greatest value of D is the critical weight container. All subsequent wheel load calculations should be based upon this load. Experience in the use of the previous edition of the manual indicates that when the containers being handled comprise of 100% 40 ft (12 m) containers, the critical load is commonly 48,400 lb (22,000 kg). When 20 ft (6 m) containers are being handled, the critical load is 44,000 lb (20,000 kg). In general, mixes of 40 ft (12 m) and 20 ft (6 m) containers have a critical container weight of 46,200 lb (21,000 kg). These values may be used in preliminary design studies. The number of repetitions used in design can be calculated accurately using a load value weighted system. However, if the total number of repetitions calculated solely from operational data is used, a negligible error will be generated. In the case of pavements trafficked by highway vehicles, an equivalent wheel load of 22,500 lb (100 kN) may be used.

Table 6. Percentages of containers of different weights for five different combinations of 40 ft (12 m) to 20 ft (6 m) containers derived from statistics provided by UK ports.

Container Weight (kg)	Proportion of 40 ft (12 m) to 20 ft (6 m) Containers				
	100/0	60/40	50/50	40/60	0/100
0	0.00	0.00	0.00	0.00	0.00
1000	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.18	0.23	0.28	0.46
3000	0.00	0.60	0.74	0.89	1.49
4000	0.18	1.29	1.57	1.84	2.95
5000	0.53	1.90	2.25	2.59	3.96
6000	0.98	2.17	2.46	2.76	3.94
7000	1.37	2.41	2.67	2.93	3.97
8000	2.60	3.05	3.16	3.27	3.72
9000	2.82	3.05	3.11	3.17	3.41
10,000	3.30	3.44	3.48	3.52	3.66
11,000	4.43	4.28	4.24	4.20	4.04
12,000	5.73	5.24	5.12	4.99	4.50
13,000	5.12	4.83	4.76	4.69	4.41
14,000	5.85	5.38	5.26	5.14	4.67
15,000	4.78	5.12	5.21	5.29	5.63
16,000	5.22	5.58	5.67	5.76	6.13
17,000	5.45	5.75	5.83	5.91	6.21
18,000	5.55	5.91	6.00	6.10	6.46
19,000	6.08	6.68	6.83	6.98	7.58
20,000	7.67	8.28	8.43	8.58	9.19
21,000	10.40	8.93	8.56	8.18	6.72
22,000	9.95	7.60	7.02	6.43	4.08
23,000	5.53	4.31	4.00	3.69	2.47
24,000	2.75	1.75	1.50	1.25	0.24
25,000	0.95	0.63	0.55	0.47	0.15
26,000	0.67	0.40	0.33	0.27	0.00
27,000	0.72	0.43	0.36	0.29	0.00
28,000	0.53	0.32	0.27	0.21	0.00
29,000	0.43	0.26	0.22	0.17	0.00
30,000	0.28	0.17	0.14	0.11	0.00
31,000	0.03	0.02	0.02	0.01	0.00
32,000	0.03	0.02	0.02	0.01	0.00
33,000	0.00	0.00	0.00	0.00	0.00
34,000	0.05	0.03	0.02	0.02	0.00

Tires

The contact area of a tire under handling equipment is assumed to be circular with a contact pressure equal to that of the tire pressure. Some larger equipment has tires for operating over soft ground. When such tires travel over a paved area the contact area is not circular and the contact stress under the tread bars is greater than the tire pressure. Although this affects the stresses in the surfacing material, stress concentrations are dissipated substantially at lower levels of the pavement. Some terminal trailers are fitted with solid rubber tires. The contact stress depends upon the trailer load but a value of 238 psi (1.6 MPa) is typical and the higher pressure is dispersed satisfactorily through the interlocking concrete pavement.

Dynamics

The effects of dynamic loading from cornering, accelerating, braking, and surface unevenness are considered by the factor f_d. Where a section of a pavement is subjected to dynamic effects, the wheel loads are adjusted by the factors given in Table 7, and as explained in the notes to the Table.

Table 7. Dynamic load factors(f_d). Static loads are increased by the percentage figures in the Table.

Condition	Equipment Type	f_d
Braking	Front Lift Truck	±30%
	Straddle Carrier	±50%
	Side Lift Truck	±20%
	Tractor and Trailer	±10%
Cornering	Front Lift Truck	40%
	Straddle Carrier	60%
	Side Lift Truck	30%
	Tractor and Trailer	30%
Acceleration	Front Lift Truck	±10%
	Straddle Carrier	±10%
	Side Lift Truck	±10%
	Tractor and Trailer	±10%
Uneven Surface	Front Lift Truck	20%
	Straddle Carrier	20%
	Side Lift Truck	20%
	Tractor and Trailer	20%

Note: Where two or three of these conditions apply simultaneously, f_d should account for additive dynamic effects. For example, in the case of a front lift truck cornering and accelerating over uneven ground, the dynamic factor is 40%+10% +20%, i.e. 70% so that the static wheel load is increased by 70%. In the case of braking, the dynamic factor is additive for the front wheels and subtractive for rear wheels. In the case of equipment with near centrally located wheels (e.g. straddle carriers), braking and accelerating dynamic factors to be applied to the near central wheels are reduced according to geometry. See Chapter 5 - Design Example.

Lane Channelization

Equipment movements over a wide pavement do not follow exactly the same course but wander to one side or the other. If there are lane markings approximately the same width as the equipment, then channeling becomes significant. As the lane width increases relative to the width of the equipment, channelization becomes less significant. The less channelized traffic causes an "ironing out" over the area. For straddle carriers stacking containers in long rows, the wheels are restricted to very narrow lanes and consequently severe rutting may take place. In such a case, the operation techniques of the equipment in that area should be reviewed periodically.

Static Loading

Static loads from corner casting feet on containers apply very high stresses to the pavement. In the case of the storage of empty containers, a pavement designed to carry repetitive wheel loads will be able to carry the associated static loads without structural failure. This may also be the case for full containers in low stacks. However, the surface must be designed to withstand high contact stresses and loads. In the first edition of this manual, some users found that pavements could not be designed to withstand the effect of containers stacked more than three high. In this edition, container storage areas are specifically dealt with. The design chart in Chapter 6 includes a design curve which relates to corner castings.

Container Corner Casting Load Values

Containers are usually stacked in end-to-end rows or corner-to-corner blocks and, until recently, usually no more than three high with a maximum of five high. In recent times, containers have been stacked up to 8 high in a few locations, and this may become more common. Corner castings measure 7 in. x 6 in. (175 mm x 150 mm) and frequently they project 0.5 in. (13 mm) below the underside of the container. Table 8 gives the maximum loads and stresses for most stacking arrangements. Since it is unlikely that all containers in a stack will be fully loaded, the maximum gross weights will be reduced by the amounts shown. The values shown in Table 8 can be used directly in the design chart in Chapter 6. In the case of empty containers, pavement loads can be calculated assuming that 40 ft (12 m) containers weigh 6,000 lb (2,727 kg) and 20 ft (6 m) containers weigh 4,000 lb (1,818 kg).

Table 8. Pavement loads from stacking full containers.

Stacking Height	Reduction in Gross Weight	Contact Stress in psi (MPa)	Load on Pavement in kips (kN) for each stacking arrangement		
			Singly	Rows	Blocks
1	0	376 (2.59)	17.1 (76.2)	34.3 (152.4)	66.8 (68.6)
2	10%	677 (4.67)	30.9 (137.2)	61.7 (274.3)	123.4 (548.6)
3	20%	903 (6.23)	41 (182.9)	82.3 (365.8)	164.6 (731.5)
4	30%	1054 (7.27)	48.0 (213.4)	96 (426.7)	192 (853.4)
5	40%	1128 (7.78)	51.4 (228.6)	102.9 (457.2)	205.7 (914.4)
6	40%	1353 (9.33)	61.7 (274.3)	123.4 (548.6)	246.8 (1,097)
7	40%	1581 (10.9)	72 (320)	144 (640)	288 (1,280)
8	40%	1812 (12.5)	82.3 (365.8)	164.6 (731.6)	329.2 (1,463.2)

Trailer Wheels

There are often two pairs of small steel wheels on trailers. These are typically 4 in. wide x 9 in. (100 mm x 225 mm) in diameter. When the trailer is parked, the contact area of each wheel is approximately 0.5 in. x 4 in. (13 mm x 100 mm) and stresses are 5,600 psi (38.6 MPa). Some trailers have pivot plates which measure 6 in. x 9 in. (150 x 225 mm) and produce contact stresses of 280 psi (2 MPa), which is sufficiently low to be evenly distributed through to the base structure of the pavement.

Wheel Proximity Factors

The design constraint is horizontal tensile strain at the bottom of the base course. If only one-wheel load is considered, the maximum horizontal tensile strain occurs under the center of the wheel and reduces with distance from the wheel. If two wheels are sufficiently close together, the strain under each wheel is increased by a certain amount contributed from the other wheel.

Wheel loads are modified by the appropriate proximity factor from Table 9. These factors are obtained as follows. If a load from a second wheel was not considered, the relevant stress would be the radial tensile stress directly beneath the loaded wheel. If there is a second wheel nearby, it generates tangential stress directly below the first wheel. This tangential stress is added to the radial stress contributed by the primary wheel. The proximity factor is the ratio of the sum of these stresses to the radial tensile stress resulting from the primary wheel. The following equations are used to calculate the stress:

$$\sigma_R = \frac{W}{2\pi}\left[\frac{3r^2z}{\alpha^{5/2}} - \frac{1-2v}{\alpha + z.\alpha^{1/2}}\right]$$

$$\sigma_T = \frac{W}{2\pi}\left[1-2v\right].\left[\frac{z}{\alpha^{3/2}} - \frac{1}{\alpha + z.\alpha^{1/2}}\right]$$

Where: σ_R = radial stress

σ_T = tangential stress

W = load

r = horizontal distance between wheels

z = depth to position of stress calculations

v = Poisson's ratio

a = $r^2 + z^2$

When more than two wheels are in close proximity, the radial stress beneath the critical wheel may have to be increased to account for two or more tangential stress contributions. Table 9 shows that the proximity factor depends on the wheel spacing and the effective depth to the bottom of the pavement base. The Effective Depth can be approximated from the following formula. It represents the depth from the pavement surface to the underside of the base, should the base have been constructed from subgrade material.

$$\mathit{Effective\ Depth} = 300.\sqrt[3]{\frac{35000}{CBR \text{ x } 10}}$$ Where CBR = California Bearing Ratio of the subgrade

For example, consider a front lift truck with three wheels at each end of the front axle. The critical location is beneath the center wheel. Suppose a pavement were designed on soil with a CBR of 7% and the wheel lateral centers were 24 in (600 mm). From the formula, the approximate effective depth of the bottom of the pavement base is:

$$Effective\ \ Depth = 300.\sqrt[3]{\frac{35000}{7\ x\ 10}} = 2381\text{mm (94 in.)}$$

By linear interpolation from Table 4 the proximity factor is 1.86. This should be applied twice for the center wheel. This means that the effective single load increased by 0.86 twice i.e., 1 + 0.86 + 0.86 = 2.72. Note that 2.72 is approximately 10% less than 3. Therefore, this type of wheel arrangement effectively reduces pavement load by 10%. For wheels bolted side by side where the wheel centers are separated by less than 12 in. (300 mm), the entire load transmitted to the pavement through one end of the axle can be considered to represent the wheel load. An investigation of the actual equivalent wheel load indicates that the actual equivalent wheel load is approximately 1.97 times one wheel load when there are two wheels bolted together at an axle end.

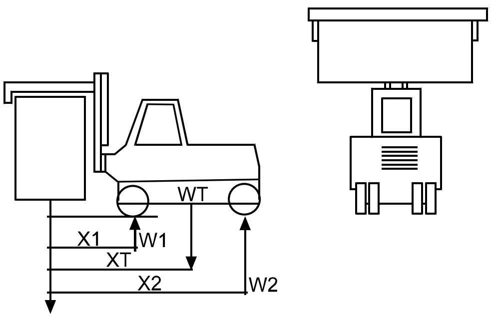
Table 9. Wheel proximity factors.

Wheel Spacing inches (mm)	**Proximity factor for effective depth to base of:**		
	40 in. (1016 mm)	**80 in. (2032 mm)**	**120 in. (3048 mm)**
12 (300)	1.82	1.95	1.98
24 (600)	1.47	1.82	1.91
36 (910)	1.19	1.65	1.82
48 or 4 ft (1220)	1.02	1.47	1.71
72 or 6 ft (1830)	1.00	1.19	1.47
96 or 8 ft (2440)	1.00	1.02	1.27
144 or 12 ft (3660)	1.00	1.00	1.02
192 or 16 ft (4875)	1.00	1.00	1.00

Wheel Load Calculations for Handling Equipment

The following formulas are for guidance only and relate to equipment having wheel configurations as illustrated in the diagrams. In cases where equipment has an alternative wheel configuration, the loads can be derived from them following a similar approach. Wheel loads are often provided by equipment manufacturers and those values should be used. For each pass of the equipment, the pavement is loaded from all of the wheels on one side of the equipment. Therefore, in the wheel load calculations, only one side of the equipment is considered. In the case of asymmetrical equipment, the heavier side should be chosen.

Front Lift Trucks



$$W_1 = f_d \text{ x } \frac{A_1.W_c + B_1}{M}$$

$$W_2 = f_d \ x \ \frac{A_2.W_c + B_2}{2}$$

Where: W_1 = Load on front wheel (lb)

W_2 = Load on rear wheel (lb)

W_c = Weight of Container (lb)

M = Number of wheels on front axle (usually 2, 4 or 6)

f_d = Dynamic factor

A_1, A_2, B_1 and B_2 are:

$$A_1 = \frac{-X_2}{X_1 - X_2}$$

$$A_2 = \frac{X_1}{X_2 - X_1}$$

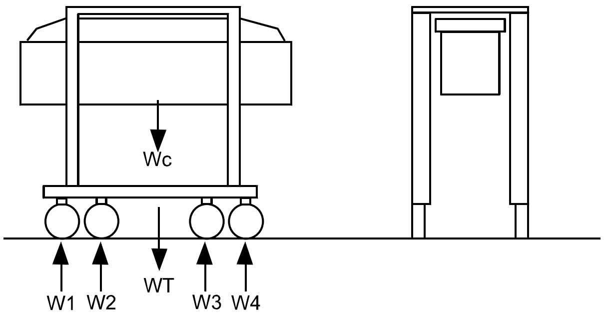
$$B_1 = \frac{W_T(X_T - X_2)}{X_1 - X_2}$$

$$B_2 = \frac{W_T(X_T - X_1)}{X_2 - X_1}$$

X_1, X_2 and W_T are shown in the diagram

W_T = Self weight of the truck

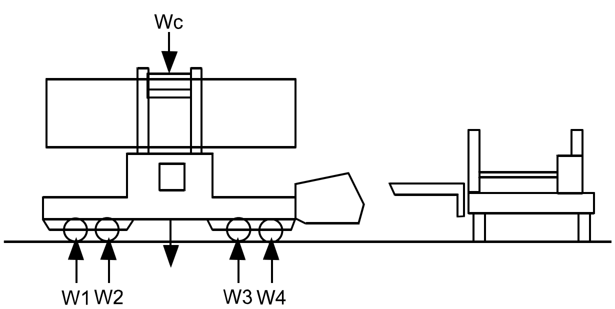
Straddle Carriers



$$W_i = f_d \; x \; [U_i + \frac{W_c}{M}]$$

Where: W_i = Wheel load of laden equipment (lb)
U_i = Wheel load of unladen equipment (lb)
W_c= Weight of Container (lb)
M = Total number of wheels on equipment
f_d = Dynamic factor

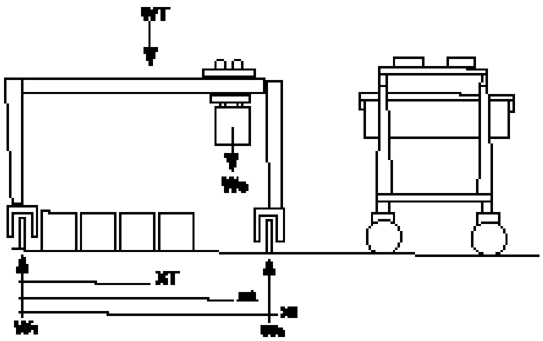
Side Lift Trucks



$$W_i = f_d \; x \; [U_i + \frac{W_c}{M}]$$

Where: W_i = Wheel load of laden equipment (lb)
U_i = Wheel load of unladen equipment (lb)
W_c= Weight of Container (lb)
M = Total number of wheels on equipment
f_d = Dynamic factor

Yard Gantry Cranes



$$W_1 = f_d \text{ x } [U_1 + \frac{A_1.W_c}{M} \;]$$

$$W_2 = f_d \text{ x } [U_2 + \frac{A_2.W_c}{M} \;]$$

Where: W_1 = Wheel load on side 1 (lb)
W_2 = Wheel load on side 2 (lb)
W_c = Weight of container (lb)
M = Number of wheels on each side (possibly 2)
f_d = Dynamic Factor

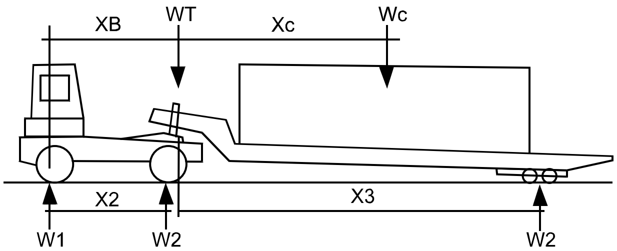
$$A_1 = 1 - \frac{X_c}{X_2}$$

$$A_2 = \frac{X_c}{X_2}$$

U_1 = Unladen weight of gantry crane on each wheel of side 1 (lb)
U_2 = Unladen weight of gantry crane on each wheel of side 2 (lb)
X_2 and X_c are shown in the diagram.

Note: The front and rear wheels may have different unladen loads. This is considered by using the equation for both wheels on each side with their respective f_d values.

Tractor and Trailer Systems



$$W_1 = f_d \text{ x } \left[U_1 + \frac{W_c\left[1-A\right].\left[1-B\right]}{M_1}\right]$$

$$W_2 = f_d \text{ x } \left[\mathrm{U}_2 + \frac{W_c\left[1-A\right].B}{M_2}\right]$$

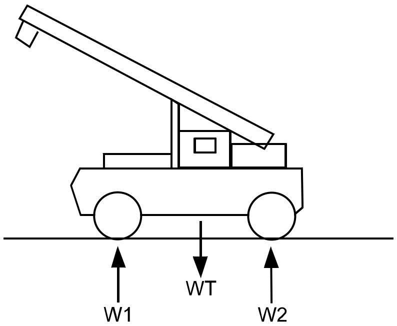
$$W_3 = f_d \text{ x } \left[\mathrm{U}_3 + \frac{W_c.A}{M_3}\right]$$

Where: W_1 = Load on front wheels of tractor (lb)
W_2 = Load on rear wheels of tractor
W_3 = Load on trailer wheels (lb)
W_c = Weight of container (or load) (lb)
M_1 = Number of front wheels on tractor
M_2 = Number of rear wheels on tractor
M_3 = Number of wheels on trailer
U_1 = Load on front wheels of tractor - unladen (lb)
U_2 = Load on rear wheels of tractor - unladen (lb)
U_3 = Load on trailer wheels - unladen (lb)
f_d = Dynamic factor

$$A = \frac{X_c}{X_3} \qquad B = \frac{X_b}{X_2}$$

X_c, X_b, X_3 and X_2 are shown in the diagram.

Mobile Cranes (unladen)



$W = W_T/M$

Where:

W_T = Self weight of crane
M = Total number of wheels on crane

Chapter 2 - Pavement Materials

Base Materials

The design chart presented in Chapter 6 has been constructed with reference to 1,400 psi (10 MPa) compressive strength CTB with a flexural strength of 280 psi (2 MPa). The thickness of this material produced by the design chart may be exchanged for an equivalent amount of an alternative material of greater or lesser strength using Material Conversion Factors in Table 10. The rationale for this technique of exchanging one material for another is described below.

It should be recognized that experience in the use of Material Conversion Factors indicates that within a limited range, they can prove to be an efficient means of expanding one design solution into many alternatives, each of similar structural capability. Cost comparisons can then be made.

The Conversion Factors shown in Table 10 are derived from the AASHTO pavement design guide. In the AASHTO guide, asphalt-treated bases, CTB, and granular materials are each assigned a structural layer coefficient which is a measure of its relative stiffness, and indirectly of performance. For example, 1,400 psi (10 MPa) CTB has a layer coefficient of 0.28. (Figure 2.8 of the AASHTO guide) and an asphalt-treated base with a modulus of 170,000 psi (1,200 MPa) has a layer coefficient of 0.2. This means that the asphalt-treated base has a Conversion Factor of 0.28/0.2 i.e., 1.4. Therefore, if a design exercise resulted in a 6 in. (150 mm) CTB, the equivalent asphalt-treated base would be 1.4 x 6 in. = 8.4 in (1.4 x 150 = 210 mm) thick.

This is a simple and effective method of adjusting layer thicknesses for different base materials. Care should be exercised in undertaking material conversion exercises when the two materials being swapped differ markedly in their engineering properties. Care also should be exercised in the use of crushed rock materials for bases. In many regions, such materials normally attain a CBR of no more than 50% and they should be avoided as base construction materials. In other regions, crushed rock CBR values can exceed 80%, in which case they may be used as a base, providing the CBR maintains 80% or higher throughout the life of the pavement.

Caution should be exercised in the use of unbound base materials where equivalent wheel loads exceed 25,000 lb (11,400 kg). For loads of this magnitude, surface deflections may exceed 1/16 in. (2 mm) when surfacing materials installed directly over crushed rock. Repeated deflections of this magnitude or higher can lead to premature deterioration of surfacing materials, including interlocking concrete pavements. In addition, shear stresses at the surface of the crushed rock base may exceed the shear strength of the base material. This may lead to instability and surface rutting.

High quality, dense-graded, crushed stone bases can withstand repeated wheel loads over 25,000 lb (11,400 kg) but they require hard aggregates, constant monitoring of gradation during construction, as well as a high degree of monitoring for density and moisture during compaction to ensure the maximum possible density. Not all projects have these resources available. In view of the variability among projects, this manual recommends the use of stabilized bases when wheel loads exceed 25,000 lb (11,400 kg).

Table 10. Different pavement base, subbase, and capping materials with permissible flexural strengths and conversion factors from 1,400 psi (10 MPa) cement-treated base.

Pavement Layer	Compressive Strength in psi (MPa)	Conversion Factor from 1,400 psi Cement-treated base
(i) Pavement quality concrete	4,200 (29)	0.80
(ii) Pavement quality concrete	5,600 (38.6)	0.70
(iii) Asphalt-treated Base (Modulus = 350,000 psi) (2,414 MPa)	-	0.93
(iv) Asphalt-treated Base (Modulus = 170,000 psi) (1.172 MPa)	-	1.40
(v) Asphalt Treated Base (Modulus = 90,000 psi) (621 MPa)	-	2.80
(vi) Cement-treated Base (Modulus = 1,100,000 psi) (7,586 MPa)	1,400 (10)	1.00
(vii) Cement-treated Base (Modulus = 820,000 psi) (5,655 MPa)	800 (5.5)	1.27
(viii) Cement-treated Base (Modulus = 620,000 psi) (4,276 MPa)	420 (2.9)	1.75
(ix) Cement-treated Base (Modulus = 470,000 psi) (3,241 MPa)	140 (1)	2.80
(x) Granular Subbase Layer (Modulus = 21,000 psi) (145 MPa)	100% CBR	2.00
(xi) Granular Subbase Layer (Modulus = 13,600 psi) (94 MPa)	22% CBR	2.80
(xii) Granular Subbase Layer (Modulus = 12,000 psi) (83 MPa)	15% CBR	3.00
(xiii) Granular Subbase Layer (Modulus = 7,000 psi) (48 MPa)	6% CBR	4.67

Note: Strengths for pavement quality concrete are 28 days and 7 days for cement-treated bases. Elastic moduli for cement-treated bases are in-service moduli and represent a cracked condition.

Interlocking Concrete Pavers

Experience in the use of the first edition of this publication indicates that little is gained by distinguishing between the structural contribution offered by different surfaces. Therefore, the selection of the surface material should be based upon functional factors rather than structural. The purpose of the surfacing material is to provide a safe, stable, and smooth pavement that is simple and inexpensive to maintain. The surfacing material should have high skid resistance, resist indentation from point loads, offer some load transfer, and help prevent functional failure of the pavement. Interlocking concrete pavements meet these requirements for port applications by offering:

- Resistance to high static loads
- Resistance to horizontal (lateral) loads
- Ease of access to underground utilities
- Ease of replacement of broken paving units
- High abrasion resistance to tires and tracked vehicles
- Rapid draining due to chamfered joints
- Complete resistance to hydraulic oils
- Integrally coloring for pavement markings
- High resistance to de-icing salts
- Mechanical installation to decrease construction time
- Immediate use by traffic upon installation
- Movement with settling soils without cracking, and still providing a serviceable pavement
- Serviceability under substantially more rutting than other pavements

Concrete pavers should be placed in a 45° or 90° herringbone pattern, as these patterns offer the greatest amount of interlock and resistance to horizontal loads. Pavers should meet the requirements of ASTM C936 for applications in the U.S. or CSA A231.2 for uses in Canada. These standards can be purchased online from these standards organizations.

Concrete pavers having a minimum thickness of 3.125 in. (80 mm) are recommended in all port and industrial pavements. Thicker pavers have been used in various U.S. ports subject to container operations such as Oakland, CA and Baltimore, MD. Concrete pavers should be placed in a 1 in. (25 mm) to 1.5 in. (40 mm) thick layer of bedding sand. For design purposes, the elastic modulus of the paver and bedding sand layer is at least 350,000 psi (2,400 MPa) and Poisson's ratio is 0.3. These values are similar to asphalt materials. An advantage of interlocking concrete pavers is that they progressively stiffen or "lock up" as they are trafficked, thereby offering higher stiffness and structural capacity as expressed by elastic modulus. The rate of stiffening varies with traffic but it occurs early in the life of the pavement. The 580,000 psi (4,000 MPa) elastic modulus used in the finite element model expresses the higher side of stiffness due to trafficking the composite interlocking concrete paver and bedding sand and layer.

Bedding Sand Durability

Under repeated traffic, bedding sand beneath the concrete pavers can break down due to abrasion of the particles against each other. This can lead to pumping and loss of sand, as well as premature rutting. The guide specifications in Chapter 3 reference the micro-Deval test (ASTM D7428) for assessing the hardness and durability of bedding sand for port applications. The reader should also review ICPI Tech Spec 17 *Bedding Sand Selection for Interlocking Concrete Pavements in Vehicular Applications* in Appendix D.

Joint Stabilization

Port and industrial pavement do not normally require stabilization of the joint sand with a polymer sealer. In some cases, where early stabilization of the joint sand is required, a paver joint stabilization material can help maintain the integrity of the surface. Such situations may be in areas of heavy rainfall or construction during a rainy season. Urethane sealers are the most expensive but the most durable. Acrylic and mixes of epoxy and acrylic materials can provide shorter term stabilization and are less expensive. ICPI Tech Spec 5, *Cleaning and Sealing Interlocking Concrete Pavement—A Maintenance and Protection Guide*, provides further information on sealers and their applications. This is available in at www.icpi.org.

Chapter 3 - Guide Construction Specifications

Port pavement engineers often use local, state, or provincial construction standards for the subbase and base specifications. The following is offered as a guide in lieu of these specifications.

Capping Layer, Subbase, and Granular Base Materials

Pavements constructed over subgrades with a California Bearing Ratio (CBR) of less than 5% will require a capping layer between the subgrade and the subbase. Capping material is low-cost locally available material with a minimum laboratory CBR of 15% with a maximum Plasticity Index (PI) of 10. The material should be compacted to 100% standard Proctor density if cohesive or to at least 95% standard Proctor density if non-cohesive. Cement or lime stabilization of existing subgrade material may be used. Table 15 on shows capping thicknesses required for different CBR values.

Granular Subbases and bases should be constructed using crushed rock or slag. Base and subbase material should conform to ASTM D2940, Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports. Subbase material up to 8 in. (200 mm) compacted thickness may be spread in one layer so that after compaction the total thickness is as designed. Subbase material of greater compacted thickness than 8 in. (200 mm) should be laid in two or more layers and the minimum compacted thickness of any such layer should be 4 in. (100 mm). Subbases should be compacted to a minimum of 98% modified Proctor density.

The recommended level of compaction required for granular base materials is at least 98% modified Proctor density. Compaction should be completed as soon as possible after the material has been spread. At the completion of compaction, the surface of every layer of material should be closed, free from movement under compaction equipment or tires from construction equipment. It should also be free from ridges, cracks, loose material, potholes, ruts, or other defects. All loose, segregated, or otherwise defective areas should be removed to the full thickness of the layer, and new material placed and compacted. The surface tolerance of granular base under CTB should be ± 1/2 in. (13 mm) over a 10 ft (3 m) straightedge.

Cement-treated Base (CTB)

Delivery, Storage and Batching of Concrete Materials - Cement should be kept dry and used in the order in which it is delivered to the site. Ground granulated blast furnace slag or pulverized-fuel ash (PFA) for mixing on site with Portland cement should be delivered separately and stored in separate silos. Different types of cements should be stored separately. Silos for storing PFA should be equipped with aerators to ensure free flow within the silo. Aggregate for the base should be delivered to and stored on the site in one of the following ways:

(i) in separate nominal single sizes of coarse aggregate and fine aggregate
(ii) as graded coarse and fine aggregates of appropriate size.
(iii) as aggregate for concrete of compressive strength 3,000 psi (20 MPa) or below.

Aggregate brought on to the site should be kept free from contact with deleterious matter. Fine aggregate nominally below No. 4 (6 mm) sieve should have been deposited at the site for at least 8 hours before use. Batching equipment and storage of aggregate should comply with the following requirements as appropriate to the method of delivery:

(i) If separate gradations of aggregate are stockpiled, separate accommodation should be provided for each nominal size of coarse aggregate or blend of fine aggregate. The area under stockpiles should be hard surfaced to prevent contamination of the aggregate. Drainage of the stockpiled bases should be provided.
(ii) Aggregate should be measured by mass and provision should be made for batching each nominal size or blend of aggregate separately.
(iii) All aggregate should be delivered and stockpiled in such a manner that avoids segregation.

Mixing cement-treated base - CTB should be mixed on site in a stationary batch type mixer unless ready-mixed concrete is supplied from an approved source.

Transport and Delivery - Freshly mixed CTB may be transported in dump trucks or ready-mix trucks. The mixed material should be covered during transit and while awaiting discharge to prevent wetting by rain or evaporation of moisture. It should be transported and delivered so that segregation or loss of the materials is minimal.

Construction by Machine - Cement-treated bases should be constructed in a continuous process by slip-form, fixed form paving equipment, laser guided screeding machines, small paving machines, or by hand-guided methods. The base may be constructed in one, two or three layers. In two- or three-layer construction, the thickness of the top layer should not be less than 2 in. (50 mm) or twice the maximum size of the course aggregate, whichever is greater.

Compacting - Compaction should be carried out immediately after the cement-treated base has been spread and in such a manner as to prevent segregation. Special care should be taken to obtain full compaction in the vicinity of both longitudinal and transverse construction joints. Compaction is to be completed within two hours of the addition of cement. Laboratory density should be verified and reported to the engineer per ASTM D558, Moisture-Density Relations of Soil-Cement Mixtures, and verified in the field using ASTM D1556 (sand-cone method), D2167 (rubber balloon method), or D2922 (nuclear method). Field densities of at least 98% of laboratory density are recommended. ASTM D560 may be used to evaluate the reaction of the compacted CTB samples to freeze and thaw.

After compaction has been completed, compacting equipment should not bear directly on cement-bound material for the duration of the curing period. On completion of compaction and immediately before overlaying, the surface of any layer of cement-bound material should be closed, free from movement under compaction equipment, and free from ridges, cracks, loose material, potholes, ruts or other defects. All loose, segregated or otherwise defective areas should be removed to the full thickness of the layer, and new cement-bound material laid and compacted. The surface tolerance of the finished CTB should ± 3/8 in. (10 mm) over a 10 ft (3 m) straightedge.

Curing - Cement treated bases should be cured for a minimum period of 7 days by the application of an approved resin-based aluminized curing compound, or polyethylene sheets, or an approved sprayed plastic film which hardens to a plastic sheet capable of peeling. Insulation blankets may be used for accelerated curing to achieve high early strength for early use by vehicles. Samples should be tested for compressive strength prior to placement per ASTM D1632, Standard Practice for Making and Curing Soil-Cement Compression Flexure Test Specimens in the Laboratory and per ASTM D1633, Standard Test Method for Compressive Strength of Molded Soil-cement Cylinders.

Trial Areas - The Contractor should demonstrate the materials, mix proportions, equipment, equipment and methods of construction that are proposed for the cement-treated base, by first constructing a trial area of base of at least 2,000 ft^2 (200 m^2). The mix proportions decided by trial mixes may be adjusted during the trial but should not be changed once the trial area has been adopted. The trial area should be constructed in two portions over a period comprising at least a portion of two separate working days, with a minimum of 600 ft^2 (60 m^2) constructed each day. The trial area should be constructed at a similar rate to that which is proposed for the base construction. The trial area should comply with the project specification in all respects and, providing the trial area is accepted, it may be incorporated into the main area of the base.

Further guidance on the construction of CTB is provided in the Portland Cement Association publication, *Guide to* Cement-*treated Base*, EB236, from http://secement.org/wp-content/uploads/2017/04/EB236.pdf.

Interlocking Concrete Pavers and Bedding Sand

The following is a guide specification for the installation of concrete pavers and bedding sand. This guide specification is available in Word format on www.icpi.org for downloading and editing to project conditions.

SECTION 32 14 13
MECHANICALLY INSTALLED INTERLOCKING CONCRETE PAVEMENT

Note: This is a guide specification for installation of interlocking concrete pavers in the U.S. using mechanical equipment. This document is intended for large road, industrial and port pavements involving engineers, project inspectors, general contractors, paver installation contractors, and paver manufacturers. Like every large paving project, mechanical installation of interlocking concrete pavements requires forethought and planning among all these parties from its inception. This specification should be used as a tool to facilitate that planning process, as well as for quality control and quality assurance processes during the project. ***The text must be edited by a qualified, licensed design professional to suit specific project requirements. ICPI makes no representations or warranties of any kind, expressed or implied, and disclaims any liability for damages resulting in the use of this guide construction specification.***

Notes are provided for consideration in the editing process. Selected paragraphs and phrases are [bracketed] for editing during project planning and drafting this specification. The following should be read as preparation for editing this guide specification: ICPI Tech Spec 11 Mechanical Installation of Interlocking Concrete Pavements *and ICPI Tech Spec 15* A Guide for the Specification of Mechanically Installed Interlocking Concrete Pavements, *as well as ICPI Tech Spec 17* Bedding Sand Selection for Interlocking Concrete Pavements in Vehicular Applications. *Structural design for street pavements is covered in ICPI Tech Spec 4* Structural Design of Interlocking Concrete Pavements *and in ASCE 58-16* Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways.

The term Contractor designates the general contractor, Subcontractor designates the concrete paver installation subcontractor, and Manufacturer designates the concrete paver producer or supplier. The contractual relationships among the Owner, Engineer, General Contractor, Subcontractors, and Manufacturers will vary with each project. This document assumes that the Engineer works for the Owner who hires a General Contractor to build the project. The General Contractor subcontracts to a company specializing in interlocking concrete paving. The Subcontractor purchases pavers from a paver Manufacturer. The Engineer or employees working for the owner inspect and accept the paving. This guide specification provides a Quality Control Plan and mock-up as the bases of acceptance before paving begins.

PART 1 – GENERAL

1.01 SUMMARY
- A. Section includes:
  1. Interlocking concrete pavers (mechanically installed).
  2. Bedding sand and joint filling sands.
  3. Joint sand [sealer] [stabilization] materials.

B. Related Sections
1. Section [ ] - Earthwork and Aggregate Base.
2. Section [ ] - Cement-treated Base.
3. Section [ ] - Asphalt-treated Base.
4. Section [ ] – Asphalt Concrete Paving
5. Section [ ] - Portland Cement Concrete Paving.
6. Section [ ] - Drainage Appurtenances.
7. Section [ ] – Concrete Curbs.

1.02 REFERENCES

A. American Society of Civil Engineers (ASCE)
1. 58-16 Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways.

B. American Society for Testing Materials (ASTM)
1. C33 Specification for Concrete Aggregates.
2. C136 Method for Sieve Analysis for Fine and Coarse Aggregate.
3. C140 Sampling and Testing Concrete Masonry Units.
4. C144 Standard Specification for Aggregate for Masonry Mortar.
5. C418 Test Method for Abrasion Resistance of Concrete by Sandblasting.
6. C936 Specification for Solid Interlocking Concrete Paving Units.
7. C1645 Standard Test Method for Freeze-thaw and De-icing Salt Durability of Solid Concrete Interlocking Paving Units.

C. Interlocking Concrete Pavement Institute (ICPI)
1. Port and Industrial Pavement Design with Concrete Pavers – Second Edition.
2. Tech Spec 4 Structural Design of Interlocking Concrete Pavements.
3. Tech Spec 5 Cleaning, Sealing and Joint Sand Stabilization of Interlocking Concrete Pavement.
4. Tech Spec 11 Mechanical Installation of Interlocking Concrete Pavements.
5. Tech Spec 15 A Guide for the Specification of Mechanically Installed Interlocking Concrete Pavements.
6. Tech Spec 17 Bedding Sand Selection for Interlocking Concrete Pavements in Vehicular Applications

1.03 DEFINITIONS

A. Wearing surface: Top surface of the paver surrounded by a chamfer.
B. Wearing course: Surfacing consisting of interlocking concrete pavers and joint sand on a sand bedding layer.
C. Interlock: Frictional forces between pavers which prevent them from rotating or moving horizontally or vertically in relation to each other.
D. Bedding course: A screeded sand layer on which the pavers are bedded.
E. Laying face: Working edge of the pavement where the laying of pavers occurs.
F. Base: Layer(s) of material under the wearing course.
G. Cluster: A group of pavers forming a single layer that is grabbed, held, and placed by a paver-laying machine on a screeded sand bedding course.
H. Bundle: Paver clusters stacked vertically, bound with plastic wrap and/or strapping, and tagged for shipment to and installation at the site. A bundle may or may not be secured to a wooden pallet. Bundles of pavers are also called cubes of pavers.

Note: Concrete paver bundles supplied without pallets can reduce material handling costs. In such cases, bundles are strapped together for shipment then delivered and transported around the site with clamps attached to various wheeled equipment. The Subcontractor may provide some wooden pallets at the site to facilitate movement of bundles.

I. Joint filling sand: Sand used to fill spaces between concrete pavers.
J. [Joint sand sealer: A liquid capable of penetrating joint sand and holding it in place upon curing.] [Joint sand stabilizer: water-activated polymers mixed with sand that help render it immobile.]

Note: Edit the following four articles per the General Conditions of the Contract.

K. Owner: The project owner, manager, or a representative of the Owner such as a project Engineer.
L. Contractor: General Contractor responsible for selected work and coordination of work by subcontractors including the paving installation subcontractor.

M. Subcontractor: A paving installation company who enters into a contract with the General Contractor to install bedding sand, interlocking concrete pavers, joint sand and accessory materials or work as indicated in the project contract.
N. Manufacturer: Producer of interlocking concrete pavers for mechanical installation on the project. The manufacturer typically enters into an agreement with Subcontractor to supply pavers. In some cases, the supply agreement can be with the General Contractor or project Owner.

1.04 SUBMITTALS

A. 4 pavers with the date of manufacture marked on each
B. Manufacturer's catalog cut sheets and production mold drawings.
C. The stitching pattern for joint clusters when the pavers are placed on the bedding sand.
D. 6 lbs (3 kg) bedding sand.
E. 3 lbs (1.5 kg) joint filling sand.
F. [Manufacturer's catalog cut sheets of joint stabilization material].

Note: Joint sand sealer and stabilization materials are optional and are selected if early stabilization of joint sand is desired.

G. [1-quart (1-liter) joint sand stabilizer].
H. Quality Control Plan.

1.05 QUALITY CONTROL PLAN

A. General

The Contractor shall provide the Engineer, Subcontractor, and Manufacturer with a Quality Control Plan describing methods and procedures that assure all materials and completed construction submitted for acceptance conform to contract requirements, The Plan applies to specified materials manufactured or processed by the Contractor or procured from subcontractors or manufacturers. The Contractor shall meet the requirements in the Plan with personnel, equipment, supplies and facilities necessary to obtain samples, perform and document tests, and to construct the pavement.

The Contractor shall perform quality control sampling, testing, and inspection during all phases of the work, or delegate same, at a rate sufficient to ensure that the work conforms to the Contract requirements. The Plan shall be implemented wholly or in part by the Contractor, Subcontractor, Manufacturer, or by an independent organization approved by the Engineer. Regardless of implementation of parts of Plan by others, its administration, including compliance and modification, shall remain the responsibility of the Contractor.

B. Pre-construction Conference

The Plan shall be submitted to the Engineer at least [30] days prior to the start of paving. The Contractor, paving Subcontractor, and Manufacturer shall meet with the Engineer prior to start of paving to decide quality control responsibilities for items in this Section. The Engineer shall determine meeting time and location.

C. The Plan shall include as a minimum:
   1. Quality Control organization chart.
   2. Names, qualifications, addresses, email and telephone contact information of responsible personnel.
   3. Area of responsibility and authority of each individual.
   4. A listing of outside testing laboratories employed by the Contractor and a description of the services provided.
   5. Indicate tests performed by Contractor personnel.
   6. Preparation and maintenance of a Testing Plan containing a listing of all tests to be performed by the Contractor and the frequency of testing.
   7. Procedures for ensuring tests are conducted according with the Plan including documentation and that corrective actions when necessary.

D. Quality Control Plan Elements

Note: Testing laboratories should have on-site facilities for testing bedding and joint sands.

   1. Independent testing laboratory(ies) Plan includes, but is not limited to the following:
      a. A letter certifying calibration of the testing equipment to be used for the specified tests.

b. Upon approval of the Engineer, perform testing of samples prior to commencement of paving to demonstrate their ability to meet the specified requirements.

2. Paver manufacturer, facilities, and paver transport to the site
    a. Provide evidence of experience in the manufacture of interlocking concrete pavers including history of supplying projects of similar application and size.
    b. Include project references in writing with contact information for verification.
    c. The project history and references shall demonstrate ability to perform the paver installation and related work indicated in the plans and specifications to the satisfaction of the Engineer.
    d. List the personnel and experience producing pavers for this project.
    e. Describe ability to manufacture, cure, package, store, and deliver the concrete pavers in sufficient quantities and rates without delay to the project.
    f. Provide diagrams and photos showing the number and stacked height of pavers on pallets, or in bundles without pallets, banding of the pavers, use and placement of plastic wrap, pallet dimensions and construction, and overall loaded pallet or bundle dimensions.
    g. Provide a storage and retrieval plan at the factory and designate transportation routes to the site.

Note: Paver purchasing typically includes the price of shipment and delivery to the site, i.e., F.O.B. at the site. On occasion, the purchase price may be F.O.B. at the plant. The Contractor and Subcontractor should verify the terms of the purchase and delivery with the manufacturer.

    h. Description of the transportation method(s) of pavers to the site that incurs no shifting or damage in transit that may result interference with and delay of their installation.
    i. Typical daily production and delivery rate to the site for determining on-site testing frequencies.
    j. Test results from test conducted within [one (1) year] of the project contract demonstrating the capability of the manufacturer to meet the requirements of ASTM C936.

3. Manufacturer quality control of paver dimensional tolerances - General
    Provide a plan for managing dimensional tolerances of the pavers and clusters so as to not interfere with their placement by paving machine(s) during mechanical installation. The contents of this plan include, but are not limited to the following:
    a. Drawings of the manufacturer’s mold assembly including overall dimensions, pattern, dimensions of all cavities including radii, spacer bars, and the top portion of the mold known as a head or shoe.
    b. The actual, measured dimensions of all mold cavities prior to manufacture of concrete pavers for this project.

Note: Production mold wear is a function of the concrete mix, mold steel, and production machine settings. A manufacturer manages growth in paver size typically through use of several production molds. These should be rotated through the production machine(s) on an appropriate schedule so that all experience approximately the same amount of wear on the inside of the mold cavities. The number of production molds utilized for a project will increase with the size of the project.

    c. Anticipated production cycles per mold and a mold rotation plan.
    d. A statement of how often mold cavities in each production mold will be measured during production and recording thereof.
    e. Production records for each bundle showing at a minimum the date of manufacture, a mix design designation, mold number, mold cycles, and sequential bundle numbers.

Note: Variation in cluster size can make them difficult to install thereby reducing the quality of the pavement while increasing mechanized paving productivity and increasing costs. Following certain procedures during manufacture will reduce the risk of concentrated areas of cluster sizes that will not fit next to previously placed clusters. They are (1) consistent monitoring of mold cavity dimensions and mold rotation; during manufacture, (2) consistent filling of the mold cavities, (3) providing pavers with a water/cement ratio that does not cause the units to slump or produce “bellies” on their sides after the pavers are released from the mold, and (4) moderating the speed of production equipment such that pavers are not contorted or damaged when released from the mold. All of these factors are monitored by regular measurement of the cluster sizes by the Manufacturer and the Subcontractor.

Note: Any device or jig used in the paver production plant to check cluster dimensions should be duplicated in the field for measurements at the site. The sampling frequency should provide at least a 95% confidence level. The ICPI does not recognize the stack test as a means for determining dimensional consistency, i.e., stacking 8 to 10 pavers *on their sides to indicate square sides from a stable column of pavers, or leaning and instability due to bulging sides (i.e., "bellies").*

  f. Provide the method and sampling frequency for measuring the overall length and width of clusters at the factory and in the field. Provide written agreement among Owner, Contractor, Subcontractor, and Manufacturer.
4. Subcontractor quality control procedures include, but are not limited to the following:
  a. Demonstrate installation using mechanical installation by key staff in single projects having a similar application and loads.
  b. Provide mechanical installation project history including references in writing with contact information for verification. The history and references shall demonstrate ability to perform the paver installation and related work indicated in the plans and specifications to the satisfaction of the Engineer.
  c. List the experience and certification of field personnel and management who will execute the work shown on Contract Drawings and specified herein.
  d. Provide personnel operating mechanical installation and screeding equipment on job site with prior experience on a job of similar size.
  e. Provide supervisory personnel on site at all times that hold a current certificate in the ICPI Concrete Paver Installer Certification program.
  f. Report methods for checking slope and surface tolerances for smoothness and elevations.
  g. Record actual daily paving production, including identifying the location and recording the number of bundles installed each day.
  h. Show diagrams of proposed areas for storing bundles on the site, on-site staging of storage and use, and the starting point(s) of paving the proposed direction of installation progress for each week of paving.
  i. Provide the number of paver installation machines to be present on the site and anticipated average daily installation rate in square feet (m^2).

Note: The Subcontractor and Manufacturer should hold memberships in the Interlocking Concrete Pavement Institute.

1.06 MOCK-UP

Note: Mock-up size should be at least 1000 sf (100 m). Adjust area below to an area appropriate for the job.

A. Initially construct a mock-up at least [1,000 sf (100 m^2)] with sand, pavers, [and sealer(s)] as specified.
B. Locate mock-up on project site as directed by the Engineer.
C. Demonstrate use of all mechanical installation and screeding equipment.
D. Demonstrate quality of workmanship that will be produced for the remainder of the project including cut pavers at edges, paver border courses, paver pattern(s) in the field of pavement, laying face configuration, cluster placement and offsets, [stitching of half or full pavers among clusters,] pattern direction, typical surcharge and compaction depth of bedding sand and pavers, typical joint widths, joint lines, joints filled with sand, [typical depth of sealer penetration in joints].
E. Notify Engineer in advance of dates when mock-up will be erected.
F. Obtain Engineer's acceptance of mock-up(s) in writing before start of paving.
G. Retain and maintain mock-up during construction in undisturbed condition as a standard for judging work.
H. Accepted mock-up in undisturbed condition at time of substantial completion may become part of completed work.

1.07 DELIVERY, STORAGE AN
1.08 D HANDLING

A. All required testing for products or materials shall be completed and approved in writing by the Engineer and received prior to delivery of that product or material to the site.
B. Deliver concrete pavers, sand, or any other material to the site in such a way that no damage occurs to the product during hauling or unloading.
C. Deliver all pavers to the site in a manner that maintains reasonable variation in cluster size. Stage them on the site as per the Plan.
D. Identify each bundle of pavers with a weatherproof tag. Mark each tag with the manufacturer, the date of manufacture, the mold number, the project [project phase,] for which the pavers were manufactured, and the

sequential bundle number. Any breaks in numbering shall be reported immediately by the Manufacturer to the Subcontractor, Contractor, and Engineer in writing.

E. Deliver joint sand to the site. Protect from wind and rain.

F. Subcontractor equipment and processes shall not interfere with other site operations.

1.09 ENVIRONMENTAL CONDITIONS

A. Do not install sand and pavers during heavy rain or snowfall.

B. Do not install sand and pavers on frozen granular base material

C. Do not install frozen sand.

D. Do not install pavers on saturated or frozen sand.

E. Do not install joint sand during conditions where it might become damp.

PART 2 - PRODUCTS

2.01 CONCRETE PAVERS

A. Size

Length: [ ] Width: [ ] Thickness: [ ]

Note: Spacer bars are required mechanical installation and are not included in the overall dimensions.

B. Manufactured by ICPI member: [name, address, phone, fax, email]

C. Meet the following requirements in ASTM C936:

1. Absorption: 5% average with no individual unit greater than 7% per ASTM C140.
2. Abrasion resistance: No greater volume loss than 0.915 in.^{3} per 7.75 in.^{2} (15 cm^3 per 50 cm^2) and average thickness loss shall not exceed 3 mm (0.118 in.) when tested in accordance with Test Method ASTM C418.

Note: Sometimes the project schedule requires that pavers be installed at job site prior to 28 days. If that is the case, the manufacturer can develop strength-age curves to demonstrate the relationship of compressive strength at 3, 7 or 14 days with respect to what the strength will be at 28 days.

Note: Delete article D3 on freeze-thaw testing below and edit D5, D6 and D7 for projects in non-freezing climates.

3. [Freeze-thaw deicing salt durability: average weight loss not exceeding 225 g/m^2 of surface area after twenty-eight (28) cycles or 500 g/m^2 after forty-nine (49) cycles.]
4. Dimensional tolerances: Length and width shall not exceed ±0.5 mm from specified dimensions, excluding spacer bars. Height shall not exceed ±1/8 (3 mm) from specified dimensions. Check dimensions with calipers.
5. Color(s): [Natural gray without the use of pigments].

D. Quality Assurance Testing

1. Employ an independent testing laboratory qualified to undertake tests in accordance with the applicable standards specified herein.

Note: The General Conditions may specify who pays for testing. It is recommended that the General Contractor be responsible for all testing. Coordinate the article below with the General Conditions of Contract.

2. Provide all test results to the Engineer, Contractor, Subcontractor, and Manufacturer. Cost of tests shall be paid by the [ ].
3. Provide all test results, pass or fail, in writing within one working day of completion of tests. Immediately notify the Engineer, Contractor, Subcontractor, and Manufacturer if any test results do not meet those specified.
4. Test for absorption, density, compressive strength and dimensional variations per ASTM C140. Use the sampling frequencies below.

Note: The ASTM C1645 freeze-thaw durability test requires several months to conduct. Often the time between manufacture and time of delivery to the site is a matter of weeks or days. In such cases, the Engineer may consider *reviewing freeze-thaw deicing salt test results from pavers made for other projects with the same mix design. These test results can be used to demonstrate that the manufacturer can meet the freeze-thaw durability requirements in ASTM C936. Once this requirement is met, the Engineer should consider obtaining freeze-thaw durability test results on a less frequent basis than stated here.*

5. [Test according to ASTM C1645 for freeze-thaw deicing salt resistance using a 3% saline solution with the lowest temperature in each freezing cycle reaching –15° C.]

Note: The number of pavers sampled for testing will depend on whether freeze-thaw deicing salts tests are conducted. Adjust sampling frequency below as needed.

6. For the initial testing frequency, randomly select [fourteen (14)] full-size pavers from initial lots of [25,000 sf (2,500 m^2)] manufactured for the project, or when any change occurs in the manufacturing process, mix design, cement, aggregate or other materials.

Note: 25,000 sf (2,500 m^2) approximates an 8-hour day's production by one paver manufacturing machine. This can vary with the machine and production facilities. This quantity and the sample size should be adjusted according to the daily production or delivery from the paver supplier. Consult the paver supplier for a more precise estimate of daily production output. Initial sampling and testing of pavers should be from each day's production at the outset of the project to demonstrate consistency among aggregates and concrete mixes.

7. Test five (5) pavers for dimensional variations, three (3) pavers for density and absorption; and three (3) pavers for compressive strength [and (3) pavers for freeze-thaw durability].
8. If all tested pavers pass all requirements for a sequence of [125,000 sf (12,500 m^2)] of pavers, then reduce the testing frequency for each test to 1 (one) full-sized paver from each [25,000 sf (2,500 m^2)] manufactured. If any pavers fail any of these tests, then revert to the initial testing frequency in paragraphs 3 and 4 above.

Note: 125,000 sf (12,500 m^2) approximates 5 days of production by one paver manufacturing machine. This can vary with the machine and production facilities. This quantity and the sample size should be adjusted according to the daily production or delivery from the paver supplier. Consult the Manufacturer for a more accurate estimate of 5-day or one week's production output.

9. The entire cluster [bundle] of pavers from which the tested paver(s) were sampled shall be rejected when any of the individual test results fails to meet the specified requirements. Additional testing from clusters [bundles] manufactured before and after the rejected test sample to determine, to the satisfaction of the Engineer, the sequence of the paver production run that should be rejected. Any additional testing shall be performed at no cost to the owner.

Note: The extent of nonconformance of test results may necessitate rejection of entire bundles of pavers or larger quantities. The Engineer may need to exercise additional sampling and testing to determine the extent of non-conforming clusters and/or bundles of pavers, and base rejection of clusters of entire bundles on those findings.

2.02 BEDDING SAND

A. Conform to gradation of ASTM C33 with modifications as noted in Table 1. Supply washed, natural or manufactured, angular sand that conforms to the grading below.

Table 1
Grading Requirements for Bedding Sand
ASTM C33

Sieve Size	Percent Passing
3/8 in.(9.5 mm)	100
No. 4 (4.75 mm)	95 to 100
No. 8 (2.36 mm)	85 to 100
No. 16 (1.18 mm)	50 to 85
No. 30 (0.600 mm)	25 to 60

No. 50 (0.300 mm)	10 to 30
No. 100 (0.150 mm)	2 to 10
No. 200 (0.075 mm)	0 to 1

1. Conduct gradation test per ASTM C136 for every [10,000 sf (1,000 m^2)] of wearing course or part thereof.
2. Testing intervals may be increased upon written approval by the Engineer when sand supplier demonstrates delivery of consistently graded materials.

B. Pass the following degradation test:

1. Obtain a representative sample weighing 3 lbs (1.5 kg). The samples shall be dried for 24 hours or to a constant weight in a thermostatically controlled oven at a temperature of 240-250° F.
2. Obtain three sub-samples each weighing one-half pound by passing the main sample several times through a riffle box. Conduct a sieve analysis test in accordance with ASTM C136 on each sample.
3. Remix each sub-sample and place in a 4 3/4 in. (120 mm) diameter quart nominal capacity porcelain jar together with two 1 in. (25 mm) diameter steel ball bearings each with a mass of 75 ± 5 grams.
4. Place each jar on a bottle roller to rotate at 50 rpm for a period of six hours.
5. Repeat the sieve analysis on each sub-sample.
6. Report the individual and mean sieve analysis. The samples shall comply if the maximum average increase in the percentages passing each sieve and the maximum individual percent passing are as follows:

Sieve Size	Max. Increase	Max. % Passing
No. 200 (0.075 mm)	2%	2%
No. 100 (0.150 mm)	5%	15%
No. 50 (0.300 mm)	5%	35%

7. Repeat the test for every [250,000 sf (25,000 m^2)] of bedding sand or when there is a change in sand source.

2.03 JOINT FILLING SAND

A. Conform to gradation of ASTM C144 with modifications as noted in Table 2.

Table 2
Grading Requirements for Joint Filling Sand
ASTM C144

Sieve Size	Percent Passing
No. 4 (4.75 mm)	100
No. 8 (2.36 mm)	95 to 100
No. 16 (1.18 mm)	70 to 100
No. 30 (0.600 mm)	40 to 75
No. 50 (0.300 mm)	10 to 35
No. 100 (0.150 mm)	2 to 15
No. 200 (0.075 mm)	0 to 5

B. Conduct gradation test per ASTM C136 for every [10,000 sf (1,000 m^2)] of concrete paver wearing course.

C. Testing intervals may be increased upon written approval by the Engineer when sand supplier demonstrates delivery of consistently graded materials.

Note: Sealer or stabilization materials for joint filling sand are optional. They help achieve early stabilization of joint sand. Delete the article below if no joint sealer or stabilization materials are specified.

2.04 [JOINT SAND SEALER] [STABILIZER]

A. [Liquid sealer: 24-hour cure time, capable of penetrating joint sand to a minimum depth of 0.5 in (13 mm) prior to curing as manufactured by [Specify]].

B. [Polymeric joint sand stabilizer as manufactured by [Specify]].

PART 3 – EXECUTION

3.01 EXAMINATION

Note: The elevations and surface tolerance of the base determine the final surface elevations of concrete pavers. The paver installation contractor cannot correct deficiencies in the base surface with additional bedding sand or by other means. Therefore, the surface elevations of the base should be checked and accepted by the General Contractor or designated party with written certification of compliance to project specifications provided to the paving Subcontractor prior to placing bedding sand and concrete pavers.

A. Acceptance of Site Conditions - Contractor shall inspect, accept and certify in writing to the Subcontractor that site conditions meet specifications for the following items prior to installation of interlocking concrete pavers:
   1. Subgrade preparation, compacted density and elevations conform to specified requirements.
   2. Geotextiles [geogrids], if applicable, placed according to drawings and specifications.
   3. [Aggregate] [Cement-treated] [Asphalt-treated] [Concrete] [Asphalt] base materials, thickness, [compacted density], surface tolerances and elevations conform to specified requirements.

Note: Edge restraints (typically concrete curbs) should be in place before pavers are installed. Some projects can have completed curb edge restraints with paving starting from them while the construction of curb(s) opposite from them may be under construction. In such cases, the General Contractor may propose an edge restraint installation schedule for approval by the Engineer at the pre-construction conference.

Note: All bollards, lamp posts, utility covers, fire hydrants and like obstructions in the paved area should have a square or rectangular concrete collar.

   4. Location, type, and elevations of edge restraints, [concrete collars around] utility structures, and drainage inlets.

C. Verify that the surface of the base surface is free of debris, standing water or obstructions prior to placing the bedding sand and concrete pavers.

D. Provide drainage during installation of the wearing course and joint fill sand by means of weep holes per the drawings, temporary drains into slot drains, dikes, ditches, etc. to prevent standing water on the base and in the bedding sand.

E. Inspect all locations of paver contact with other elements of the work, including but not limited to, weep holes, slot drains, edge restraints, concrete collars, utility boxes, manholes, and foundations. Verify that all contact surfaces with concrete pavers are vertical.

F. Areas where clearance is not in compliance or the design or contact faces at adjacent pavements, edges, or structures are not vertical shall be brought to the attention of the General Contractor and Engineer in writing including location information.

G. Remediation method(s) shall be proposed by the General Contractor for approval by the Engineer. All such areas shall be repaired prior to commencing paver installation.

3.02 INSTALLATION

A. Bedding Sand Course:
   1. Screed a uniform layer to a maximum 1 in. (25 mm) thickness. Maintain a uniform thickness within a tolerance of ±1/4 in. (±6 mm). Allow for surcharge and settlement from compaction of the pavers.
   2. Do not expose the screeded bedding course to foot or vehicular traffic.
   3. Fill voids with sand from removal of screed rails as the bedding proceeds.
   4. Do not allow screeded bedding sand to become saturated, displaced, segregated, or consolidated.

B. Concrete Pavers
   1. Locate and secure string lines or snap chalk lines on the bedding sand in the direction of paving at approximately 50 ft (15 m) intervals to establish and maintain joint lines at maximum allowable width of clusters.
   2. Lay paver clusters in pattern(s) as shown on the Plans.

Note: Interlocking patterns such as herringbone patterns are recommended for street, industrial and port pavements. The orientation of the pattern is typically governed by the site layout should be included in the drawings.

3. Lay pavers from the existing laying face or edge restraint in such a manner as to ensure squareness of pattern. This may require hand installation to initiate the pattern for laying clusters.
4. Place machine-laid pavers against the existing laying face.
5. Adjust cluster and pavers with rubber hammers and pry bars to maintain straight joint lines.
6. If the cluster pattern is shipped to the site with half-sized paver units, [adjust locations] [remove and fill openings with full-sized pavers] so that each cluster is stitched and interlocked with adjacent clusters into the designated laying pattern. The resulting final pattern shall be part of the method statement.
7. Hand install a string course of pavers as paving proceeds around all obstructions such as concrete collars, catch basins/drains, utility boxes, foundations, and slabs.

Note: Cutting pavers with mechanical (non-powered) splitters for industrial pavement is an acceptable method as long as joint tolerances can be maintained.

8. Do not allow concrete materials emitted from cutting operations to collect or drain on the bedding sand, joint sand, or in unfinished joints. If such contact occurs, remove and replace the affected materials.
9. Cut pavers subject to tires shall be no smaller than one-third of a full paver.
10. Insert cut pavers into laying pattern to provide a full and complete surface.
11. Straighten joint lines and bring joint widths into conformance with this specification.

Note: Paver compaction equipment typically exerts a minimum centrifugal force of 5,000 lbs or 22 kN. Higher force equipment may be required on pavers over 3 1/8 in. (80 mm) thick.

12. Remove debris from surface prior to initial compaction.
13. Compact the pavers using a vibrating plate compactor with a plate area not less than 2.5 sf (0.2 m^2) that transmits a force of not less than 14 psi (0.1 MPa) at 75 to 100 Hz.
14. After initial compaction, remove cracked or broken pavers, and replace with whole units.

Note: Initial compaction should occur within 6 ft (2 m) of all unrestrained edges at the end of each day. However, large areas of paving are placed each day and often require inspection by the Engineer or other owner's representative prior to initial and final compaction. In these cases, the total allowable uncompacted area should be decided by the Engineer based on the daily production of the Subcontractor, inspection schedules, and weather. Edit article below to reflect maximum distance to laying face for uncompacted pavers.

15. Initial compaction of the all placed pavers shall be within [6 feet (2 m)] of all unrestrained edges.

C. Joint Filling Sand
1. After initial compaction of the pavers, sweep and vibrate joint sand into the joints until all are filled to the top and sand is consolidated in the joints.
2. Complete vibration and filling joints with sand to within [6 ft. (2 m)] of any unconfined edge at the end of the day.

Note: Joint sand should be spread on the surface of the pavers in a dry state. If is damp, it can be allowed to dry before sweeping and vibration so it can enter the joints readily.

Note: If joint sealer or stabilizer is not specified, excess joint sand may remain on the paver surface until proof rolling occurs for commercial projects. However, the extent of sand on the surface should not obscure observation of joints such that those with unconsolidated sand in them cannot be identified by visual inspection. For large paving projects, removal of excess sand after filling the joints may be necessary to prevent displacement by wind.

D. Proof Rolling
1. After compaction, remove loose sand and debris from the surface.
2. Engineer shall accept consolidation of joint filling sand in the joints prior to proof rolling.
3. Proof roll the pavement with a minimum 30-ton (27 T) rubber-tired roller with offset wheels.
4. Make a minimum of four passes with a static roller.
5. If sand levels in joints fall after proof rolling, add joint filling sand.
6. Sweep area clean and proof roll again until no change occurs in joint sand levels.

7. Clean the surface on completion of proof rolling so it is free from excess sand and any loose debris.

Note: Delete article below if joint sand stabilization materials are not specified for the project.

E. [Joint Sand Stabilization]

1. [Install joint sand stabilizer within [one week] after completion of a proof rolled area. Clean or re-clean the surface prior to the installation of the stabilizer. Install the stabilizer in accordance with the manufacturer's recommendations.]

F. Tolerances on Completion

Note: The minimum joint width is determined by the size of the spacer bar used for the project. This is typically 2 mm. The maximum joint width depends on the paver shape and thickness. Generally, thicker pavers with more than four sides will require slightly larger joints, often 5 to 6 mm. Consult the Manufacturer for the recommended maximum joint width.

1. Joint widths: 2 mm to [5] mm. No more than 10% of the joints shall exceed [5] mm for the purposes of maintaining straight joint lines.

Note: Surface tolerances on flat slopes should be measured with a rigid straightedge. Tolerances on complex contoured slopes should be measured with a flexible straightedge capable of conforming to the complex curves in the pavement.

Note: Surface tolerances may need to be smaller if the longitudinal and cross slopes of the pavement are 1%.

2. Smoothness: [±3/8 in. (10 mm)] over a [10 ft (3 m)] straightedge.
3. Bond or joint lines: ±½ in. (15 mm) within a 50 ft. (15 m) string line.
4. Check final surface elevations for conformance to drawings.

Note: The top surface of the pavers may be 1/8 to 1/4 in. (3 to 6 mm) above the final elevations after compaction. This helps compensate for possible minor settling normal to flexible pavements.

5. The surface elevation of pavers shall be 1/8 in. to ¼ in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels.

3.03 PROTECTION AND CLEAN UP

A. The Contractor shall insure that no vehicles other than those from Subcontractor's work are permitted on any pavers until completion of this unit of Work.

B. Maintain close coordination of vehicular traffic with other contractors working in the area.

C. Protect completed work from damage, fuel or chemical spills, or theft until Final Acceptance. Repair or replace damaged work to original condition, or as directed by the Engineer.

D. Remove all debris and other materials from the pavement.

END OF SECTION

Chapter 4 - Overlays: Principles and Procedures

A well-designed and constructed pavement should remain serviceable for its intended life. During its service life, a pavement is subjected to surface stresses from traffic and to internal stresses caused by thermal and moisture movement. Even a well-designed pavement may be damaged by being overloaded or by being subjected to abnormal internal stresses during severe weather. At some stage the pavement may need to be strengthened, otherwise it will have to be taken out of service.

Immediately following construction of a new area, a survey of the pavement is recommended to establish baseline conditions. This information provides a basis for comparison to surveys taken later in the life of the pavement, and the comparison can help determine when a rehabilitative overlay might be required. The survey should be of the general condition and elevations using instruments accurate to 1 mm. Elevation points are as follows:

(i) rigid concrete: at each corner of each slab.
(ii) asphalt or pavers: one elevation for each 1,000 ft^2 (100 m^2) of paving, at locations possible to re-establish later.

In the case of asphalt or pavers, elevations should be taken in one or more 30 ft x 30 ft (10 m x 10 m) representative areas, using a 3 ft (1 m) grid. There are several standard references for assessing the condition and severity of distresses on asphalt and concrete pavements. Appendix C provides guidelines for interlocking concrete pavements.

In many types of pavement, once deterioration commences, total unserviceability is imminent and rapid degradation takes place over a short time, particularly during severe weather. If rehabilitation occurs before deterioration becomes severe, the residual strength of the existing pavement can be utilized. This can decrease the cost of strengthening while extending pavement life considerably. The time between the onset of degradation and complete failure is rapid, and the difference in cost can rise substantially if strengthening is delayed.

Once the residual strength of a pavement has been assessed, the overlay design must include the thickness and properties of strengthening materials. The purpose of strengthening may be to extend the life of the pavement or to allow an existing pavement to carry heavier equipment. This second reason for strengthening a pavement is of relevance to ports.

This chapter covers both aspects of pavement strengthening, i.e.,

(1) Assessment of residual strength of pavement, and
(2) Selection of thicknesses and properties of additional pavement layers.

Pavement rehabilitation may take place for reasons other than strength, for example to restore skidding resistance or to eliminate ponding. This chapter is concerned only with structural rehabilitation, i.e., to increase the strength of the pavement. The term `overlay' is used to indicate the provision of extra pavement construction material (or materials) in order to strengthen the pavement. The overlay can be additional base placed under an existing installation of interlocking concrete pavements, or concrete pavers placed over existing PCC or asphalt pavement. Overlay procedures for pavers, PCC concrete and asphalt are summarized in Table 11.

Interlocking concrete pavements - If settlement has taken place and the pavers are substantially undamaged, it may be possible to remove them, make repairs to the base, re-screed the bedding sand and re-lay the pavers without disturbing the underlying materials. ICPI Tech Spec 6, *Reinstatement of*

Interlocking Concrete Pavements in the appendices provides further guidance on removal and reinstatement. If the analysis of the existing pavement shows the base thickness to be inadequate, then an additional thickness of base material will be required. The existing pavers may then be removed and re-laid over new base material.

Overlays on PCC pavements - Concrete pavers make a suitable overlay on PCC pavements that exhibit functional distresses, such as spalling or cracking, but are in sound structural condition. In some cases, the slab can be overlaid with asphalt to rehabilitate the surface and provide some structural contribution. In other cases, it may be advantageous to crack and seat the existing PCC and overlay it with asphalt, as well as bedding sand, and pavers. In other cases, cracks and joints in the PCC can be resealed prior to applying geotextile, bedding sand, and concrete pavers. The geotextile prevents migration of the bedding sand into slab joints and cracks. Structural distresses such as cracked slabs with heaving or settlement due to base or subgrade movement should not be overlaid with concrete pavers and bedding sand. Such conditions often require removal and replacement of the PCC pavement.

Overlays on asphalt pavements - Asphalt which has deteriorated should be removed before overlaying pavers and bedding sand. When pavers are overlaid, do not use bedding sand to fill depressions in the surface of the asphalt. This will lead to depressions in the asphalt base reflecting to the surface of the pavers. Should the existing (or remaining) asphalt be in good condition and a greater increase in strength be required, new asphalt may place over the existing surface prior to placing pavers and bedding sand.

Table 11. Suggested alternative overlay techniques for three types of existing pavement.

Concrete Pavers	PCC Pavement	Asphalt Pavement
Remove pavers, make base repairs, re-screed sand and reinstate pavers	Lay concrete or asphalt over slabs, install pavers	Remove asphalt surface and install new pavers
Remove pavers, strengthen (thicken) base and reinstate pavers	Reseal joints, seal cracks and install pavers	Install new pavers over existing or thickened asphalt
Remove worn pavers, remove sand and install replacement pavers	Crack and seat or rubble-ize and recycle, apply asphalt install pavers	

Note: All applications of concrete pavers should include bedding sand. Geotextile may be required under the bedding sand in some overlay applications.

Overlay Design Technique

Techniques used by pavement engineers to assess the strength of existing highway and heavy-duty pavements are:

(1) Falling Weight Deflectometer (FWD) Method
(2) Component Analysis Method (The Asphalt Institute)

The falling weight deflectometer (FWD) has been used extensively in the evaluation of the structural response of highway and heavy-duty pavements. There is a substantial body of literature on FWD calibration, test methods, interpretation of data, and its use in pavement management. This test method measures the elastic deflection in the pavement beneath a mass dropped onto the surface of the pavement. An arrangement of springs converts the impact load into an equivalent load which can range up to 50,000 lb (22,800 kg). The deflection is recorded electronically by sensors (geophones) resting on the surface of the pavement.

Deflection data can be used to calculate pavement material properties, specifically the elastic modulus of the various layers as they interact as a pavement structure. These are entered into a computer model that calculates the strains at the various places in the pavement by comparing the actual deflections measured to those modelled. The process of using the measured deflections to model the elastic properties and strains in the pavement is called back-calculation.

For flexible pavement, those locations where critical strains are modelled are at the bottom of the (stabilized) base and the top of the soil subgrade. Finite element or layered elastic models are used to compute critical stresses and strains in the pavement. The strains are entered into an equation with estimated future loads to predict when the pavement will become fatigued and no longer be serviceable. The analytical method uses structural response (deflection) as a surrogate for estimating the future performance of the pavement.

FWD testing is a useful method for assessing the structural life remaining in a pavement. FWD data should be combined with distress survey data, data from core samples, experience and engineering judgement to obtain an estimate of remaining life. Pavement materials are then selected that will add to the life of the pavement. An FWD is an effective analytical tool for most overlay situations and is highly recommended.

The second method used in this chapter is the Component Analysis Method first introduced by the Asphalt Institute. It is used here because it is fast, inexpensive, and reasonably accurate. The method accounts for functional and structural distresses.

The Asphalt Institute method transforms each course in a pavement to its equivalent thickness of asphalt. A major modification to this method is the transformation of base materials to an equivalent thickness of 1,400 psi (10 MPa) cement-treated base (CTB). This modified method presented below, called The Component Analysis Method, is applicable to both rigid and flexible pavements. The transformation of base materials to an equivalent thickness of CTB is accomplished using Conversion Factors shown in Table 12. These factors are the inverse of the structural layer coefficients in the AASHTO guide. Because CTB is the material to which each course of the pavement is transformed, the method is compatible with the remainder of this manual.

Component Analysis Method

The existing pavement is transformed into an equivalent thickness of 1,400 psi (10 MPa) CTB. The equivalent thickness of CTB is that which would be required to give the same load carrying capability as the existing pavement. The existing pavement constitutes a portion of the pavement to be strengthened. Therefore, it is essential to determine accurately the thickness of each of the existing courses and the degree of degradation that each of these courses has undergone.

If records of the original design of the pavement are not available, it will be necessary to take core samples to obtain this information. Even if records do exist, cores should be taken to verify the as-built condition. These should be taken at a minimum of every 5,000 ft^2 (500 m^2) of pavement. There should be a minimum of three cores and a maximum of seven for larger pavements of uniform construction and condition. In areas used for dissimilar types of traffic, each location should be considered as a separate area for analysis purposes. Similarly, if the initial cores show that certain areas of pavement are stronger than others, it may be preferable to divide the overlay area into several zones and each zone should have at least three cores taken.

In some circumstances, the properties of the pavement materials may have changed since they were initially placed. Change such as cementing action can strengthen the pavement or change such as from the intrusion of materials from another pavement course can weaken the pavement. It is essential to know what kinds of changes occurred in the pavement. Sampling should also be used to determine the condition of each course so that the appropriate Condition Factors may be selected. It may be difficult to assess the condition of lower pavement courses, particularly regarding cracking. In such situations, conservative assumptions should be made.

Once each course has been identified, it is transformed to an equivalent thickness of 1,400 psi (10 MPa) CTB by dividing its actual thickness by the appropriate Material Conversion Factor from Table 12. Most of the materials shown are defined in the AASHTO pavement design guide. The transformed thickness is multiplied by two Condition Factors. Values of the first Condition Factor CF1 are given in Table 13 and are used for both rigid and flexible pavements.

Table 12. Material Conversion Factors for different pavement construction materials.

Pavement Layer	Conversion Factor from 1,400 psi (10 MPa) Cement-treated base
(i) Pavement quality concrete	0.80
(ii) Pavement quality concrete	0.70
(iii) Asphalt Treated Base (Modulus = 350,000 psi) (2,414 MPa)	0.93
(iv) Asphalt Treated Base (Modulus = 170,000 psi) (1,172 MPa)	1.40
(v) Asphalt Treated Base (Modulus = 90,000 psi) (621 MPa)	2.80
(vi) Cement Treated Base (Modulus = 1,100,000 psi) (7,586 MPa)	1.00
(vii) Cement Treated Base (Modulus = 820,000 psi) (5,655 MPa)	1.27
(viii) Cement Treated Base (Modulus = 620,000 psi) (4,276 MPa)	1.75
(ix) Cement Treated Base (Modulus = 470,000 psi) (3,242 MPa)	2.80
(x) Granular Subbase Layer (Modulus = 21,000 psi) (145 MPa)	2.00
(xi) Granular Subbase Layer (Modulus = 13,600 psi) (94 MPa)	2.80
(xii) Granular Subbase Layer (Modulus = 12,000 psi) (83 MPa)	3.00
(xiii) Granular Subbase Layer (Modulus = 7,000 psi) (48 MPa)	4.67

Table 13. Condition Factors for cracking and spalling.

Condition of Material	CF1
As new	1.0
Slight cracking	0.8
Substantial cracking	0.5
Fully alligator cracked and unravelled	0.2

The second Condition Factor, CF2 in Table 14, accounts for reduced strength of each layer from rutting and settlement in the surface of flexible pavements. This is measured as a difference in elevations under a 10 ft (3 m) straight edge. If a pavement has deformed, cores should be taken to determine which courses of the pavement are affected. When there is no deformation or cracking, the Condition Factors are taken as 1.0, i.e. the material is as new. The transformation procedure is carried out for each course in the pavement and the sum of the transformed thicknesses is taken as the equivalent thickness of the existing pavement. The equivalent thickness is used in the design of the overlay.

Table 14. Condition Factors for maximum degree of localized rutting and localized settlement.

Degree of localized rutting or localized settlement in. (mm)	CF2
0 to ½ (0 to 13)	1.0
½ to 1 (13 to 25)	0.9
1 to 3 ¼ (25 to 80)	0.6
$3^1/_4$ + (80 +)	0.3

Pavement evaluation example 1:

A cross section of an existing rectangular pavement 120 ft (36 m) x 300 ft (91 m) is shown in Figure 2.

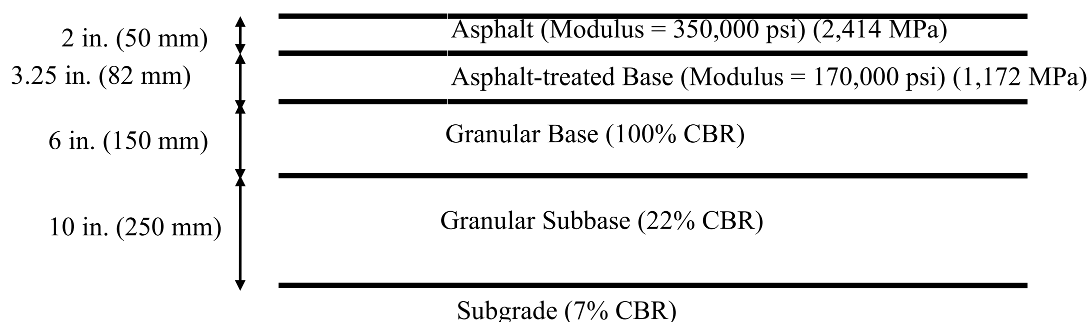


Figure 2

Rutting up to 1.5 in. (40 mm) has developed from shear failure in the granular base. The granular subbase is intact. The hot mix asphalt surfacing has alligator cracks and is unravelled but the underlying asphalt base shows only slight cracking. This description applies to the poorest of 8 core samples. Other samples show no rutting but a similar state of cracking and crazing in the asphalt surface.

From Tables 12, 13, and 14 the following table is constructed showing how each course is transformed to an equivalent thickness of 1,400 psi (10 MPa) CTB and how the thicknesses are added.

Rutted Area

Course	Actual Thickness in. (mm)	Material Conversion Factor	CF1	CF2	Equivalent Thickness of 1,400 psi (10 MPa) cement- treated base in. (mm)
Asphalt	2 (50)	0.93	0.2	0.6	0.26 (7)
Asphalt-treated base	3.25 (82)	1.40	0.8	0.6	1.11 (30)
Granular base	6 (150)	2.00	1.0	0.6	1.80 (45)
Granular Subbase	10 (250)	2.80	1.0	1.0	3.57 (90)
Subgrade CBR 7%		-			
TOTAL					**6.74 (172)**

The analysis shows this pavement to be equivalent to 6.74 in (172 mm) of 1,400 psi (10 MPa) CTB. Cores in other areas give the following analysis where no rutting has taken place, but where slight cracking in the asphalt surface only has occurred.

Non-rutted Area

Course	Actual Thickness in. (mm)	Material Conver-sion Factor	CF1	CF2	Equivalent Thickness of 1,400 psi (10 MPa) cement-treated base in. (mm)
Asphalt	2 (50)	0.93	0.8	1.0	1.72 (44)
Asphalt-treated base	3.25 (82)	1.4	1.0	1.0	2.32 (60)
Granular base	6 (150)	2.00	1.0	1.0	3.00 (75)
Granular Subbase	10 (250)	2.8	1.0	1.0	3.57 (91)
Subgrade CBR 7%					
TOTAL					**10.61 (270)**

This shows that in the non-rutted area, the pavement is equivalent to 10.61 in. (270 mm) of 1,400 psi (10 MPa) CTB. The difference between 10.61 in. (270 mm) and 6.74 in. (172 mm) could be significant in that it may be cost effective to design two thicknesses of overlay, one for the rutted areas and one for the non-rutted area. The asphalt surface is contributing little to the structural integrity of the pavement and may be removed. A cost-effective design may involve removing the asphalt in this rutted area and using the depth so created for strengthening with pavers.

Consider a situation where the chart in Chapter 6 showed that this pavement needs 9 in. (225 mm) of 1,400 psi (10 MPa) CTB. In the non-rutted areas, it would be possible to overlay with pavers or to remove the rolled asphalt and provide pavers as an inlay. In the rutted areas, since the existing pavement is equivalent to only 6.74 in. (172 mm) of 1,400 psi (10 MPa) CTB, a further course of material would be required between the new pavers and the existing material. The additional course would need to be equivalent to 9 - 6.74 = 2.26 in. (60 mm) of 1,400 psi (10 MPa) CTB. The Material Conversion Factors in Table 12 could be used to select an alternative material.

Pavement evaluation example 2:

A cross section of an existing 26 ft (7.8 m) wide by 656 ft (198 m) long road is shown in Figure 3.

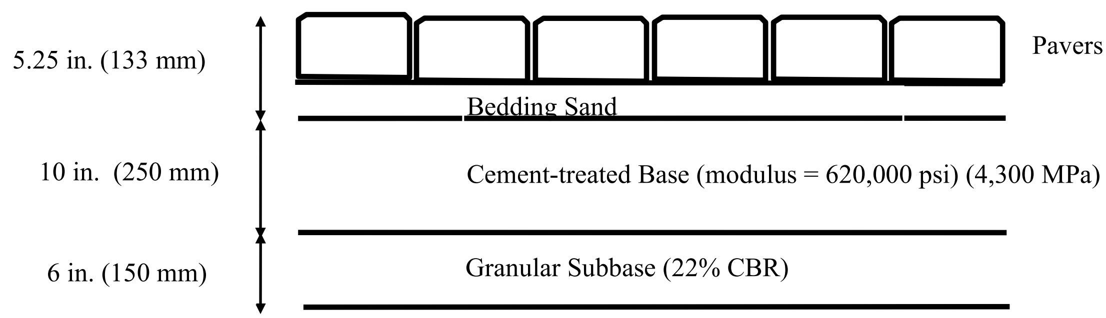


Figure 3

Settlement has taken place in the subgrade resulting in local deformations of 4 in. (100 mm) over much of the pavement. Each course has this amount of settlement. No cracking or spalling has taken place at the surface, although the cement-treated base is cracked substantially. From Tables 12, 13, and 14 the following table can be constructed showing how each course is transformed to an equivalent thickness of CTB, and how the thicknesses of CTB are added.

Course	**Actual Thickness in. (mm)**	**Material Conversion Factor**	**CF1**	**CF2**	**Equivalent Thickness of 1,400 psi (10 MPa) cement-treated base in. (mm)**
Pavers on Sand	5.25 (133)	2.00	1.0	0.3	0.79 (20)
Cement Treated Base	10 (250)	1.75	0.5	0.3	0.86 (22)

Granular Subbase	6 (150)	2.80	1.0	0.3	0.64 (16)
Subgrade CBR 5%					
TOTAL					**2.29 (58)**

The analysis shows this pavement to be equivalent to 2.29 in. (58 mm) of 1,400 psi (10 MPa) CTB. Had the settlement not taken place, the pavement would have been equivalent to 9.25 in. (235 mm) of CTB. In this case, either the pavement was under-designed, or no account was taken of a compressible subgrade material. It is possible that the settlement was predicted when the pavement was originally designed, hence the use of pavers. This pavement is now of little value in terms of its equivalent thickness of 1,400psi (10 MPa) CTB. This analysis indicates that it may be best to recover the pavers (which probably represent the only part of the pavement with any inherent value) and install a new subbase and base prior to reinstalling the pavers. While in some instances reinstallation of used pavers can prove cost-effective, sorting and cleaning costs sometimes outweigh the price of new pavers.

Pavement evaluation example 3

A weakened PCC pavement has previously been strengthened by the application of an asphalt wearing course which is still intact. The port is, however, shortly to take delivery of heavier handling equipment and wishes to upgrade the pavement further. During the first strengthening operation, photographs were taken of the concrete which showed it to be substantially cracked (corner cracking and mid-slab cracking) but not spalled or crazed. Slight reflective cracking has occurred in the asphalt overlay. There is no rutting. The existing pavement is shown in Figure 4.

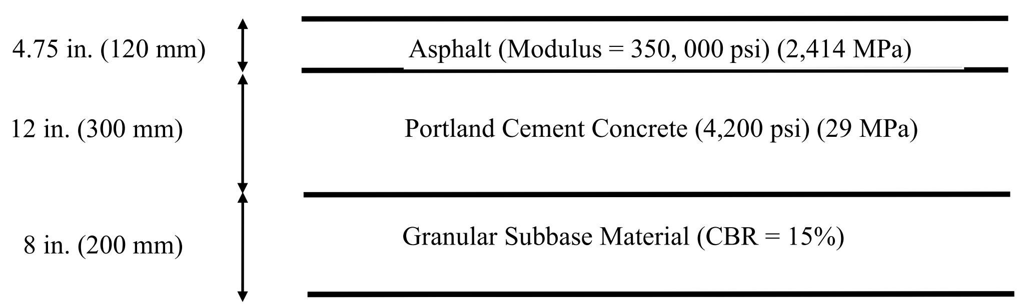


Figure 4

From Tables 12, 13, and 14 the following table is constructed. It shows how each course is transformed to an equivalent thickness of CTB and how the thicknesses are added.

Course	Actual Thickness in. (mm)	Material Conversion Factor	CF1	CF2	Equivalent Thickness of 1,400 psi (10 MPa) cement-treated base in. (mm)
Asphalt	4.75 (120)	0.93	0.8	1.0	4.09 (104)
PCC (4,200 psi) (29 MPa)	12 (300)	0.80	0.5	1.0	7.50 (190)
Granular Subbase (15%CBR)	8 (200)	3.00	1.0	1.0	2.67 (68)
Subgrade CBR 5%					
TOTAL					**14.26 (362)**

The analysis shows this pavement to be equivalent to 14.26 in. (362 mm) of 1,400 psi (10 MPa) CTB. The pavement could be strengthened by installing pavers over the asphalt, but care should be taken to ensure that sand is not lost into the cracked asphalt. A geotextile may be applied to the surface to prevent the loss of bedding sand into the cracks. Alternatively, a paver inlay could be undertaken by removing the asphalt and installing pavers in its place. Care should be exercised in installing pavers directly over cracked concrete. It may be that the slabs are deflecting under wheel loads (especially if corner cracking has developed) in which case, interlock may fail to develop in the pavers and surface instability may occur. It may be preferable to selectively repair the underlying concrete prior to the installation of pavers.

Overlay Design

The basic overlay material types and their properties are as described in Chapter 1. This is demonstrated in the following examples. In order to derive the thickness of the overlay it is first essential to design a new pavement structure for the design criteria required using this manual. The design criteria are:

Design Life
CBR of subgrade
Equivalent Single Load of handling equipment
Type of overlay considered

First, a "new" pavement is designed comprised of a 1,400 psi (10 MPa) CTB with pavers as the surface. The equivalent thickness of the transformed pavement is then subtracted from the thickness of the CTB determined from the design chart in Chapter 6. This gives the thickness required for an overlay. Note that although the method produces an overlay thickness for 1,400 psi (10 MPa) CTB, other materials can be used as the overlay by using material conversion factors from Table 12.

Overlay design example 4

Existing Situation: an existing pavement comprised of a substantially cracked PCC slab overlaying 6 in. (150 mm) of 6% CBR granular subbase material as shown in Figure 5. The pavement has been trafficked by a terminal trailer system. When dynamic factors and wheel proximity factors have been applied, the equivalent single wheel load is 44,000 lb (20,000 kg). The most severely trafficked part of the pavement is subjected to 700 passes per day of a laden terminal trailer. There is no rutting.

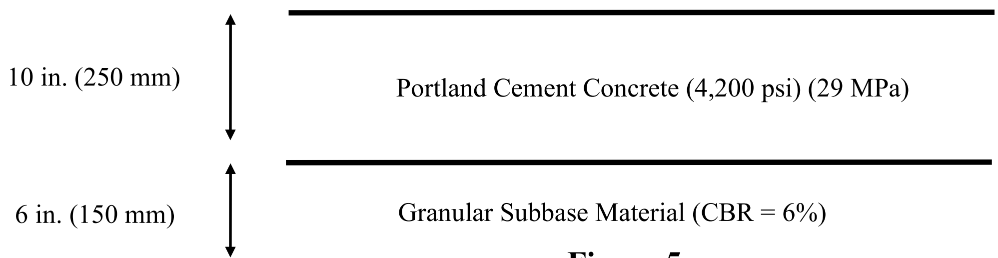


Figure 5

Proposed Use: It is proposed to continue with the same operation and two designs are required. These will be needed for the purposes of cost comparisons, one to last 5 years and one to last 25 years, each for 300 working days.

(i) 5 years - number of repetitions = 700 x 300 x 5 = 1,050,000

(ii) 25 years - number of repetitions = 700 x 300 x 25 = 5,250,000

The Design Chart in Chapter 6 shows that for the 5 years extended life design, a cement-treated base of thickness 10 in. (250 mm) is required, and 14 in. (350 mm) for 25 years of life.

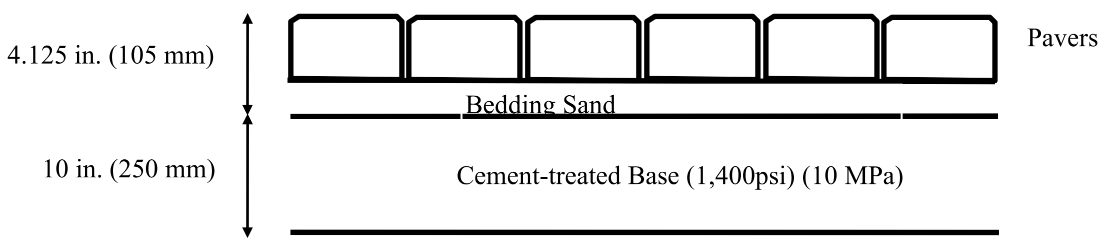


Figure 6. Pavement section required for 5 years' design life

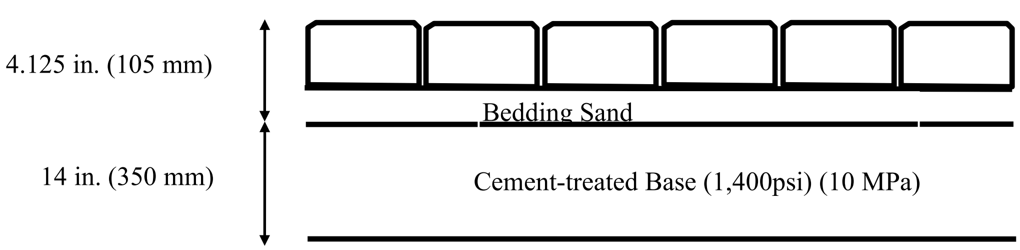


Figure 7. Pavement section required for 25 years' design life

The existing pavement can be converted to its equivalent thickness of cement-treated base in the following table.

Course	Actual Thickness in. (mm)	Material Conversion Factor	CF1	CF2	Equivalent Thickness of 1,400 psi (10 MPa) cement-treated base in. (mm)
PCC concrete	10 (250)	0.80	0.5	1.0	6.25 (159)
6% CBR granular Subbase material	6 (150)	4.67	1.0	1.0	1.28 (33)
Subgrade CBR ≤ 5%					
TOTAL					**7.53 (192)**

Therefore, for each of the two design lives, the additional thickness of 1,400 psi (10 MPa) CTB required is:

(i) 5 years
10 in. (250 mm) - 9 in. (225 mm) = 1 in. (25 mm)

(ii) 25 years
14 in. (350 mm) - 9 in. (225 mm) = 5 in. (125 mm)

The two strengthened pavements would be formed by placing either 5 in. (125 mm) or 1 in. (25 mm) of 1,400 psi (10 MPa) CTB base over the existing pavement, then installing pavers as the surface material. Providing 1 in. (25 mm) of CTB would be impractical and an alternative material should be provided by exchanging the 1 in. (25 mm) of cement-treated base for a greater thickness of an alternative material using the appropriate Material Conversion Factor in Table 12.

Chapter 5 - Design Example

In this example a typical straddle carrier operation is assessed for loading and subsequent use with the Base Thickness Design Chart to produce a pavement section. In the loading calculations, the damaging effect of one side of the item of equipment is considered as explained in this example.

DATA

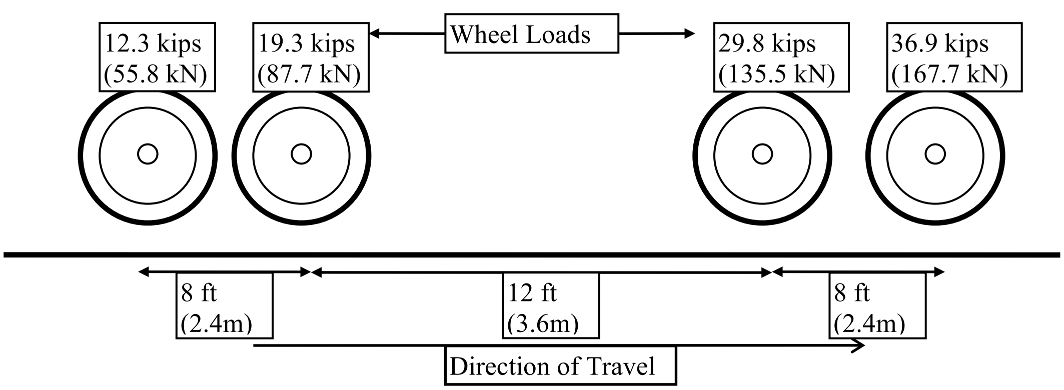
Unladen weight (W_T) of straddle carrier including spreader beam	= 124 kips (56,310 kg)
Critical container weight	= 48.4 kips (22,000 kg)
Track Width	= 15 ft (4.5 m)
Wheel Spacings	= 8 ft - 12 ft - 8 ft = 2.4 m - 3.6 m - 2.4 m (see Diagram)

Number of passes of straddle carriers over the most highly trafficked portion of the pavement during the design life of pavement = 960,000 passes

CBR of soil = 5%

From the information regarding the soil strength and through the use of Table 15 in Chapter 6, the foundation materials can be specified as:

Subbase= 9 in. (225 mm)
Capping not required
Having defined the foundation material properties, the base thickness, which is dependent on the load applied, is now calculated.



Straddle Carrier Wheel Loads During Braking

Total number of wheels on equipment (8)
Wheel load of unladen equipment = 124/8=15.5 kips (56,310/8 = 7,039 kg)
Weight of critical container = 48.4 kips (22,000 kg), see Chapter 1
f_d = Dynamic factor for braking - ±50% for extreme wheels, see next paragraph for inner wheels

Static wheel load = $15.5 + \frac{48.4}{8} = 21.55$ kips ($7{,}039 + \frac{\underline{22{,}000}}{8} = 9789$ kg = 97.9 kN)

The proximity of the wheel loads is now considered to assess their stress interaction using the equation given in Chapter 1 to calculate the effective depth.

$$\textit{Effective Depth} = 300.\sqrt[3]{\frac{35000}{5 \ x \ 10}} = 2664 \text{ mm } (8.73\text{ft})$$

From Table 9, the proximity factor can be interpolated to be 1.14. Therefore, the Effective Static Wheel Load is 21.55 x 1.14 = 24.57 kips (97.9 x 1.14 = 111.6 kN). Consider the worse loading case of braking and apply the appropriate dynamic factor of ± 50% to the wheels at the extreme front and rear, applying the increase in load to the front wheels and the decrease to the rear wheels.

The inner wheel loads need to be similarly adjusted but using a factor lower than ±50% determined by considering the relative distance from the vehicle's center line. In this case, each extreme wheel is 14 ft (4.2 meters) from the center of the vehicle and each inner wheel is 6 ft (1.8 m) from the center. Therefore, the lower braking factor to be applied to the inner wheels is ± 21.4% i.e. (± 50% x 6/14). We now need to express the four load values which will pass over one spot into an equivalent number of passes of the highest wheel load (36.9 kips or 167.7 kN) as follows. The Damaging Effect equation in Chapter 1 is applied to each wheel load in turn:

Front wheel is equivalent to one pass of a load of 36.9 kips (167.7 kN)

Second wheel is equivalent to $(29.8/36.9)^{3.75}$ i.e. 0.45 equivalent passes of the front wheel load.

Third wheel is equivalent to $(19.3/36.9)^{3.75}$ i.e. 0.09 equivalent passes of the front wheel load.

Fourth wheel is equivalent to $(12.3/36.9)^{3.75}$ i.e. 0.02 equivalent passes of the front wheel load.

All of the repetitions are converted to an equivalent number of repetitions of the heaviest wheel so that the Equivalent Single Load used in the design charts is derived from the heaviest wheel load. It would be unsafe to convert wheel loads to one of the equipment's lower wheel load values.

Therefore, each time the straddle carrier passes over one spot, it applies the equivalent of (1+0.45+0.09+0.02) = 1.56 repetitions of the front wheel load of 36.9 kips (167.7 kN). This means that the pavement needs to be designed to accommodate 1.5 million passes (i.e. 1.56 x 960,000) of a load of 36.9 kips (167.7 kN). The base thickness design chart can now be used as follows:

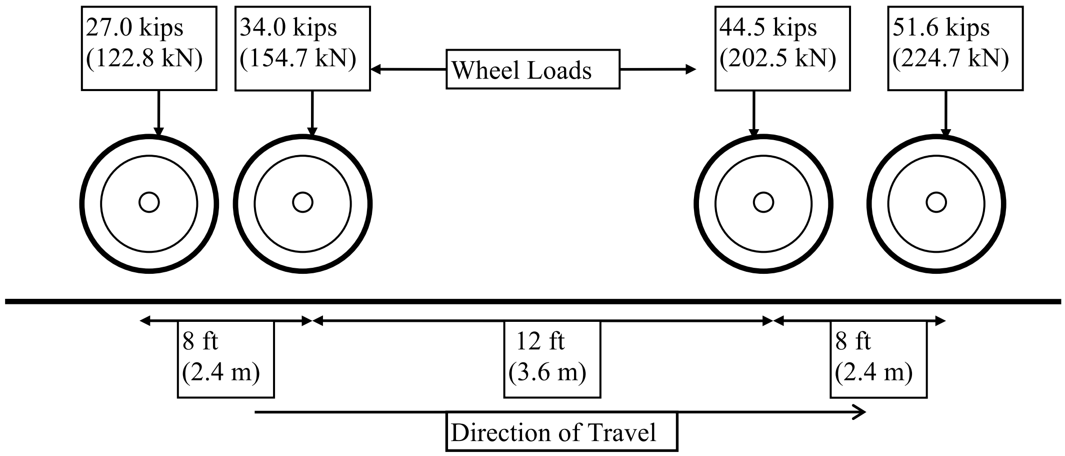
- on the vertical axis, the Equivalent Single Load is 36.9 kips (167.7 kN)
- the appropriate curve is the one corresponding to 1.5 million passes
- the 1,400 psi (10 MPa) CTB thickness corresponding to the above which is read from the horizontal axis on the design chart is 10.5 in (260 mm).

The 10.5 in (260 mm) of 1,400 psi (10 MPa) CTB may be exchanged for an alternative thickness of another material, and examples are given below:

420 psi (2.9 MPa) cement-treated base ⇒ Requires 1.75 x 10.5 = 18.4 in. (470 mm)

Asphalt-treated base (Modulus = 170,000 psi or 1,172 MPa) ⇒ Requires 1.4 x 10.5 = 14.7 in. (370 mm)

Consider how the pavement section required would change if alternative dynamic factors were used. For example, if the straddle carriers were to brake while cornering, the wheel loads would increase by 60% of their static value (i.e. 0.6 x 24.6 = 14.7 kips) so that the wheel loads would be as in the diagram below.



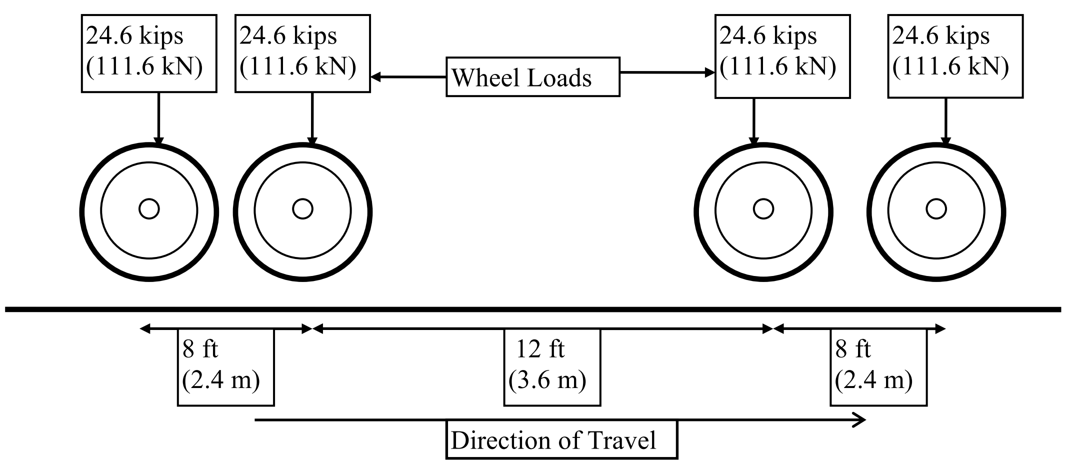
Straddle Carrier Wheel Loads During Braking & Cornering

We now need to express the four load values which will pass over one spot into an equivalent number of passes of the highest wheel load (51.6 kips or 224.7 kN) as follows. The Damaging Effect equation in Chapter 1 is applied to each wheel load in turn:

Front wheel is equivalent to one pass of a load of 51.6 kips (224.7 kN)
Second wheel is equivalent to $(44.5/51.6)^{3.75}$ i.e. 0.68 equivalent passes of the front wheel load.
Third wheel is equivalent to $(34.0/51.6)^{3.75}$ i.e. 0.25 equivalent passes of the front wheel load.
Fourth wheel is equivalent to $(27.0/51.6)^{3.75}$ i.e. 0.10 equivalent passes of the front wheel load.
Therefore, each time the straddle carrier passes over one spot, its outside wheels apply the equivalent of (1+ 0.68 + 0.25 + 0.10) = 2.03 repetitions of the front wheel load of 51.6 kips (224.7 kN). This means that the pavement needs to be designed to accommodate 2 million passes (i.e. 2.03 x 960,000) of a load of 51.6 kips (224.7 kN). The base thickness design chart can now be used as follows:

- on the vertical axis, the Equivalent Single Load is 51.6 kips (224.7 kN)
- a 2,000,000 passes curve has to be interpolated between the 1,500,000 and the 4,000,000 curves
- the 1,400 psi (10 MPa) CTB thickness corresponding to the above which is read from the horizontal axis on the design chart is 13 in. (325 mm).

Finally, consider the case where straddle carriers are running freely on a smooth surface so that no dynamic factors need be applied. In this configuration, the wheel loads are shown in the diagram below.



Straddle Carrier Wheel Loads During Free Running

The pavement withstands four repetitions of a wheel load of 24.6 kips (111.6 kN) as each straddle carrier passes so the pavement must be designed to withstand 3,840,000 passes (say 4,000,000) of an Equivalent Single Load of 24.6 kips (111.6 kN). The design chart indicates a thickness of 9 in (225 mm) of 1,400psi (10 MPa) CTB.

In this example, different operational conditions led to pavement thicknesses required varying between 9 in. (225 mm) and 13 in. (325mm). In some cases, it may be possible to take advantage of known modes of operation and proportion the pavement courses to meet the thicknesses required. While this may reduce initial construction costs, it has the disadvantage of constraining future operations and may lead to additional complexity in the construction process. It may prove cost-effective to provide an initial pavement which will not sustain all potential operational situations and to allow the equipment to become the proof testing system so that small areas may have to be strengthened later.

While this staged approach has the advantage of lowering initial costs, this must be balanced against the disadvantage associated with the disruption which may occur should the pavement need to be upgraded later. The staged approach might be more compatible with a paver surfaced facility whereby many of the pavers would be recovered for re-use in the reconstruction of the strengthened areas.

Chapter 6 - Design Table and Chart

This chapter of the manual comprises Table 15 which shows subbase and capping thicknesses for different CBR subgrades, and the pavement design chart. Note that the design chart on the next page includes a separate design curve for container stacking.

Table 15. Table of foundation thicknesses for pavements on various strength subgrades.

CBR of Subgrade	Capping Thickness inches (mm)	Subbase Thickness inches (mm)
1%	24 (600)	6 (150)
2%	14 (350)	6 (150)
3%	10 (250)	6 (150)
5%-7%	Not required	9 (225)
>7%	Not required	6 (150)

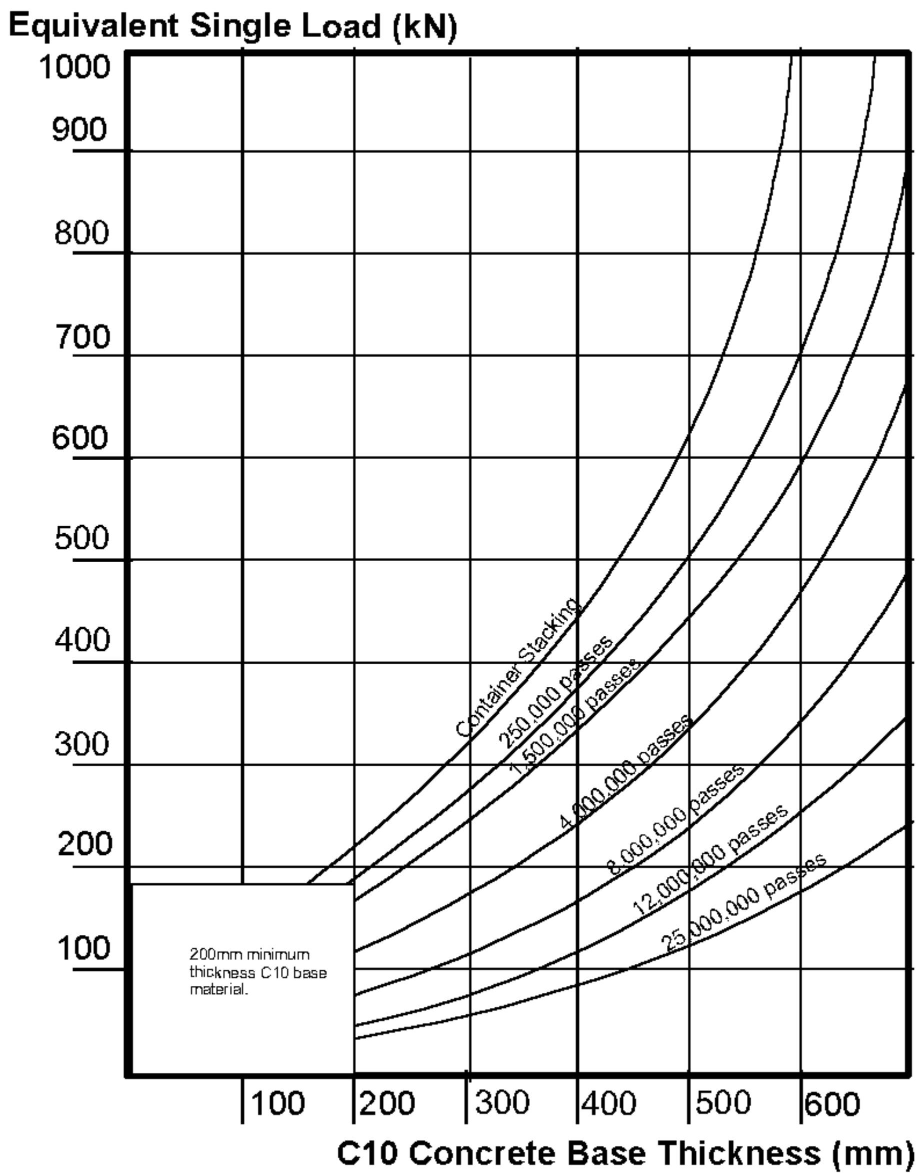


Figure 8. Equivalent Single Load Design Chart for Equipment and Stacked Containers

Note: To convert kilonewtons to pound-force multiply by 224.809 C10 = 10 MPa CTB or 1400 psi at 7 days' age

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Appendix A - Distress Criteria for Condition Surveys

Surface distress types shall be identified within unique randomly selected sample areas. Each sample shall be 5,000 sf (500 m^2). The total selected sample area should be at least 50 percent of the total area (it may be 100 percent of the total area if time permits).

1. TYPE OF DISTRESS: LOSS OF SAND IN JOINTS

Description: Normal block paving has full joints. Full is defined as sand that comes up to the bottom of the chamfer around the sides of the block. Sand in the joints can be lost due to any combination of the following factors; surface runoff, sucking of sand from tires, or wind. Loss of sand will cause the units to move, often loosening and furthering more loss of sand.

Measurement: Sand loss is measured by inserting a thin ruler into joints of pavers and reading from the bottom of the sand to the bottom of the chamfer. Sampling can be done in areas subject to repeated traffic, as well as areas adjoining other pavements or edges.

Severity levels:

L = 0 to ¼ in. (0 to 6 mm) loss.
M = ¼ in. (6 mm) to ¾ in. (19 mm) loss.
H = Over ¾ in. (19 mm) loss.

Remedy: Reapply sand to joints. Sealer to stabilize joint sand may be necessary in places where joint sand loss cannot be easily controlled.

2. NAME OF DISTRESS: INCONSISTENT JOINT WIDTHS

Description: Joint widths are specified in the original construction document. Actual joint widths should be as close to those nominally specified. Obtain baseline field measurements from sample areas subject to loads at the beginning of service. Excessive joint widths are caused by deformations, settlement, rutting, or loss of edge restraints. Variations from baseline measurements should not vary more than +1/8-in. (3 mm) or -1/16 in. (2 mm).

Measurement: Visually inspect the area for irregular joint widths. Identify an area that exhibits this distress. Insert calipers into the joint below the chamfer at the middle of the length of the unit and read measurement. Measure the number exceeding tolerances in a 6 ft (2 m) line within the area under inspection. Joint widths that are too narrow or too wide can be precursors to edge spalling or joint seal damage.

Severity levels:

L = Only a few joints out of dimensional tolerances, movement of only scattered units.
M = Joint widths are out of tolerance, concentrated in one (1) sample unit.
H = Joint widths are out of tolerance in several sample units.

Remedy: Once the cause is identified and solved, the units can be cleaned and replaced with joints to specification and compacted.

3. NAME OF DISTRESS: CORNER OR EDGE SPALLING
Description: A corner or edge spall intersects the joint at an angle. It does not extend vertically through the paving unit. It can be caused by loss of sand, loads and/or settlement that cause the top edges of adjacent units to creep together and break.

Measurement: If one or more than one severity level occurs, the higher level should be recorded for the area.

Severity levels:

L = Spall has little or no loose particles. Width of spalling is less than 1/8 in. (3 mm) wide.
M = Moderately spalled with some loose, in-place particles. Spalling is 1/8 in. (3 mm) to 1 in. (25 mm) wide.
H = Spall is greater than 1 in. (25 mm) wide with loose, in-place, or missing particles. Tire damage is a risk.

Remedy: For M & H severity levels, remove damage blocks, replace.

4. NAME OF DISTRESS: CRACKED BLOCKS
Description: Longitudinal, transverse, or diagonal cracks are caused by loads and run vertically through the unit. Cracks can be caused by defective pavers that break under loads. The cracks divide the unit into two or more pieces. Cracks have little or no openings. The units may perform for a time in a cracked state but should be replaced as the cracking may lead to corner or edge spalling. Units generally do not crack under loss of subgrade support.

Measurement: Identify cracked blocks at each severity level.

Severity Level:

L = Units have cracks that are not spalled or chipped.
M = Units have cracks that are lightly spalled with loose particles.
H = Units have cracks that are severely spalled with loose or missing particles.

Remedy: For M and H severity, remove cracked blocks and replace.

5. NAME OF DISTRESS: JOINT SEAL DAMAGE (if joint sand stabilization material is used)
Description: This is caused by joints opening and allowing water or soil into them. Sand or other material in the joints may loosen due to lack of sealant to bind them together. Joint seal damage from opening joints is due to greater problems such as loss of edge restraint, depressions, or rutting.

Measurement: Joint widths and visual surveys are measured against a baseline survey of areas subject to loads.

Severity levels:

L = Joint widths exceed baseline measurements but there is no debonding of sealant from the sand or paving unit.
M = Debonding of sealants from joints and paving units but no loss of stabilized sand.

H = Debonding of sealants allows loss of sand, sand is loose and loss has occurred. Joints may have soil/rocks in it and allow infiltration of water.

Remedy: For M & H severity, resealing may serve as a temporary solution until the units are removed, replaced with tight joints, and sealed.

6. NAME OF DISTRESS: DISINTEGRATION
Description: This is the breaking up of a unit or units into small loose particles. It is caused by defective concrete mix, unsuitable aggregates, high repetitions of freeze-thaw, deicing or anti-icing agents, or very high impact loads. Disintegration may be caused by crazing (also known as map cracking) or scaling due to manufacture with mix that was deficient in water, the action of freeze-thaw, and/or unsuitable aggregates.

Measurement: Identify areas with disintegrating pavers. Disintegration typically occurs among groups of pavers.

Severity levels:

L = Small cracks in surface of unit. No loose material.
M = Cracked surface and slight amount of loose material forming on top of units.
H = Most or entire surface of units are loose or missing. Rough surface is exposed.

Remedy: M & H severity, replace units.

7. NAME OF DISTRESS: DEPRESSIONS/DISTORTIONS
Description: These are a change in pavement surface resulting from settlement of the base, expansive soils, frost susceptible soils, or undermining of the base due to subsurface drainage problems. The transition from the areas at normal elevation to the depressed areas is gradual. Slight depressions are not noticeable except from ponding after a rainstorm.

Measurement: Depressions are measured in square feet (square meter) of surface area. The maximum depth determines the level of severity. Place a 10 ft. (3 m) straightedge across the depressed are and measure the maximum depth in inches (meters). Depressions larger than 10 ft. (3 m) across must be measured by either visual estimation or by direct measurement when filled with water.

Severity levels:

L = Depression can be observed by stained areas or brief ponding after a rainstorm. Depression ranges from ½ in. (13 mm) to 1 in. (25 mm).
M = Depression are visible without ponding. Depression ranges from 1 in. (25 mm) to 2 in. (50 mm).
H = Depression can be readily observed and severely effects riding quality. Depression is greater than 2 in. (50 mm).

Remedy: Remove the units, locate and repair the cause of the settlement, reinstate sand and units.

8. NAME OF DISTRESS: SETTLEMENT OR FAULTING
Description: This is defined as a clear difference in elevation between areas of pavers caused by movement of underlying layers or differential consolidation of the sand or base.

Measurement: The surface area of the affected pavement is recorded in square feet (square meter) and differentiated by severity level.

Severity levels:

L = ¼ in. (6 mm) to ½ in. (13 mm) difference in elevation.
M = ½ in. (13 mm) to 1 in. (25 mm).
H = Greater than 1 in. (25 mm).

Remedy: Remove the units, locate and repair source of settlement; reinstate units at correct elevations.

9. NAME OF DISTRESS: POLISHED AGGREGATES
Description: Some aggregates polish quickly under traffic or polish naturally from weather.

Measurement: Friction testing in accordance ASTM E274, Standard Test Method for Skid Resistance Surfaces using a Full-Scale Tire, or local skid resistance test methods.

Severity level: Use skid resistance standards.

Remedy: Sand blast to regain roughness. Wash thoroughly, dry and seal. If units polish quickly, replace with units with harder sand/aggregate composition.

10. NAME OF DISTRESS: PUMPING AND WATER BLEEDING
Description: Pumping is the ejection of material by water through joints caused by deflection of the units under passing loads. Sand is ejected through the joint resulting in surface staining. Material on the pavement close to joints are evidence of pumping. Pumping indicates poor joint sealing usually accompanied by base or soil deformation.

Measurement: Identify area that is pumping.

Severity levels: No degrees of severity are defined. It is sufficient to indicate that pumping exists.

Remedy: Remove units, repair base, install drainage as needed, and reinstate pavers.

11. NAME OF DISTRESS: RUTTING
Description: Rutting is a surface depression in a wheel path. In many cases, ruts are only noticeable only after a rainfall when the wheel paths are filled with water. Rutting is caused by consolidation from traffic loads that can permanently deform the sand, base, or soil subgrade. Rutting is a structural deficiency that is normally indicative of a pavement structured that is under-designed for the intended loading condition.

Measurement: The area of rutting is documented with the mean depth of the rut. Depth is measured at the deepest point (center) of the rut, along the length of the rut.

Severity level:

L = ¼ in. (6 mm) to ½ in. (13 mm)
M = ½ in. (13 mm) to 1 in. (25 mm)

H = greater than 1 in. (25 mm)

Remedy: For M & H severity, remove units and sand, repair base, install pavement materials to desired elevation. Reinstate sand, pavers, vibrate with sand. Full depth repair of base and subbase layers may also be required to provide adequate structural support.

12. NAME OF DISTRESS: HORIZONTAL CREEPING

Description: Creeping of units is caused by repeated braking, accelerating, or turning in an area. The joint lines will bend following the direction of the moving wheel(s). Creeping will eventually open paver joints, damage joint sealing, and accelerate deterioration.

Measurement: At the opening of the areas, two points should be marked on the pavement across areas subject to turning, braking, or accelerating. The points should align with the joints of the pavers. These are the reference lines. Deviations from these lines should be checked to monitor creeping.

Severity levels:

L = ¼ in. (6 mm) or less deviation from reference line.
M = ¼ in. (6 mm) to ½ in. (13 mm) deviation from reference line.
H = Greater than ½ in. (13 mm) deviation from reference line.

Remedy: For H severity, remove units back to area with stable, consistent joints. Open joints slightly in pavers adjacent to opening. Reinstall pavers in opening with consistent joints, matching those widths to those in the areas adjacent to the opening. Spread sand, vibrate, and remove excess sand.

13. NAME OF DISTRESS: SWELL

Description: Swell is an upward bulge in the pavement's surface. A swell is usually caused by frost action in the subgrade or swelling soil; however, swelling can be caused by other factors. Therefore, the cause of the swelling should be investigated.

Measurement: The maximum rise in pavement over a 10 ft. (3 m) straightedge would be measured as well as the area of the swell.

Severity levels:

H = Less than ¾ in. (19 mm) height differential. Swell is barely visible.

Remedy: Remove pavers, correct base and reinstate units.

Appendix F - Life-cycle Cost Information

Interlocking concrete pavements are fairly new, so there is a paucity of life-cycle cost data based on actual maintenance costs. The following life-cycle costs are excerpted from various studies that made assumptions about those. This information is intended to provide a point of departure for developing maintenance costs for life-cycle analyses for port paving projects. ICPI offers free Excel-based LCCA software for comparison of asphalt, concrete and interlocking concrete pavements downloaded from www.icpi.org.

Initial construction costs are not presented here because they vary widely depending on the material costs, distance of materials to the site, labor costs, site access, job size, and labor efficiencies. Contractors experienced in the installation of interlocking concrete pavers for street, industrial, and port applications should be contacted to obtain budget estimates for supplying and manually or mechanically installing bedding sand and concrete pavers. Likewise, estimated reinstatement costs of the pavers and bedding sand can be obtained from experienced contractors.

Life-cycle cost analysis should be based on reasonable assumptions about maintenance costs and discount rates. In the case of concrete pavers, reasonable assumptions are made in lieu of years of maintenance cost data (including salvage value). The studies are essentially sensitivity analyses to find the break-even point (years and discount rate) at which concrete pavers cost less than asphalt or PCC pavements. Actual performance of interlocking concrete pavements in the ports reviewed below indicates that maintenance costs are lower than those projected in the life-cycle cost studies.

In 1991, the Port of New Orleans, Louisiana, conducted a 40-year life-cycle cost analysis for the first phase (414,675 sf or 41,400 m^2) of a multi-year construction project for container marshaling yards. Using 1991 market rates for asphalt, the study concluded that concrete pavers would be less expensive to maintain than asphalt after 20 years of life.

The analysis made very liberal projections on maintenance by assuming \$0.05/sf/year (\$0.54/m^2/year) maintenance costs and 5% of the pavers replaced every ten years as part of a major rehabilitation. The actual amount of pavers replaced over 25 acres of pavement (108,900 m^2) built from 1991-1995 is reported to be about 10 sf (1 m^2). The pavement for which the life-cycle analysis was conducted is subject to front lift truck traffic bearing wheel loads of 50,000 lb (222 kN) with a design life of 1,000,000 repetitions. The first edition of this manual was used to develop the base thickness design for concrete pavers over cement-treated base.

Constructed in 1995, Berth 208 of the Port of Tampa, Florida, received 495,000 sf (49,500 m^2) of concrete pavers over 18 in. (450 mm) of dense-graded aggregate base reinforced by geogrid. Like the Port of New Orleans, the design load was a front lift truck with over 50,000 lb (222 kN) on each tire on the front axle. While the pavement opened to a trailer operation, the estimated lift truck deign repetitions are between 2 and 2.5 million over 25 years. The life-cycle cost analysis demonstrated a break-even with asphalt after six years of use.

Berth 30 at the Port of Oakland, California, has 7.5 acres (33,000 m^2) of concrete pavers on asphalt-treated base under container and trailer operations since 1993. No life-cycle study was done for the owner. There has been no maintenance on the pavement for the first ten years. There has been cracking of pavers under some container corner castings. These have not been of sufficient severity or delay operations to warrant repair.

Also at the Port of Oakland, almost 5 million sf (464,515 m^2) of 100 x 200 x 100 mm thick, mechanically installed concrete pavers were placed from 2002 to 2004 over a 3 in. (75 mm) thick asphalt base and an average 18 in. (450 mm) thick layer of Caltrans Class 2 subbase in Berths 57-59. Most pavement repairs have been due to subgrade settlement as much of the area was built on dewatered material dredged from the bay. Some settlement was expected due to this material. The pavers are subject to container handling equipment and withstood such loads well with little if any maintenance.

The performance of the concrete pavers is very dependent on the design and quality of construction of the base, since it is a flexible pavement surface. The better the base, generally the lower the maintenance and lower life-cycle costs for the concrete pavers. Based on the performance of these pavements, and low maintenance reported from UK and European ports, an estimated annual cost of \$0.005 to \$0.01 per sf (\$0.5 to \$.10/m^2) appears to be a reasonable assumption for use in life-cycle costs analyses. Actual costs may be lower, and these costs can be lower than PCC or asphalt, depending on the maintenance costs assumed for each. The following article provides an overview of LCCA factors.

LIFE-CYCLE COST ANALYSIS OF CONCRETE PAVERS

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INTRODUCTION

Selection of the most appropriate alternative for a particular pavement requires consideration of a number of factors that can significantly affect the use, performance, and cost of the pavement. Although the use of premium materials such as concrete pavers may increase the initial capital cost of construction, the performance benefits over the life span of the pavement can result in significant savings over conventional pavement alternatives. In addition to the increased service life that results from the use of premium materials in pavement construction, the adoption of a systematic and timely maintenance and rehabilitation program will increase the pavement performance that results from such a program.

LIFE-CYCLE COST ANALYSIS

The pavement which is the least expensive for the owner is not the pavement which costs the least to construct, but the pavement which gives the best return for the amount spent on it while it is in service. The process to determine the best pavement alternative should therefore be based on an economic analysis of the construction, maintenance and/or rehabilitation requirements for each alternative pavement.

To evaluate essentially equivalent (from a structural viewpoint for pavements) design alternatives using alternate materials, it is necessary to consider not only the initial cost of each alternative but also the total costs accumulated over its service life. The alternative having the lower initial cost may not be the least expensive once factors such as maintenance, rehabilitation, inflation and interest (the value of money invested today for future use), are considered. The most effective method of measuring the cost-effectiveness of alternative designs is life-cycle cost analysis.

Present Worth Analysis - The present worth method has been adopted by most agencies using life-cycle cost analysis procedures. This method requires knowledge of the rate of inflation, the interest rate and the discount rate in order to accurately predict the life-cycle costs of each alternative. The rate of inflation (the relative increase in price levels of commodities such a construction prices), and the interest rate (the rate of return on investment) vary depending on the economic climate of the time. The discount rate (the nominal increase in the value of money over time) is derived from the interest and inflation rates as given by the following equation:

$$\text{discount rate} = \frac{\text{interest rate - inflation rate}}{1 + \text{inflation rate}/100}$$

The present worth method equates present and future expenditures for each alternative, and associated maintenance and rehabilitation costs over the life of the project. This concept, known as discounting, is used to permit comparison of alternatives that require expenditure over an extended period, and allows the designer to consider the dual effects of interest rates and inflation on project cost.

Analysis Period - The life-cycle analysis periods used for pavements are generally 20 to 30 years. This reflects the trend by some agencies towards longer-lasting pavements and the consideration of extended life-cycle analysis periods. It is generally acknowledged that pavements designed for longer traffic or life-cycle analysis have lower life-cycle costs. It also represents the time period that the design axle loads and traffic must be considered for design purposes.

Service Life of Pavement Types - The service life of each pavement alternative must also be taken into consideration for equivalent life-cycle cost comparisons. The timing or schedule of each major maintenance and rehabilitation activity for each pavement alternative must be considered and the most appropriate service life selected for life-cycle cost analysis.

COMPONENTS OF PAVEMENT LIFE-CYCLE COST ANALYSIS

There are several major cost components that influence the outcome of a life-cycle cost analysis. They include:

1. Inflation rate
2. Interest rate
3. Discount rate
4. Initial costs - all costs to construct the selected pavement structure (capital cost)
5. Maintenance costs - cost for systemic routine maintenance activities that increase pavement service life.
6. Rehabilitation - costs for major maintenance activities including removal, regrading base, relaying or replacing damaged pavers, required when the pavement condition (riding quality for instance) reaches a certain minimum level of serviceability, which generally depends on the classification of road or highway.
7. Residual value - the unused benefit (remaining service life) of any maintenance or rehabilitation activity at the end of the analysis period.
8. Salvage value - value of any of the components that may be reused at the end of the analysis period. This may be a significant value for concrete pavers as the individual pavers may be reusable.
9. User costs - the main user costs are vehicle operating costs, user travel time costs, traffic delay costs due to construction, accident costs and discomfort costs. These user costs are difficult to quantify and should be in terms of extra user costs over those usually anticipated.

The relative influence of the major cost components on life-cycle cost analysis for concrete pavers is shown in Table 1.

Table 1
Factors Affecting Life-Cycle Cost Analysis
For Concrete Pavers

ITEM	RELATIVE INFLUENCE ON ALTERNATIVE SELECTION
Inflation Rate	Low
Interest Rate	Low
Discount Rate	High
Initial Costs	Moderate-High
Maintenance Costs	Moderate
Rehabilitation Costs	Moderate
Residual Value	Low-Moderate
Salvage Value	Moderate
User Delay Costs	Low-Moderate

Initial Costs - The life-cycle cost analysis is intended to determine the relative cost of each pavement alternative. Minor differences in the unit prices should not affect the results of the analysis significantly.

Maintenance Costs - Systematic routine maintenance activities should be scheduled over the service life of a pavement. For example, a systematic program to remove and replace cracked or damaged pavers and reapplication of a surface/joint sealer (should it be used) can be scheduled at timely intervals after initial construction.

Rehabilitation Costs - Some form of major maintenance or rehabilitation will generally be required to maintain the pavement condition at or above a minimum acceptable serviceability level and extend the service life of the pavement alternatives for the life-cycle cost period being considered. The scheduling for such activities is highly dependent upon the pavement materials employed and the systematic maintenance program adopted (which also assumed that quality materials and procedures are followed).

Residual and Salvage Values - In addition to the initial cost of construction, maintenance and rehabilitation costs over the life of the pavement, residual values and salvage can be incorporated to represent the remaining or unrealized value of the pavement structure and individual components/materials at the end of the analysis period. The residual and salvage values for concrete pavers may be more significant than traditional pavement materials.

User Delay Costs - User delay costs can be incorporated in the life-cycle cost analysis to represent the impact of scheduled maintenance and/or rehabilitation activities on the users for each pavement. The user delay cost is estimated by assigning a financial penalty for the time that the pavement is not available for use by the public. Pavements constructed with concrete pavers have reduced user delay costs compared to asphalt concrete or concrete pavements as they can be put into service immediately after construction.

Value Engineering - Value engineering is the systematic analysis process for a product (pavement) to identify how its required function(s) should be achieved at the lowest possible cost consistent with the requirements for performance, maintenance and safety. Value engineering is a process that looks at ways to: improve the overall project design; simplify project construction; improve project maintenance; and lower the project life-cycle cost.

CONCLUSION

Life-cycle cost analysis is the most effective method of measuring the cost-effectiveness of alternate pavement designs for initial or maintenance pavement projects. It also forms an important component of project value engineering. Public officials should recognize the need for a comprehensive engineering analysis, which should include life-cycle cost analysis for urban or rural new construction or rehabilitation projects.

Appendix C - ICPI Tech Specs

Tech Spec 6

Interlocking Concrete Pavement Institute

Reinstatement of Interlocking Concrete Pavements

Introduction

Concrete pavers can act as a zipper in the pavement. When the need arises to make underground repairs, interlocking concrete pavements can be removed and replaced using the same material. Unlike asphalt or poured-in-place concrete, segmental pavement can be opened and closed without using jack hammers on the surface and with less construction equipment. This results in no ugly patches and no reduction in pavement service life. In addition, no curing means fast repairs with reduced user delays and related costs.

The process of reusing the same paving units is called reinstatement. This Tech Spec covers how to reinstate or "unzip and zip" interlocking concrete pavement. The following step-by-step procedure applies to any interlocking concrete pavement, including pedestrian areas, parking lots, driveways, streets, industrial, port and airport pavements.

The methods described here will work for permeable interlocking concrete pavements with a few exceptions. The excavation through the open graded base and subbase aggregates will require shallower side slopes. This will require a larger area of of pavers to be removed before excavation. Additionally, aggregates placed back into the excavation and compacted should be new materials meeting the specifications of the original project.

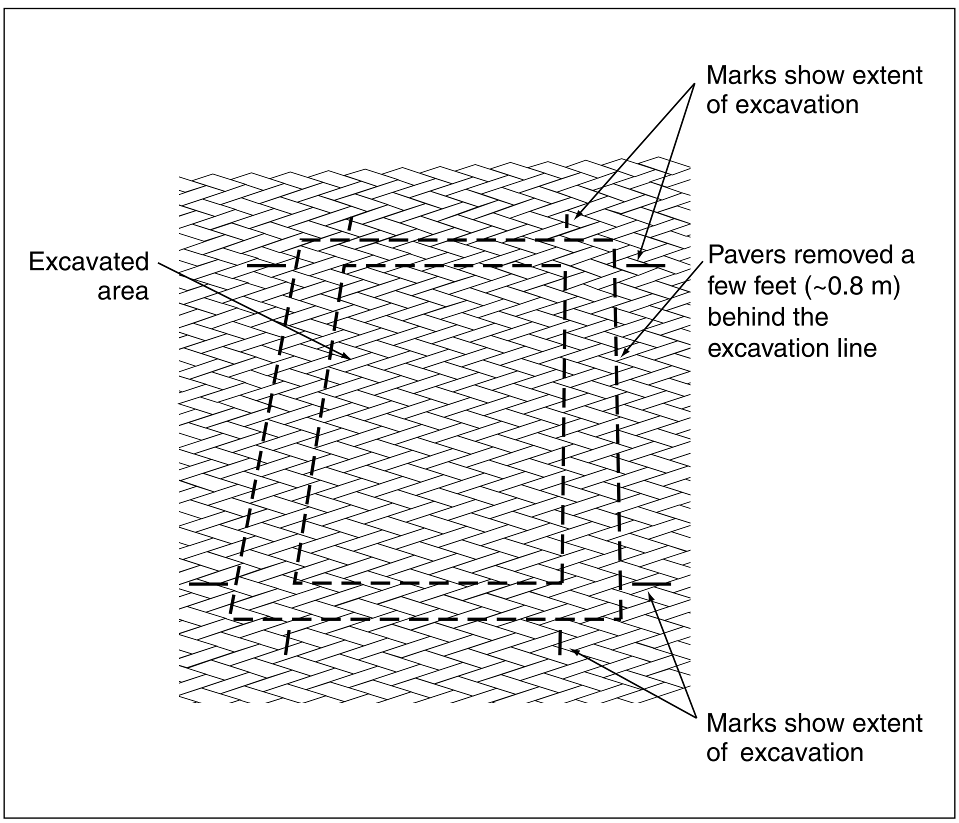

Figure 1. Pavement markings show the extent of paver removal and trench area.

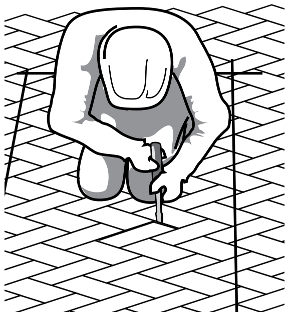

Figure 2. Removing joint sand surrounding the first paver to be removed.

Figure 3. Prying the paver upwards with two large screwdrivers.

Figure 4. Prying with a screwdriver and pulling the paver out.

Step 1—Locate Underground Utilities in the Area to be Excavated

The location and depth of existing utilities should be established prior to excavating. Many localities have one telephone number to call for obtaining marked utility locations. Set cones, traffic signs, or barricades around the area to be excavated according to local and state or provincial standards.

Determine and mark the area of pavers to be removed. Remove pavers a few feet (~0.8 m) wider on each side of the trench opening. This shoulder around the opening should consist of undisturbed bedding sand. It will be used as a guide for reinstating the sand and pavers later (Figure 1).

Figure 5. Using a paver extractor to remove a paver

Paint or crayon should be used to mark the area of pavers for removal. The trench area can be marked on the pavers as well. Paint may be necessary to establish a more permanent marking than crayon, especially if there is vehicular traffic, or if there will be an extended period of time between marking and excavation. The same paving units will be reused, so in some instances paint on them may not be desirable, especially if there is little traffic to wear it away over time.

Step 2—Remove the First Paver

Locate the first paver to be removed. This is typically at one end of the marked area. Scrape the sand from the joints around the first paver using a putty knife or small trowel (Figure 2). Carefully pry each side upward with one or two large screwdrivers. Begin prying on the short ends of the paver. The paver will rise a small distance with each prying (Figure 3). When the paver is high enough to grasp, wiggle it loose, pulling upward. If necessary, pry with a screwdriver using one hand while pulling upward with the other (Figure 4). Sometimes, one end of the paver can be pulled above the others so a pry bar can be inserted under it. The paver can then be pried out.

Paver extractors can also be used to remove the first paver and subsequent ones (Figure 5). They are designed to clamp the paver tightly. These work most efficiently in removing the first paver if some of the joint sand is removed before clamping and pulling. Water can be applied to lubricate the joint sand to facilitate extraction.

If the pavement has been subject to vehicular traffic for a length of time, the first paver may be need to be broken in order to be removed. A small sledge hammer (3 lb. maul) applied to an appropriate chisel will break a paver into small pieces. Protective eye goggles should be worn during this procedure. Remove all broken pieces from the space until the bedding sand is completely exposed. Pneumatic hammers or cutting saws are generally not required to remove the first unit.

Step 3—Remove the Remaining Pavers

After the first one is removed, surrounding pavers can be loosened and pried out (Figure 6). Grab the pavers by the short end, as it offers less resistance than the long side (Figure 7). Remove pavers to the marks on the pavement for the opening.

Sand sticking to the sides and bottoms of pavers can interfere with their reinstatement and compaction into the bedding sand. Scrape off sand from each unit as it is being removed. A small trowel, wide putty knife, wire brush, or another paver works well.

The direction of removal should consider where pavers are going to be stacked. Stack the pavers neatly near the opening, out of the way of excavation equipment such as backhoes or dump trucks. If the pavers need to be removed from the site, stack them on wooden pallets and secure them tightly so there is no loss during transit.

Figure 6. Prying out the remaining pavers

Figure 7. Pulling out a paver by the short end provides greater leverage and makes extraction easier.

Equipment used to move pallets with pavers should be capable of lifting in excess of 3,000 lbs. (1,365 kg). If the pavers need to be moved only a short distance, then stack them directly on a paver cart at the opening and set them nearby. They will then be ready for pick up by the paver cart when reinstated.

For every project, a small stockpile of spare pavers should be stored and used for repairs during the life of the pavement. Weathering, wear and stains may change the appearance of removed pavers compared to spares kept in storage for repairs. When pavers are removed for base or utility repairs, all undamaged units should be retained for future reinstatement. Pavers from the stockpile that replace damaged or broken units should be scattered among the pattern of the existing reinstated pavers. This will reduce the visual impact of color variations.

Step 4—Remove the Bedding Sand

The removed pavers will reveal compacted bedding sand. It may be removed and reused, or removed during excavation of the base. For some projects with time constraints, the

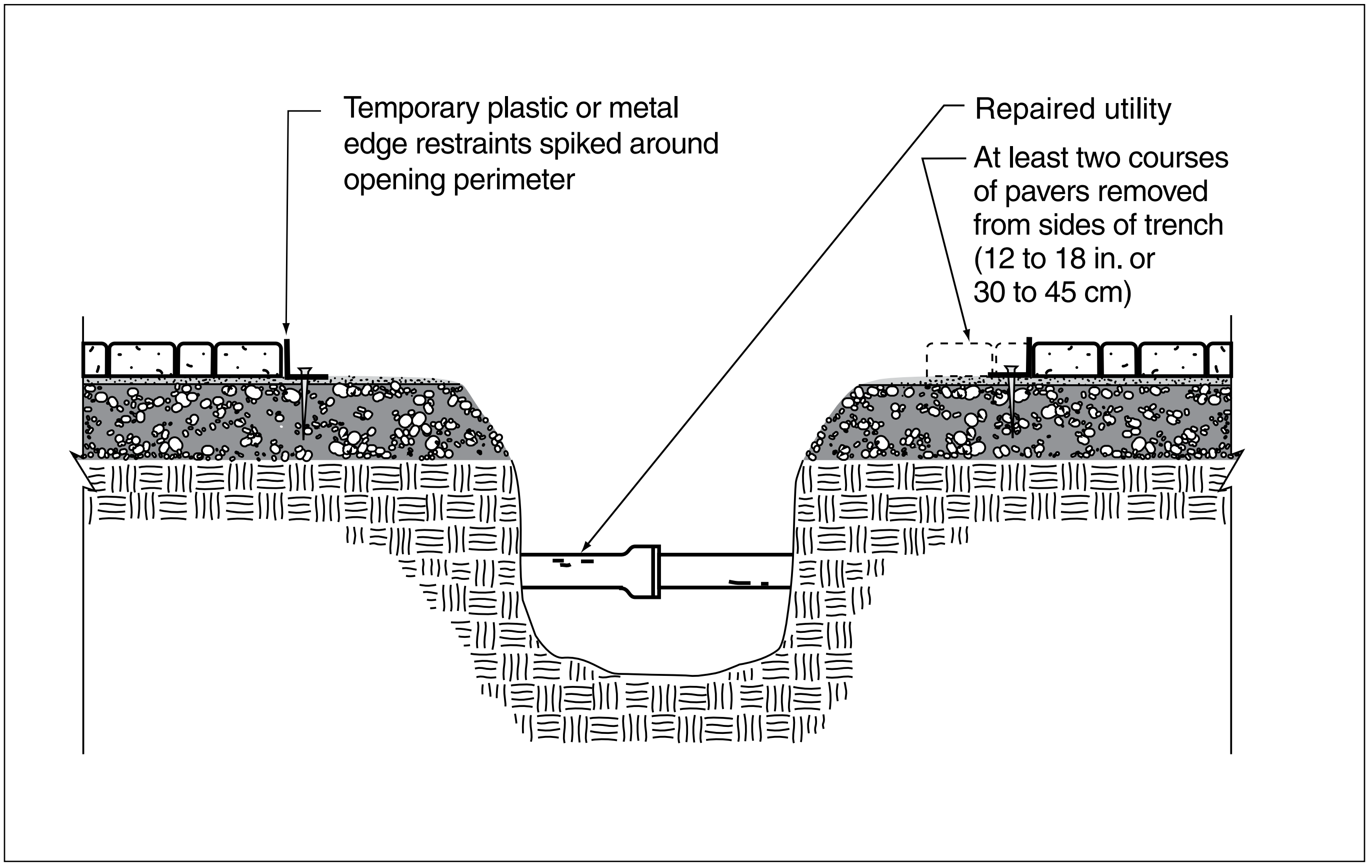

Figure 8. T-shaped cross section of the excavated opening

sand will probably be removed during excavation and not reused.

If the sand is reused, it may need to be loosened with rakes before removal by shoveling. The sand should be neatly stockpiled and kept free from soil, aggregate base, or foreign material. If the sand is mixed with these materials, it should not be reused, and it should be replaced with clean sand.

Whether or not it is reused, always leave an undisturbed area of sand 6 to 12 in. (15 to 30 cm) wide next to the undisturbed pavers. This area will provide a stable support for temporary edge restraints and for screeding the bedding sand after the base is reinstated.

Step 5—Excavate the Base Material and Soil

If aggregate base material is removed, it may be possible to stockpile it near the opening for reuse. Keep the aggregate base material separate from excavated subgrade soil. Any soil removed should be replaced with base material unless local regulations require reinstatement of the native soil. The final shape of the excavated opening should be T-shaped in cross section. (Figure 8). This helps prevent undermining and weakening of the adjacent pavement. Follow local codes on the use of shoring, as it may need to be inserted to prevent collapse of the trench sides.

Figure 9 illustrates temporary bracing with plastic or metal edge restraints around the perimeter of the opening. This is recommended practice. The restraints are pinned to the base using metal spikes. Bracing helps keep the undisturbed pavers in place during excavation and fill activities, and will enable reinstatement of units into the existing laying pattern without cutting them to fit.

Step 6—Replace the Base Material

After the repairs are complete, soil at the bottom of the trench should be compacted prior to placing and compacting the base material. Repairs typically use the same base material that was removed. A crushed stone aggregate base should be placed and compacted in 2 to 4 in. (50 to 100 mm) lifts (Figures 10 and 11). If the excavated base material was stabilized with asphalt or cement, it should be replaced with similar materials.

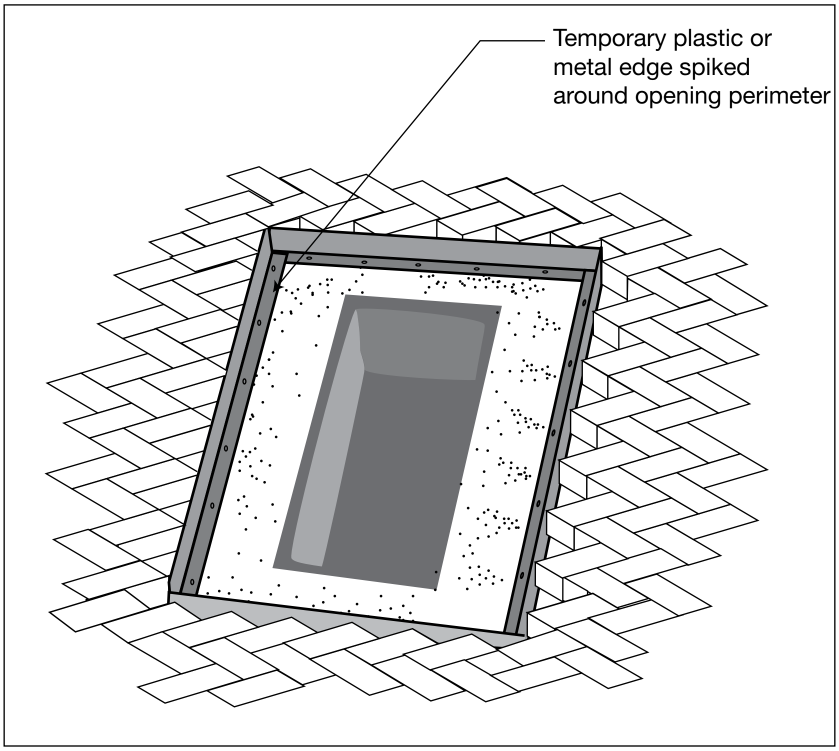

Figure 9. Temporary bracing at the pavement opening will help keep units in place during excavation, repairs and reinstatement.

Monitoring density of the compacted soil subgrade and base is *essential* to reinstating any pavement, including interlocking concrete pavements. It will help prevent rutting and premature failure. A dynamic cone penetrometer is an effective means for monitoring the density of each lift while working in the opening. If the soil or base material is too dry during compaction, a small amount of water can be sprayed over each lift prior to compacting. This will help achieve maximum density. A nuclear density gauge is recommended for checking the density of the completed compaction of the soil and base layers. A qualified civil engineer should monitor compaction for conformance to local standards.

If there are no local standards for compaction, a minimum of 98% standard Proctor density is recommended for the soil subgrade, and a minimum of 98% modified Proctor density for the base. Compaction equipment companies can provide guidelines on equipment selection and use on the soil and the base. For further guidance on compaction see *ICPI Tech Spec 2—Construction of Interlocking Concrete Pavements*.

The final elevation of the compacted base at the opening perimeter should match the bottom of the existing undisturbed sand layer that surrounds the opening. The elevation of the middle of the base fill placed in the opening should be slightly higher than its perimeter to compensate for minor settlement.

Controlled low-strength materials (CLSM) (sometimes called slurry mix, flowable fill, or unshrinkable fill) can be used in some applications as a replacement for unstabilized base materials (1). The fill can be made from aggregate bound with fly ash, pozzolans, or cement. Because it is poured from a truck, the fill will form around pipes and underground structures where soil or base backfill and compaction are difficult. Low-strength fill can be poured into undercuts and under pipes where it is impossible to fill and compact aggregate base. The material is also self-leveling.

Low-strength flowable fill requires a short curing time and can be used in freezing weather. It requires no compaction and with some mix designs, can be opened to traffic in 24 hours. Low-strength fill is stiffer than aggregate base and offers higher resistance to settling and rutting. This reduces deterioration of the pavement surface over time. In order to facilitate re-excavation, flowable fill should be made

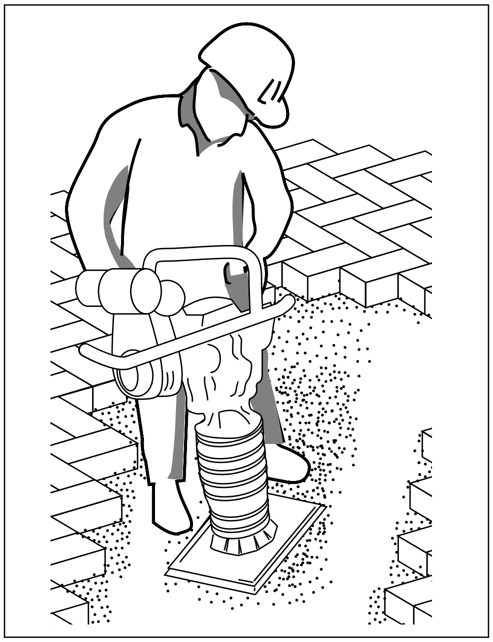

Figure 10. Compaction of the base in 2 to 4 in. (50 to 100 mm) lifts and monitoring density with a dynamic cone penetrometer or a nuclear density gauge are essential to minimizing settlement.

with a small amount of cement. Check with suppliers on the strength of in-place fill that is at least two years old, and on ease of excavation of these sites. The strength of the fill should not exceed 300 psi (2 MPa) after two years of service. Low-strength fill has been used successfully in Toronto and London, Ontario; Colorado Springs, Colorado; Cincinnati, Ohio, Kansas City, Missouri; Peoria, Illinois; and many other municipalities. It is generally more cost-effective than using aggregate base by reducing job time and future pavement repairs. Local ready-mix suppliers can be contacted for available mixes, strengths, installation methods and prices. See *ICPI Tech Spec 7—Repair of Utility Cuts with Interlocking Concrete Pavements* for further information on low-strength fill.

Step 7—Replace the Bedding Sand Layer

During the foregoing procedures, it is likely that the pavers and bedding sand around the opening were disturbed especially if no temporary edge restraints were placed to secure the pavers. If so, then remove an additional two rows of pavers, or back to an undisturbed course. Clean sand from these pavers and set them aside with the others. Be sure there is at least 6 to 8 in. (150 to 200 mm) of undisturbed bedding sand exposed after removal of the course(s) of pavers. This area of undisturbed sand can be used to guide screeding of fresh bedding sand over the compacted and leveled base. Prior to screeding, carefully remove any temporary edge restraints so that adjacent pavers remain undisturbed.

Spread the bedding sand across the base to about two thirds of its full thickness. Do not use the sand to compensate for low places in the surface of the base. Low areas should be filled with base material and compacted. Spread the remaining thickness of sand.

The undisturbed pavers on opposite sides of the opening can be used to guide screeding. It may be necessary to remove a few courses of pavers to straighten the edge of the pavers (Figure 12).

Metal screed pipes are placed on the base and in the bedding sand to control its thickness. The base should have a slight "crown" or rise in the center of the reinstated base. A crown helps compensate for minor settling after the pavers are replaced. Furthermore, as the pavers settle slightly from traffic, the reinstated surface will stiffen, increasing its structural capacity.

Step 8—Reinstate the Pavers

Pull and secure string lines across the opening along the pavement joints every 6 to 10 ft. (2 to 3 m). By following the string lines, joints of reinstated pavers will remain aligned with undisturbed ones. Lay the remaining pavers from the smaller end of the opening, generally working "uphill," i.e., from a lower elevation of the pavement to the higher one. Minor adjustments to the alignment and spacing of joints can be made with pry bars or large screw drivers. Make adjustments prior to compacting the pavers (Figure 13).

Place the pavers in the original laying pattern and compact them with at least two passes of a minimum 5,000 lbf. (22 kN) plate compactor. The path of the plate compactor should overlap onto the undisturbed pavers. Spread joint sand and compact again until the joints can no longer accept sand (Figure 14). Sweep away excess sand. The elevation of the reinstated pavers after compaction should be no higher than 1/8 in. (2 mm) at the edges and 3/16 in. (5 mm) at the center. Traffic and minor settlement will compact the pavers to a level surface. After a short period of time, the repaired area will be undetectable (Figure 15).

Applications such as airports or gas stations require joint sand stabilizers. If an area is reinstated in such uses, then a stabilizer will need to be re-applied to the joints. See *ICPI Tech Spec 5—Cleaning and Sealing Interlocking Concrete Pavements* for advice on sealers and joint sand stabilizers.

Production rates are highly variable and are dependent on several factors which include original installation methods, crew experience, weather, traffic, site access, a steady flow of

Figure 11. Trench filled with compacted aggregate base. Temporary edge restraints should be used around the opening perimeter.

Figure 12. Screeded bedding sand. Note that a few courses of pavers are removed to create even sides for screeding. Installing temporary edge restraints prior to excavating is preferred practice.

materials around the repair site, and the number of pavers to be cut. An experienced crew will reinstate pavers with little or no cutting, aligning reinstated pavers with existing joint lines, pattern, and spacing between the units.

Although existing pavers can be used in reinstatement, there may be projects where it is more cost-effective to remove and replace the area with new pavers. Stabilized joint sand may be difficult to remove and it will probably be more cost effective to discard the old pavers. An experienced paver installation contractor can provide guidance on cost-effective approaches for each reinstatement project.

Municipalities, utility companies and other users should use experienced ICPI Certified Installer to reinstate interlocking concrete pavers. Others may use in-house labor which should be trained in the procedures described above. Contact a local Interlocking Concrete Pavement Institute paver installation contractor member to assist with training. Successful reinstatement using experienced contractors will result in successful reinstatement jobs that leave no ugly patches nor do they weaken the pavement. See Figures 15 and 16.

Figure 13 (Left). Adjusting joint spacing and alignment. Figure 14 (Right). Second and final compaction of the pavers. The first compaction occurs after the pavers are placed (no sand in the joints). The second compaction works the sand on pavers into the joints. This process causes the pavers to interlock.

Figure 15 and 16. Reinstated pavers leave no ugly patches nor do they weaken the pavement.

References

1. *Controlled Low Strength Materials (CLSM)*, ACI 229R-94, American Concrete Institute, Farmington Hills, Michigan, 1994.

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Tech Spec 11

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Mechanical Installation of Interlocking Concrete Pavements

Mechanical installation originated in Germany and the Netherlands in the late 1970s. The growth of street, port, and airport projects required timely installation with fewer workers. Machines were developed to increase productivity while reducing fatigue and injury (1–4). Today, over 5,000 mechanical installation machines operate in Germany alone with thousands more in use throughout Europe. They are used for projects as small as 10,000 sf (1,000 m²) (5).

Mechanical equipment was first introduced in North America in the early 1980s. The first mechanically installed project was placed in 1981, a 1,000,000 sf (93,000 m²) container terminal in Calgary, Alberta. Since then, hundreds of commercial, municipal, port, and airport jobs have been installed mechanically in most states and provinces across North America. Some examples include city streets in Dayton, Ohio (the first mechanically installed street in the U.S.) (6); Cincinnati, Ohio; Toronto, Ontario; Northbrook, Illinois; Naples, Florida; and Palm Desert, California; container yards in Tampa, Baltimore, and Oakland; and an airfield at St. Augustine, Florida.

Mechanical installation must be viewed as a system of material handling from manufacture to on-site placement of the concrete pavers. This technical bulletin provides guidelines for the manufacturer, designer, and contractor of mechanically installed pavements in order to realize high efficiencies from this system of material handling. Successful mechanical installation relies on four factors that affect efficiency and costs. These include:

1. Equipment specifically designed to efficiently handle
   (a) transport of packaged concrete pavers onto/around the site,
   (b) screeding of bedding sand,
   (c) installation of the concrete pavers.

Figure 1. Mechanical installation equipment at Port of Tampa, Florida.

Figure 2. A cube of 90° herringbone pattern rectangular pavers ready for installation.

Figure 3. Motorized equipment with a mechanical clamp.

Figure 4. Hydraulic clamp picking up layer of pavers

2. The shape of the paver and configuration of the laying pattern.
3. Careful job planning by the contractor with support from the manufacturer before the job begins.
4. Systematic and efficient execution of the installation on the job site.

As of 2003, ICPI has released *Tech Spec 15—A Guide for Construction of Mechanically Installed Interlocking Concrete Pavements*. The guide is intended for large, mechanically installed projects and is for facility owners, design professionals, contractors, and manufacturers. It provides requirements for quality control of materials and their installation, including bedding sand and pavers. It includes a Quality Control Plan jointly developed and implemented by the paver installation contractor, the paver manufacturer and the general contractor. The specification guide facilitates planning and coordination among these entities, and it supports a systematic approach to manufacture, delivery, installation, and inspection. Even though Permeable Interlocking Concrete Pavement (PICP) is installed on different base and bedding materials, PICP can benefit from mechanical installation. See *Tech Spec 18—Construction of Permeable Interlocking Concrete Pavement*. The remainder of this document focuses on the installation of sand set interlocking concrete pavement.

1. Equipment for Mechanical Installation

Mechanized equipment includes an operator-activated clamp that lifts one layer or cluster of pavers at a time. Each layer can consist of 20 to 72 paving units. The pavers are manufactured in their prescribed laying pattern within the layer. In rare cases, two smaller layers are manufactured and combined in the factory to make one large layer. Layers are packaged in a “cube,” i.e., each layer typically stacked 8 to 10 units high. The cubes arrive at the site with each layer ready to be lifted by the mechanical equipment and placed on the screeded bedding sand. Figure 2 shows a cube of pavers opened and ready for installation by mechanical

Figure 5. Motorized equipment with a hydraulic clamp.

Figure 6. The vacuum head over the paver layer.

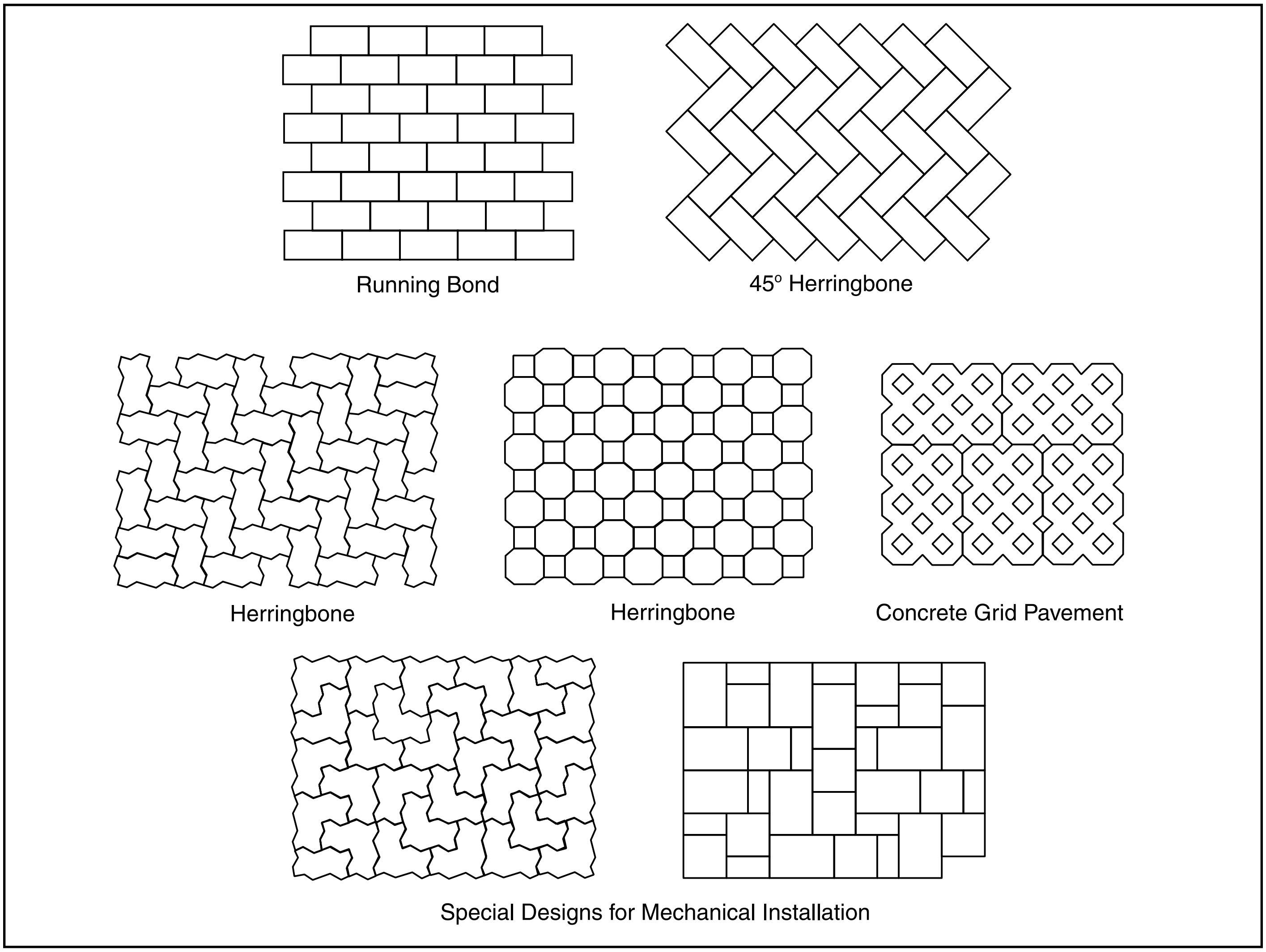

Figure 7. Paver layer categories for mechanical installation. These are representations of many available patterns.

equipment. When grasped by the clamp, the pavers remain together in the layer. They interlock from lateral pressure provided by the clamp while being lifted.

Each layer or cluster is typically about a square yard (m^2) in area. The exact layer area varies with each paver pattern. The area covered by the layer can be provided by the manufacturer.

Types of Equipment—Mechanized installation equipment may be either non-motorized or motorized. Hower, *non-motorized* equipment, consisting of a wheeled hand cart and clamp that grabs a half layer, or about 15 to 20 pavers, is rarely used in North America. While it is not as efficient as motorized equipment, a hand-held cart can save time and strain on the installation crew. Non-motorized equipment may be useful on jobs where noise from vehicles is not permitted (e.g., hospitals), or places with weight limitations and very limited working space, such as roofs.

Most *motorized* equipment prevalent in North America is no heavier than a small automobile and is almost as quiet while operating. This equipment can use three different kinds of clamps for placing concrete pavers. The first type is a *mechanical* clamp shown in Figure 3 (7). This clamp consists of many levers that are adjusted to conform to the dimensions of the paver layer prior to starting the job. The initial adjustment of the clamp ensures a tight fit against the layer when activated. When the clamp closes and picks up the layer, the movement in the levers compensates for possible slight misalignment of pavers. Misalignment can be from minor dimensional differences among the pavers in the layer, or caused by small bits of dirt that occasionally lodge between them.

When activated by the machine operator, the clamp levers close in unison to pick up a layer. The clamp tightens against its sides while being lifted. The operator then aligns the layer next to the other pavers on the bedding sand. The layer is released from the clamp when almost touching the bedding sand. The layer should not be allowed to gouge the bedding sand as this unevenness will eventually be reflected in the surface of the pavers.

The second type of clamp is hydraulic, i.e., activated by hydraulic pistons that grab the sides of the paver layer as shown in Figure 4 and 5. Prior to starting a job, the hydraulic clamps are adjusted to conform to the configuration of the layer to be placed. The pressure of the hydraulic fluid is adjusted as well, so that each clamp tightly fits onto the sides of the layer.

The clamps close on the sides of the layer when triggered by the operator. The clamps have flexible spring steel grippers on them that compensate for minor size differences or debris among the pavers. As with the mechanical clamp, each layer is grabbed, positioned, the clamp opened, and the pavers dropped a short distance onto the bedding sand. The minimum paver thickness that can be laid with hydraulic or mechanical clamps is 2³/₈ in. (60 mm).

The third kind of clamp consists of a metal head that covers the paver layer and applies a vacuum. The head has many rubber cups arranged in the paver pattern to be placed. Each cup has a hose attached to it. A vacuum is pulled through the hoses to lift and place all pavers simultaneously as shown in Figure 6. The machine operator controls the vacuum in the cups that lifts and releases the pavers. This installation equipment tends to be heavier than the other kinds of motorized installation machines.

Vacuum equipment relies on suction to lift the pavers. No particles should be on the surface of the pavers because they will interfere with the seal between the cups and the paver surfaces. For different laying patterns, the arrangement of the cups on the head must be adjusted or new ones used. Vacuum equipment for installing interlocking concrete pavers is not prevalent in North America. Similar kinds of vacuum equipment are more commonly used to place larger concrete paving slabs ranging in size from 12 x 12 in. (300 x 300 mm) up to 36 x 36 in. (900 x 900 mm).

Figure 8. Clamps are an efficient method of moving cubes of pavers around the site, and can eliminate the need for wooden pallets.

2. Pavers for Mechanical Installation

There are four general categories of paver patterns used as layers. They are *running bond, cross joint bond, herringbone,* and *special designs* for mechanical installation only. Figure 7 illustrates these types of patterns. These will be referenced in the discussion below.

On some mechanical jobs in a few developing countries, pavers are manufactured and manually arranged in the factory into the laying pattern for installation by machine. While this method may create needed jobs in some regions of the world, high labor costs prohibit this approach in North America. Pavers should be molded in the final laying pattern in order to maximize efficiency and control costs. The following criteria should be used in evaluating mold/layer configurations for efficiency, cost, and performance.

Utilization of the manufacturing pallet—The size of the production machine governs the size of the mold and hence the total number of pavers in each layer. Molds for mechanical installation should be as

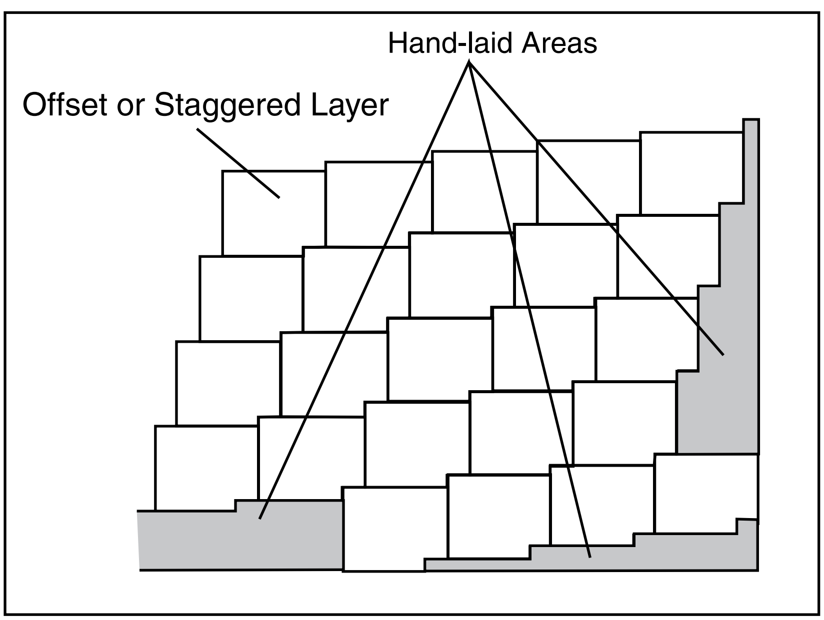

Figure 9. Staggered installation of clusters (8).

large as possible and should utilize the available space efficiently to maximize cost-effectiveness. For example, the difference between 35 and 45 pavers in a layer means a 28% increase in the number of pavers placed with the same effort and time.

The contractor can enhance the opportunity for cost-effective installations by reviewing mold layouts with the paver manufacturer for the most efficient use of pavers. The layouts present varying efficiencies in packaging, shipment, and transfer of material on the site, as well as supplemental manual installation, half pavers, bond patterns, interlock, and use of spacer bars.

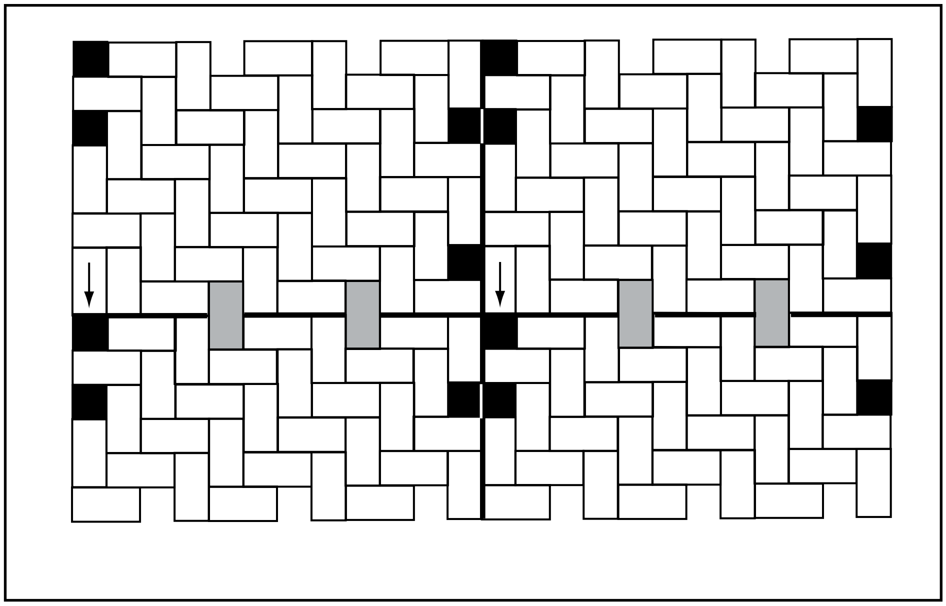

Figure 10. Half pavers to be removed from herringbone layers and filled with whole units. Gray spaces are filled with whole pavers as well.

Packaging and shipment—Pavers are banded as cubes for shipment with steel and/or plastic straps. The layer configuration should enable each cube to be tightly banded with strapping; otherwise the pavers may shift during shipping, especially when the distance from the factory to the site is great. Misaligned pavers on the cube may need to be realigned on the job site prior to placing them. Realignment with installation equipment will waste time on the job site.

Most manufacturers can provide cubes of pavers tightly banded horizontally and vertically to minimize shifting while in transit. Plastic wrap is often applied as shrink wrap or stretch wrap (stretched tightly in many layers). All packaging is removed from the cubes when they are positioned near the laying face (or edge) of the pavement.

Transfer on the site—Most layer configurations enable their transfer (packaged as cubes) around the site with fork lifts or clamps. Cubes of pavers may be moved with or without wooden pallets.

They enable transfer with fork lifts but pallets incur additional costs in handling time and charges. Mechanical clamps specifically made for transferring paver cubes can eliminate the need for pallets on the site, thereby reducing material and labor costs (see Figure 8). If pavers are delivered without pallets and no clamps are available on the site, then the contractor may supply pallets on which to place the cubes for locating them at the laying face of the job with a forklift.

Figure 11. Removal of half pavers and installation of whole units.

Supplemental manual installation—The amount of supplemental manual installation on a mechanically placed job depends on two factors. First, some areas must be placed only by hand because of the configuration of the site. They can't be reached by a machine, or the layer is too large for the area to be paved. Such areas may include those around light fixtures, utility structures, and drainage inlets.

Second, some patterns may need to be offset by a course or two when placed. In this case, the initial area of the pavers must be placed by hand. The hand-laid areas establish an offset for the coursing and the direction of the subsequent, machine-installed layers. Some herringbone patterns require an offset,

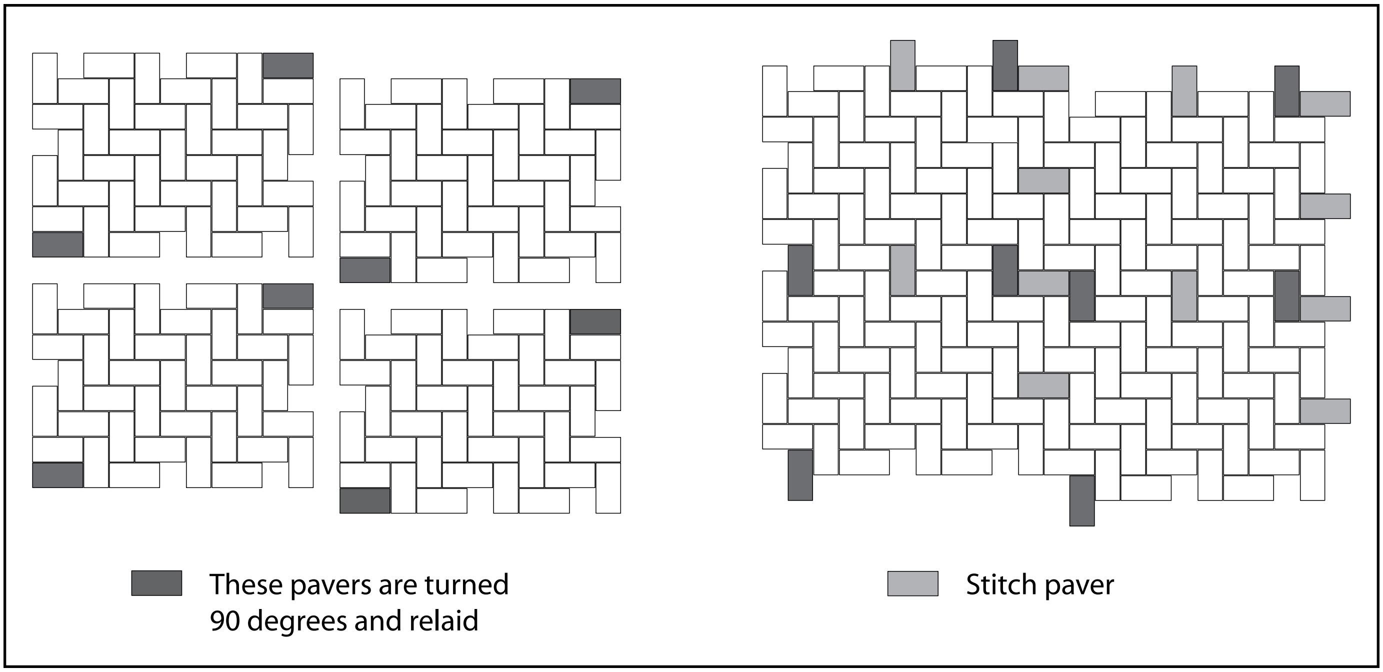

Figure 12. Herringbone pattern with no offset or half pavers.

and some special designs for mechanical installation may need to be offset to stagger the layers. For example, Figure 9 shows hand-laid areas that start a staggered pattern for the remaining machine-set layers.

Half pavers or half stones—Mechanical placement of some herringbone patterns may require half units. These minimize shifting of layers during transport and facilitate a firm grip by the clamp as it grabs each layer. When placed mechanically, herringbone laying patterns require hand removal of half pavers (nominally 4 x 4 in. or 100 x 100 mm in size) on their perimeter. As work proceeds, the removed half pavers are replaced with full-size pavers to create or stitch a pattern that continuously interlocks with no indication of layer or cluster lines. Depending on the layer configuration, two to four half units per layer may need to be removed by hand prior to placing full size units in the openings. (See Figure 10.)

Removal of half pavers is typically done by hand or with a paver extractor. However, they must be removed and replaced with whole units before the pavers are compacted. (See Figure 11.)

Herringbone patterns provide a high degree of interlock. However, a significant cost could be incurred from removing, collecting, and disposing of the half units. Therefore, installation of these patterns can generate waste material and labor costs higher than other laying patterns.

One way to reduce the waste material and extra labor required for herringbone patterns is by having them made without half units. When packaged as cubes, the vertical, half paver openings on their sides may be filled with wood or plastic pipe for the layers to remain stable during shipment. The wood or pipes are removed when each cube is opened at the site. When each layer is installed, full-sized pavers still must be placed in the openings between the layers. Figure 12 shows a herringbone pattern with an offset but with no half pavers.

Bond pattern—Likewise, cross bond and running bond patterns generally do not require an offset area laid by hand. If laid end-to-end, the openings created by running bond patterns may require filling the openings with concrete pavers. Rather than trying to mesh or key the layers into each

Figure 13. Spacer bars on the sides of concrete pavers are essential for mechanical installation.

other, a more efficient method is to butt the ends of the running bond pattern and drop in filler pavers by hand.

A running bond pattern with rectangular shaped units can be manufactured in a stack bond (all joints aligned) and the vertical joints shifted one-half unit on the job site. This can be done with mechanical and hydraulic clamps. Some shaped pavers can be made in stack bond patterns and shifted to running bond by some machines. Besides bond patterns, basket weave patterns can be installed mechanically. Concrete grid pavements can be mechanically installed as well. They are typically placed in a stack, running, or modified bond pattern as shown in Figure 7.

Cross joint bond patterns are designed with no half units to be removed by hand, thereby increasing installation efficiency. Proprietary and non-proprietary patterns have been developed for mechanical installation with no half stones. These have a herringbone-like pattern, and may or may not have completely interlocking patterns from one layer to the next. These patterns install quickly.

Interlock among layers—Most layers and patterns provide a continuous interlocking surface of pavers. Horizontal interlock and the pavement structure are further enhanced by patterns that continuously interlock with their neighbors (9). Others are placed in clusters whose patterns do not interlock from one layer to the next. These kinds of patterns can be offset by a half layer to increase interlock.

Spacer bars—Pavers should have spacer bars or nibs on their sides for mechanical installation. The nibs generally protrude no more than 1/16 in. (2 mm) from the sides of the paver. (See Figure 13.) Spacer bars maintain a minimum joint width between the pavers, especially while the units are grabbed by the clamp and placed on the bedding sand. The space allows joint sand to enter and reduces the likelihood of edge spalling should there be local settlement. Some kinds of permeable interlocking concrete pavers have spacer bars between 3/16 to 1 3/16 in. (5 and 30 mm) to encourage infiltration of stormwater. Most of these concrete pavers can be installed mechanically.

Installation of 2 3/8 in. (60 mm) thick pavers with mechanical or hydraulic equipment is facilitated when spacer bars extend the full height of the paver. Others, called "blind" spacers, extend from the bottom to within 3/16 to 1 in. (5 to 25 mm) at the top of the paver so they aren't visible from the surface. They may be tapered at the top as well.

3. Job Planning

Design considerations—Once a laying pattern is selected, coordination between the designer and the contractor when developing the project drawings can save time and costs. One way to save costs is to minimize cutting of pavers along the edges. For some patterns, this is accomplished by using edge pavers to start or close the pattern. Patterns without edge units may begin along an edge that requires little or no cutting of pavers.

Another cost-saving construction detail is surrounding bollards, water valves, gas valves, manholes, light standards, etc., with a concrete collar. The collars should be of sufficient durability and shape to withstand anticipated loads and climate. Square collars are preferred over round ones because they provide a straight surface against which a string course of pavers is placed. A string course around collars will provide additional stability and better appearance when cut pavers are placed against the course. *ICPI Tech Spec 3—Edge Restraints for Interlocking Concrete Pavements* provides additional information on this construction detail.

If the pavement abuts a high straight curb or a building, two string (running bond) courses or a soldier course of pavers should be placed along the edge (Figure 14). The double course will allow the clamp to operate in the narrow distance between the edge of the layer and the curb or wall. Placement of the laying pattern against this course, rather than directly against a curb or wall presents a clean, sharp appearance at the edges of the pavement.

Paving around a protrusion, such as a manhole, proceeds in a manner similar to manual installation. One side of the manhole is paved, courses counted, and the other side is paved with the number of courses matching the previously laid side. String lines can be pulled longitudinally and laterally across the pattern to check the alignment of joints. String lines should lie on the pavers and no higher. Mechanical installation equipment will likely move strings that are higher.

Storage and flow of materials on the site—A place to store inbound concrete pavers should be identified as part of planning each project. This location may change as the paving progresses. For example, pavers may be stored on

Figure 14. A double row of manually placed pavers along a curb or building provides maneuvering space for the mechanical installation clamp.

Figure 15. Spacing of cubes at the laying face is determined by how much area will be covered by each, as well as by the clearance required by the machine clamp. Orientation of the cubes follows the direction of paving.

Figure 16. A simple gauge for checking dimensional tolerances on the job site.

the construction site at the beginning of the job. As more paving is placed, incoming pavers can be stored directly on the paved area. Time savings are maximized when inbound loads of concrete pavers are unloaded once and moved once to the laying face.

The rate of paver delivery to the job site should be coordinated between the contractor and supplier. Too many pavers may crowd the site and slow productivity. Likewise, an insufficient rate of pavers being delivered can keep crews waiting. Time is saved by identifying places for storage on the site before the job develops and by ordering delivery of a specified number of truckloads or cubes of pavers each day. A staging area may be used to receive the delivered pavers and store them until they are ready to be brought to the laying face.

When cubes are moved from a delivery truck and stored in a staging area, they should be placed on level ground. If they are placed on uneven ground, the layers may shift and become uneven. A great amount of shifting will make clamping each layer by the installation machine difficult or impossible in extreme cases.

Cubes are usually moved from the delivery truck to the staging area or directly to the laying face by a clamp truck or a fork lift truck. When located in a staging area cubes should be spaced apart so that the clamps trucks can lift them.

When cubes are delivered near the laying face, they are usually spaced so that the installation machine operator can grab layers from each cube with the least amount of movement. A cube with eight layers will be placed in four to seven minutes, depending on the skill of the operator and the placement of the cubes. As the layers are placed on the bedding sand, a crew member brings more cubes forward to the laying face. The area between the cubes should approximate the area that the cube will cover when placed (Figure 15).

Orientation of the laying pattern—Depending on the pattern, some paver layers can be placed on the bedding sand in only one or two directions. Therefore, the orientation of the cubes on the site with respect to the direction of paving will affect efficiency. Obviously, the cubes should be moved as little as possible once they reach the site. Their location and orientation will need to be determined before starting the job. They should to be communicated to those responsible for moving the cubes on the site. This will avoid wasted time from the installation machine making additional motions or from moving the cubes into the proper position. Crew members should be informed on placement and spacing cubes as part of planning the job.

4. Systematic and Efficient Execution

Dimensional tolerances—The dimensional tolerances for mechanically placed interlocking concrete pavements should be less then the maximum variance of ±1/16 in. or ±1.6 mm as specified in the ASTM and CSA standards. These standards allow for slight growth dimensions as manufacturing of the job progresses (10, 11). This is due to wear on the manufacturing mold from the production process. If not managed, layers will become increasingly difficult to place into the pattern. This will slow crew production as the layers will require adjustment with mallets and pry bars to accept new layers next to them. Experience and computer modelling has shown that pavers will install more rapidly when growth in overall length and width dimensions are kept under 1 mm.

In addition, straight lines and consistent joint widths will be increasingly difficult to maintain. Because pavers are

Figure 17. Powered screed bucket accelerates spreading of bedding sand. The width of the bucket can be adjusted.

enlarging slightly, joint widths enlarge and joint lines will be impossible to keep straight while attempting to wedge the pavers between layers. Wider joints result in a loss of interlock which may reduce the structural integrity and stability of the pavement surface. Therefore, consistent paver dimensions throughout the job helps the crew work efficiently by maintaining straight lines, uniform joint widths, while contributing to interlock.

Dimensional growth of pavers is managed by periodically changing molds during manufacturing. This will enable pavers to enlarge consistently while staying within specified tolerances. The number of cycles a mold can run prior to changing will depend on its quality and the abrasiveness of the concrete mix. Dimensional growth is also managed by periodically checking the paver dimensions. This distribution can be done with a ruler, template, or a gauge. An example of a gauge is shown in Figure 16.

Dimensional growth is further managed by unloading and installing the largest pavers first. However, loads would need to be marked and distributed on the site in the order of production. This distribution may not be possible on some jobs.

Pavers should have straight, square sides to ensure a secure grip by mechanical or hydraulic clamps. Pavers with bulged or slightly rounded, "bellied" sides can drop while being held by these clamps (12). Furthermore, straight lines and consistent joint widths cannot be maintained and interlock decreases. Bulged sides usually result from excessive water in the concrete mix.

Establishing lines—Job site configuration determines the starting point for mechanical installation. Prior to starting, a string line is pulled or chalk line snapped on the screeded bedding sand. The line is perpendicular to the starting face (which may be a curb if it is square to the line) and several layers are placed on the line to establish straight and square courses of layers. Aligning the layers and joint lines at the beginning of the laying process is essential to keeping joints tight and the pattern "in square" as the job proceeds. The lines can guide manual installation of the starting courses (if required) as well as mechanical laying. Parallel string lines are pulled and spaced at intervals equal to several paver layer widths. The distance between string lines should represent the maximum width of the paver layers, i.e., taking into account growth in the layer width from mold wear. The allowable growth, and means of measurement of layers, should be agreed upon between the manufacturer and installer prior to laying the pavers.

Bedding sand—Besides a consistent flow of pavers, there must be a sufficient area of bedding sand screeded and ready to receive the pavers. An oversize area will not get filled with pavers by the end of the day. A small area will fill rapidly, and the crew must work quickly to prepare more screeded sand. The optimum area to screed depends on the productivity of the machine operator and the continuous flow of pavers. This area is different for each project.

Figure 18. A screeding machine can evenly and rapidly spread bedding sand.

Spreading of bedding sand can be accomplished with a powered screed bucket as shown in Figure 17 or with a screeding machine, illustrated in Figure 18. Mechanical installation machines have broom attachments that sweep the joint sand into the joints of pavers (Figure 19). These are much more efficient than using push brooms.

Color blending—Pavers with two or more colors can be blended together in the factory or on site for mechanical installation (13). This will reduce efficiencies normally achieved with mechanical installation. Consistency of the distribution of the pigment in each layer should be verified by inspecting the manufacturer's product at the factory. Sometimes the distribution of pigments among the layers in the cube can create a checkerboard appearance when the layers are placed. However, concrete pavers made with only one color should not create a checkered appearance when installed. This can be minimized by installing from two or three cubes at a time. There may be slight color variations from layer to layer due to the nature of concrete.

Figure 19. Broom attachments accelerate spreading and filling of joint sand.

Installation crews—Crew sizes and assignments will vary among contractors. A typical crew for mechanical installation is two to five persons. It consists of the machine operator and a helper at the clamp. One person is needed at the laying face to keep lines straight and place pavers between clusters for a continuous interlocking pattern, if required. A crew member can bring cubes to the laying face with a lift truck, while another can cut and fill in units along the edges, and the last crew member can work at compacting the pavers.

Figure 20. Adjusting joint lines with a pry bar prior to compaction.

Clamping, lifting, and placing of pavers are executed as a continuous motion of the machine to maximize productivity. Excess travel of the machine is minimized by placing cubes close to the laying face. The cubes are spaced so that as one cube covers an area, the machine moves easily to the next cube for placing. The machine operator works in a small area supported by a crew that keeps machine travel to a minimum.

The helper at the laying face adjusts the clamp's position before each layer is released onto the bedding sand. The helper removes half pavers and places full-sized pavers as required. He also aligns the pavers with a rubber mallet, making sure that the joints widths are tight and consistent. The alignment of joints and lines is checked by the helper and machine operator using observation by eyesight, string lines, and a transit as the job progresses. Due to the speed at which pavers are mechanically placed, checks should be made with string lines every 20 to 40 ft (6 to 13 m) of paved distance. Joint lines may require adjustment with a pry bar in order to maintain straight lines. See Figure 20.

Project specifications for joint widths should be followed with the contractor straightening uneven jointlines and closing excessively wide joint spaces. While not possible on some jobs, installation of pavers in the order in which they were made enables the contractor to save time and avoid wedging layers of different dimensions between others. Widened joints and uneven joint lines will be reduced as well.

The crew rotates jobs among spreading and screeding the bedding sand ahead of the machine(s), moving cubes into place, removing and neatly storing steel straps and wooden pallets (if used) from the job site, cutting, compacting, spreading joint sand, sweeping, and compacting the pavers behind the installation machine(s). The crew rotates jobs so that no one is fatigued by doing one job continuously.

Any movement of heavy trucks and forklifts should be avoided on a paved area in which units are not yet compacted, joints not filled and compacted again. This will prevent creeping, lipping, breaking or rutting of the surface of the pavement. The pavers should be compacted, joints filled with sand, and recompacted at the end of each day within 6 ft (2 m) of the laying face.

Average productivity per machine and crew including screeding bedding sand, placing, and compacting pavers can be between 3,000 sf (300 m²) and 6,000 sf (600 m²) per eight-hour day (1) (3) (4) (14). Keys to high productivity are pre-job planning among the contractor and material suppliers, as well as high quality pavers. They include careful coordination of deliveries, regulated flow of materials onto the site, and crew members who know their tasks. By careful planning, saving even 15 seconds per layer translates into saving many labor hours. For example, a 100,000 sf (10,000 m²) project may involve placing 10,000 layers. Saving 15 seconds per layer saves 42 labor hours.

Mechanical installation may be appropriate for some jobs and not for others. Naturally, the experience of the foreman and crew will influence productivity. Experienced contractors document productivity and labor costs for mechanical and manual installation through a job costing system. Comparisons of previous job costs between the two installation methods will help indicate whether a proposed job should be placed manually or mechanically. In some cases, a close project deadline, rather than job costs, may dictate the use of mechanical installation.

Reinstatement with mechanical equipment— *ICPI Tech Spec 6—Reinstatement of Interlocking Concrete Pavements* provides guidelines for removing and replacing concrete pavers when making repairs to underground utilities. Prior to extracting layers of pavers with mechanical equipment, an area the size of three layers should first be removed by hand. The removed pavers allow space for separating the remaining layers from each other. The remaining layers are separated in group of layers by a few inches (cm) from each other with a pry bar. This slight distance between layers enables the machine clamp to grab each one (Figure 21). The procedure works best on paving patterns other than herringbone with rectangular units. In most cases extracting individual layers is only possible if they were originally installed without pavers joining one layer to the next.

Figure 21. After the layers are separated they can be grabbed by the machine clamp.

As with manual removal of pavers, each layer removed by machine can be stacked near the pavement opening. If the pavers must be moved away from the site, the layers can be stacked on pallets for easier removal. The sides and bottoms of each layer should be checked for sand sticking to them prior to reinstatement. The sand will often be removed during handling by the machine.

Conclusion

With manual installation, most crew members move between 7 and 10 tons (6.3 and 9 tonnes) of material per day. Mechanical installation requires less physical exertion, thereby reducing fatigue and job related injuries. There are also time and money-saving advantages for the contractor, designer, and project owner. Each project is an exercise in systematic material handling from manufacture to final compaction.

The growth of mechanical installation follows the increased use of concrete pavers in commercial, municipal, port, and airport projects. Owners and designers are encouraged to contact producer and contractor members of the Interlocking Concrete Pavement Institute experienced in the use of mechanical installation in the early stages of a project. Planning will maximize time and money savings. Other ICPI Tech Spec technical bulletins provide additional information on design and construction vital to constructing successful projects with mechanical equipment.

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Tech Spec 15

A Guide for the Specification of Mechanically Installed Interlocking Concrete Pavements

Introduction

This guide assists design professionals in developing a construction specification for the mechanical installation of interlocking concrete pavement. The core is the Quality Control Plan that requires a high level of planning and detail for executing large-scale projects. When refined into a project specification, it should be a tool to obtain a commitment to its requirements by the General Contractor (GC), paver installation subcontractor, manufacturer, and facilitate coordination among them. The ultimate outcome is increased assurance for owners of large paved facilities.

The contractual relationships among the owner, engineer, GC, subcontractors, and manufacturers (suppliers) will vary with each project. This guide assumes that an engineer works for the owner who hires a GC to build the project. The GC subcontracts to a company specializing in interlocking concrete paving. The GC or subcontractor purchases pavers from a paver manufacturer. The engineer or other employees working for the owner inspect and accept the paving.

Construction specifications in North America follow various formats. A common one is by the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC) called MasterFormat (2014) and this guide is written to fit this format. Specifications using the CSI format sections have three parts; General, Products, and Execution. This guide is divided into these three parts to assist in writing each. In MasterFormat section 32 12 12.13 is for Interlocking Precast Concrete Unit Paving.

This Tech Spec does not include material or installation guidelines for permeable interlocking concrete pavement (PICP) installations. See *Tech Spec 18–Construction of Permeable Interlocking Concrete Pavement* or the ICPI manual *Permeable Interlocking Concrete Pavements*, available at ICPI.org.

1.0 PART 1—GENERAL

This specification guide includes the installation of interlocking concrete pavers with mechanical equipment, bedding and joint sand and optional joint

Figure 1. Mechanical installation of interlocking concrete pavements (left) and permeable units (right) is seeing increased use in industrial, port, and commercial paving projects to increase efficiency and safety.

Figure 2. Bundles of ready-to-install pavers for setting by mechanical equipment. Bundles are often called cubes of pavers.

sand stabilization materials. *ICPI Tech Spec 11–Mechanical Installation of Interlocking Concrete Pavements* (ICPI 2015) should be consulted for additional information on design and construction with this paving method. Other references include American Society for Testing and Materials or the Canadian Standards Association for the concrete pavers, sands, and joint stabilization materials, if specified. Placement of the base, drainage and related earthwork should be detailed in another specification section and may be performed by another subcontractor or the GC.

1.1 Definitions

This guide sets forth definitions so all project participants use the same terms within the specification:

Base: Layer(s) of material under the wearing course and bedding course.

Bedding course: A screeded sand layer on which the pavers are bedded.

Bundle: Paver clusters stacked vertically, bound with plastic wrap and/or strapping, and tagged for shipment to and installation at the site. Bundles of pavers are also called cubes of pavers. Concrete paver bundles supplied without pallets are strapped together for shipment then delivered and transported around the site with clamps attached to various wheeled equipment. The subcontractor may provide some wooden pallets at the site to facilitate movement of bundles. See Figure 2.

Chamfer: A 45° beveled edge around the top of a paver unit nominally 2 to 6 mm wide.

Cluster: A group of pavers forming a single layer that is grabbed, held and placed by a paver-laying machine on a screeded sand bedding course.

Interlock: Frictional forces between pavers which prevent them from rotating, or moving horizontally or vertically in relation to each other.

Joint: The space between concrete pavers typically filled with sand.

Joint sand: Sand used to fill spaces between concrete pavers.

Joint sand stabilizer: Liquid applied materials penetrate the in-place joint sand or an additive is mixed dry with sand prior to filling the joints. Joint sand stabilization materials are optional and may be of value in certain applications.

Laying face: Working edge of the pavement where the laying of pavers occurs.

Wearing course: Surfacing consisting of interlocking concrete pavers and joint sand on a sand bedding layer.

Wearing surface: The top paver surface that contacts traffic whose edges are typically chamfered.

1.2 Submittals

The following is submitted by the GC to the engineer for review and approval:

1. 14 pavers with the date of manufacture marked on each. These can be made available for testing.
2. Manufacturer's catalog cut sheets and production mold drawings.
3. The pattern for joining clusters when the pavers are placed on the bedding sand.
4. 6 lbs. (3 kg) bedding sand.
5. 6 lbs. (3 kg) joint filling sand.
6. Manufacturer's catalog cut sheets of joint stabilization material (if specified).
7. 1 quart (liter) joint sand stabilizer or joint sand additive (if specified), or 2 lbs. (1 kg) joint sand stabilizer additive.
8. Quality Control Plan.

1.3 Quality Control Plan

The GC provides the engineer, paver installation subcontractor, and manufacturer with a Quality Control Plan describing methods and procedures that assure all materials and completed construction submitted for acceptance conform to contract requirements. The Plan applies to specified materials procured by the GC, or procured from subcontractors or manufacturers. The GC meets the requirements in the Plan with personnel, equipment, supplies and facilities necessary to obtain samples, perform and document tests, and to construct the pavement.

The GC performs quality control sampling, testing, and inspection during all phases of the work, or delegates same, at a rate sufficient to ensure that the work conforms to the GC requirements. The Plan is implemented wholly or in part by the GC, a subcontractor, manufacturer, or by an independent organization approved by the engineer. Regardless of implementation of parts of Plan by others, its administration, including compliance and modification, remains the responsibility of the GC.

The Plan should be submitted to the engineer at least 30 days prior to the start of paving. The GC, paving subcontractor, and manufacturer then meet with the engineer prior to start of paving to decide quality control responsibilities for items in the Plan. The Plan includes:

1. Quality Control organization chart with the names, qualifications, and contact information of responsible personnel, and each individual's area of responsibility and authority.
2. A listing of outside testing laboratories employed by the

GC and a description of the services provided.
3. Preparation and maintenance of a testing schedule containing a listing of all tests to be performed, who will do them and the frequency of testing.
4. Procedures for ensuring that tests are conducted according with the Quality Control Plan including documentation and steps for taking corrective actions if materials do not meet criteria for meeting the standards.
5. The paver installation subcontractor's method statement.

1.3.1 Quality Control Plan Elements

Testing—Independent testing laboratories typically are involved in testing sand and concrete pavers. They should have in-house facilities for testing bedding and joint sands. The laboratory should provide a letter certifying calibration of the testing equipment to be used for the specified tests. Upon approval of the engineer, the laboratory performs testing of sand and paver samples prior to commencement of paving to demonstrate their ability to meet the specified requirements.

Paver Manufacturer—The paver manufacturer provides evidence of capability to manufacture interlocking concrete pavers. Information may include a history of supplying projects of similar application and size with written project references and contact information for verification. Personnel and qualifications may be part of the submission. The project history and references should demonstrate ability to manufacture interlocking concrete pavers and related work indicated in the plans and specifications to the satisfaction of the engineer.

The submission should include a description of the manufacturer's ability to make, cure, package, store and deliver the concrete pavers in sufficient quantities and rates without delay to the project. Evidence can include diagrams and photos showing the number and stacked height of pavers on pallets, or in bundles without pallets, banding of the pavers, use and placement of plastic wrap, pallet dimensions and construction, and overall loaded pallet or bundle dimensions.

Transportation planning for timely delivery of materials is a key element of large interlocking concrete pavement projects. Therefore, the manufacturer should include a storage and retrieval plan at the factory and designate transportation routes to the site. In addition, there is a description of the transportation method(s) of pavers to the site that incurs no shifting or damage in transit that may result in interference with and delay of their installation. The manufacturer's portion of the quality control plan includes typical daily production and delivery rates to the site for determining on-site testing frequencies.

A key component in the plan is a method statement by the manufacturer that demonstrates control of paver dimensional tolerances. This includes a plan for managing dimensional tolerances of the pavers and clusters so as to not interfere with their placement by paving machine(s)

Figure 3. A cluster of pavers (or layer) is grabbed for placement by mechanical installation equipment. The pavers within the cluster are arranged in the final laying pattern as shown under the equipment.

during mechanical installation. The contents of this plan include, but are not limited to the following:

1. Drawings of the manufacturer's mold assembly including overall dimensions, pattern, dimensions of all cavities including radii, spacer bars, and the top portion of the mold known as a head or shoe.
2. If a job is large enough to require more than one mold, the actual, measured dimensions of all mold cavities need to be recorded prior to manufacture of concrete pavers for this project. This is needed because the new or used production molds may vary in overall cluster size. Mixing pavers from a larger mold with a smaller mold may cause installation problems.
3. Molds wear during manufacture of pavers. Production mold wear is a function of the concrete mix, mold steel, and production machine settings. A manufacturer can control wear by rotating the molds through the production machine(s) on an appropriate schedule so that all molds experience approximately the same amount of wear on the inside of the mold cavities. The manufacturer can also hold a larger mold out of the rotation until the smaller (newer) molds wear sufficiently to match its size. An initial, baseline measurement of all mold cavities provides starting point for documenting and planning for mold cavity growth.
4. The manufacturer should state the number of molds and a mold rotation plan with a statement of how often mold cavities will be measured during production, as well as the method of recording and reporting, and the criteria for mold rotation. While mold cavity wear will vary depending on a number of factors, approximately 0.1 mm wear of the mold cavities can typically be expected for every 10,000 production machine cycles. Production records for each bundle should show the

date of manufacture, a mix design designation, mold number, mold cycles and sequential bundle numbers.

A large variation in cluster size can reduce mechanized paving productivity, thereby increasing costs and lengthening production schedules. Extreme variations in cluster size can make mechanical installation impossible. Following certain procedures during manufacture reduces the risk of clusters that will not fit easily against placed clusters. Such procedures include (1) consistent monitoring of mold cavity dimensions and mold rotation during manufacture, (2) consistent filling of the mold cavities, (3) using a water/cement ratio that does not cause the units to slump or produce "bellies" on their sides after the pavers are released from the mold, and (4) moderating the speed of production equipment such that pavers are not contorted or damaged. All of these factors are monitored by regular measurement of the cluster sizes by the manufacturer and the subcontractor.

It is essential that at least two identical jigs be used to check cluster dimensions, one in the paver production plant and the second on the job site. The manufacturer should provide these two jigs. The jigs should check the overall length and width of assembled, ready-to-place clusters. The sampling frequency should provide at least a 95% confidence level and the frequency should be agreed upon in writing by the owner, GC, subcontractor and manufacturer.

In no case should the "stack test" be used as a means for determining dimensional consistency. This test consists of stacking 8 to 10 pavers on their sides to indicate square sides from a stable column of pavers, or leaning and instability due to bulging sides or "bellies." It is a test for checking for bellied pavers, thereby providing a quick field determination of the possibility of pavers that may not be capable of being installed with mechanical equipment. It is an early warning test to indicate the possibility of installation problems from bellied pavers (Probst 1998). The stack test is not reliable and should not be substituted for actually measuring the pavers to see if they meet specified tolerances.

The mold pattern, the mold rotation plan and the anticipated mold wear information should be reviewed and submitted by both the manufacturer and the paver installation subcontractor. This is necessary to insure that they have a common understanding and expectations.

The subcontractor's quality control procedures include, but are not limited to the following:

1. Demonstrate past use of mechanical installation by key staff on single projects having a similar application and loads.
2. Provide mechanical installation project history including references in writing with contact information for verification. The history and references should demonstrate ability to perform the paver installation and related work indicated in the plans and specifications to the satisfaction of the engineer.
3. List the experience and certification of field personnel and management who will execute the work. Using ICPI Certified Paver Installers is recommended.
4. Provide personnel operating mechanical installation and screeding equipment on job site with prior experience on a job of similar size.
5. Report methods for checking slope and surface tolerances for smoothness and elevations.
6. Show a means for recording actual daily paving production, including identifying the site location and recording the number of bundles installed each day.
7. Show diagrams of proposed areas for storing bundles on the site, on-site staging of storage and use, and the starting point(s) of paving the proposed direction of installation progress for each week of paving. These should be made in consultation with the GC as site conditions that effect the flow of materials can change throughout the project.
8. Provide the number of paver installation machines present on the site, and anticipated average daily installation rate in square feet (m^2).
9. Submit the paver manufacturer's pallet configuration diagram, including dimensions, of the typical cluster or layer to be used.
10. Provide a diagram of the laying pattern used to join clusters including a statement about or illustration of the disposition of half-pavers, if any.
12. The subcontractor and manufacturer are encouraged to hold memberships in the Interlocking Concrete Pavement Institute.

1.4 Mock-Up

A requirement for a test area or mock-up may or may not be included in the project specification documents. If required in the specifications, the mock-up shall serve as an example of compliance with the construction documents. The mock-up may be constructed prior to the start of construction or may be part of the first work day.

The mock-up:

1. Install a minimum paver area of 600 sq. ft. [56 m^2] or 6 cubes.
2. Use this area to determine the surcharge of the bedding sand layer, joint sizes, lines, laying pattern(s), color(s) and texture of the job.
3. Evaluate the need for protective pads when compacting paving units with architectural finishes.
4. This area will be used as the standard by which the work will be judged.
5. Subject to acceptance by owner, mock-up may be retained as part of finished work.
6. If mock-up is not retained, remove and properly dispose of mock-up.

A mock-up can be a valuable tool, because it will set the standard for workmanship and quality for the rest of the project. A collaborative effort between the contractor, specifier and owner is the best way to assure a successful project. A site visit and inspection of the installation during the first day of paving is often a much better solution to a mock-up from financial and expediency perspectives. In either case, the owner's representative shall provide the contractor with a written statement of approval.

1.5 Delivery, Storage And Handling

All required testing for products or materials should be completed and the results submitted in writing for approval by the engineer prior to delivery of paving products or materials to the site. Materials should arrive at the site with no damage from hauling or unloading, and be placed on the site according the Quality Control Plan. Each bundle of pavers should be marked with a weatherproof tag that includes the manufacturer, the date of manufacture, the mold number, the project (or project phase), for which the pavers were manufactured, and the sequential bundle number. The sequential number should be applied to the bundle based on the manufacturing run for the job, not on the order of delivery. Any breaks in numbering should be reported immediately by the manufacturer to the subcontractor, GC and engineer in writing. During production, mold wear can cause the paver produced last to be slightly larger than the paver produced at the beginning. If possible have the larger pavers delivered to site first so the will be installed at the start of the project.

Bedding and joint sand delivered to the site should be covered and protected from wind and rain. Saturated bedding cannot be installed because it will not compact. Environmental conditions precluding installation are heavy rain or snowfall, frozen granular base, frozen sand, installation of pavers on frozen sand, and conditions where joint sand may become damp so as to not readily flow into the joints.

2.0 PART 2—PRODUCTS

2.1 Concrete Pavers

In North America, concrete pavers should meet ASTM C936 (ASTM 2016) in the United States or CSA A231.2 (CSA 2014) in Canada. Besides supplier information, the color(s), plus the exact length, width, and height dimensions of the units should be stated. Spacer bars are required for mechanical installation and are not included in the overall dimensions. Spacer bars should protrude from the side of the paver a distance equal to the minimum allowable joint width. See Figure 4.

ASTM C936 includes the following requirements:

1. Absorption: 5% average with no individual unit greater than 7% per ASTM C140 (ASTM 2012).
2. Abrasion resistance: No greater volume loss than 0.92 in.^{3} (15 cm^3) per 7.75 in.^{2} (50 cm^2) and average thickness loss shall not exceed 0.118 in. (3 mm) when tested in accordance with Test Method ASTM C418 (ASTM 2012).
3. Compressive strength: Average 8,000 psi (55 MPa), with no individual unit below 7,200 psi (50MPa) when tested according to ASTM C140.
4. Freeze-thaw deicing salt durability: average weight loss not exceeding 225 g/m^2 of surface area after 28 cycles or 500 g/m^2 after 49 cycles per ASTM C1645 (2009). Freeze-thaw testing can be conducted in tap water for projects not subject to deicing salts. Furthermore, freeze-thaw testing can be omitted altogether for pavers in projects not subject to freezing.

If cut, cube-shaped coupons are tested, use the 55 MPa and 50 MPa values regardless of the initial dimensions of the paver from which the coupon was cut.

CSA A231.2 includes the following requirements:

1. Compressive strength: Average 7,200 psi (50 MPa) at 28 days with no individual unit less than 6,500 psi (45 MPa). The CSA test method for compressive strength tests a cube-shaped specimen.
2. Freeze-thaw deicing salt durability: average weight loss not exceeding 225 g/m^2 of surface area after 28 cycles or 500 g/m^2 after 49 cycles. Testing in a saline solution can be omitted for projects not subject to deicing salts. The CSA test uses a lower freezing temperature than the ASTM C1645 test method.

The ASTM and CSA freeze-thaw deicing salt tests for freeze-thaw durability requires several months to conduct. Often the time between manufacture and time of delivery to the site is a matter of weeks or even days. In such cases, the engineer may consider reviewing freeze-thaw deicing salt test results from pavers made for other projects with the same mix design. These test results can be used to demonstrate that the manufacturer can meet the freeze-thaw durability requirements in ASTM C936 and CSA A231.2. Once this requirement is met, the engineer should consider obtaining freeze-thaw deicing salt durability test results on a less frequent basis than stated here.

Concrete pavers should not be installed if they do not meet the requirements of ASTM C936 or CSA A231.2.

A key aspect of this guide specification is dimensional tolerances of concrete pavers. For length and width tolerances, ASTM C936 allows ±1/16 in. (±1.6 mm) and CSA A231.2 allows ±2 mm. These are intended for manual installation and should be reduced to ±1.0 mm (i.e., ±0.5 mm for each side of the paver) for mechanically installed projects,

Figure 4. Spacer bars are small nibs on the sides of the pavers that provide a minimum joint spacing into which joint sand can enter.

excluding spacer bars. Height should not exceed ±1/8 in. (±3 mm) from specified dimensions. Dimensions should be checked with calipers.

2.1.1 Quality Assurance Testing

An independent testing laboratory typically conducts tests on the pavers and sands. The General Conditions of the Contract (typically found in Division 01 of the project manual) may specify who pays for testing. It is recommended that the GC be responsible for all testing. All test results should be provided to the engineer, GC, subcontractor, and manufacturer, and within one working day of completion of the tests. All should be notified immediately if any test results do not meet those specified. Independent laboratory testing is intended for project quality assurance. It does not replace any testing required for quality control during production.

For the initial testing frequency, randomly select 14 full-size pavers from initial lots of 25,000 sf (2,500 m^2) manufactured for the project, or when any change occurs in the manufacturing process, mix design, cement, aggregate or other materials. 25,000 sf (2,500 m^2) approximates an 8-hour day's production by one paver manufacturing machine. This can vary with the machine and production facilities. This quantity and the sample size should be adjusted according to the daily production or delivery from the paver supplier. Consult the paver supplier for a more precise estimate of daily production output. Initial sampling and testing of pavers should be from each day's production at the outset of the project to demonstrate consistency among aggregates and concrete mixes.

Testing includes five pavers for dimensional variations, three pavers for density and absorption and three pavers for compressive strength (and three pavers for freeze-thaw durability if required). If all tested pavers pass all requirements for a sequence of 125,000 sf (12,500 m^2) of pavers, then reduce the testing frequency for each test to three full-sized pavers from each 25,000 sf (2,500 m^2) manufactured. If any pavers fail any of these tests, then revert to the initial testing frequency.

One paver manufacturing machine can produce approximately 125,000 sf (12,500 m^2) in five days. This can vary with the machine and production facilities. This quantity and the sample size should be adjusted according to the daily production or delivery from the paver supplier. Consult the manufacturer for a more accurate estimate of the five-day production output.

The entire bundle of pavers from which the tested paver(s) were sampled should be rejected when any of the individual test results fails to meet the specified requirements. Additional testing from bundles manufactured before and after the rejected test sample should be performed to determine, to the satisfaction of the engineer, the sequence of the paver production run that should be rejected. Any additional testing should be performed at no cost to the owner. The extent of nonconforming test results may necessitate

ASTM C33		CSA A23.1 FA1	
Sieve Size	Percent Passing	Sieve Size	Percent Passing
3/8 in.(9.5 mm)	100	10.0 mm	100
No. 4 (4.75 mm)	95 to 100	5.0 mm	95 to 100
No. 8 (2.36 mm)	80 to 100	2.5 mm	80 to 100
No. 16 (1.18 mm)	50 to 85	1.25 mm	50 to 90
No. 30 (0.6 mm)	25 to 60	630 μm	25 to 65
No. 50 (0.3 mm)	5 to 30	315 μm	10 to 35
No. 100 (0.15 mm)	0 to 10	160 μm	2 to 10
No. 200 (0.075 mm)	0 to 1	80 μm	0 to 1

Note: Bedding sands should conform to ASTM C33 or CSA A23.1 FA1 gradations for concrete sand. For ASTM C33, ICPI recommends the additional limitations on the No. 200 (0.075 mm) sieve as shown. For CSA A23.1 FA1, ICPI recommends reducing the maximum passing the 80 μm sieve from 3% to 1%.

Table 1. Gradation for Bedding Sand

ASTM C144		CSA A179	
Sieve Size	Percent Passing	Sieve Size	Percent Passing
No. 4 (4.75 mm)	100	5.0 mm	100
No. 8 (2.36 mm)	95 to 100	2.5 mm	90 to 100
No. 16 (1.18 mm)	70 to 100	1.25 mm	85 to 100
No. 30 (0.6 mm)	40 to 75	630 μm	65 to 95
No. 50 (0.3 mm)	10 to 35	315 μm	15 to 80
No. 100 (0.15 mm)	2 to 15	160 μm	0 to 35
No. 200 (0.075 mm)	0 to 5	80 μm	0 to 10

Note: The allowable maximum percent passing the No. 200 (0.075 mm) sieve may need to be decreased to allow for penetration of surface applied liquid joint sand stabilizer. Test penetration depths on the site mock-up area of paving.

Table 2. Gradation for Joint Sand

rejection of entire bundles of pavers or larger quantities. The engineer may need to exercise additional sampling and testing to determine the extent of non-conforming clusters and/or bundles of pavers, and base rejection of clusters of entire bundles on those findings.

2.2 Bedding Sand

Bedding sand gradation should conform to ASTM C33 (ASTM 2018) or CSA A23.1 (CSA 2014) as appropriate with modifications as noted in Table 1. Supply washed, natural or manufactured, angular sand.

At the start of the project, conduct gradation tests per ASTM C136 (ASTM 2014) or CSA A23.2A (CSA 2014) for every 25,000 sf (2,500 m^2) of wearing course or part thereof. Testing intervals may be increased upon written approval by the engineer when sand supplier demonstrates delivery of consistently graded materials.

The Micro-Deval test is recommended as the test method for evaluating durability of aggregates in North America. Defined by CSA A23.2-23A, *The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* (CSA 2014), the test method involves subjecting aggregates to abrasive action from steel balls in a laboratory rolling jar mill. In the CSA test method a 1.1 lb (500 g) representative sample is obtained after washing to remove the No. 200 (0.080 mm) material. The sample is saturated for 24 hours and placed in the Micro-Deval stainless steel jar with 2.75 lb (1250 g) of steel balls and 750 mL of tap water (See Figure 1). The jar is rotated at 100 rotations per minute for 15 minutes. The sand is separated from the steel balls over a sieve and the sample of sand is then washed over an 80 micron (No. 200) sieve. The material retained on the 80 micron sieve is oven dried. The Micro-Deval loss is then calculated as the total loss of original sample mass expressed as a percentage. ASTM D7428 (ASTM 2015) is a similar test where the test apparatus uses the same size drum and rotates at the same rpm.

Table 3 lists the primary and secondary material properties that should be considered when selecting bedding sands for vehicular applications. Other material properties listed such as soundness, petrography and angularity testing are at the discretion of the specifier and may offer additional insight into bedding sand performance.

Repeat the Micro-Deval test for every 250,000 sf (25,000 m^2) of bedding sand or when there is a change in sand source. Test intervals for other material properties should be at every 200,000 sf (25,000 m^2) of bedding sand or higher as determined by the engineer. *ICPI Tech Spec 17—Bedding Sand Selection for Interlocking Concrete Pavements in Vehicular Applications* provides additional background to these test methods and criteria.

2.3 Joint Sand

Joint sand gradation should conform to ASTM C144 (ASTM 2017) or CSA A179 (CSA 2014) with modifications as noted in Table 2. Supply washed, manufactured, angular sand.

At the start of the project, conduct gradation test for every 25,000 sf (2,500 m^2) of concrete paver wearing course. Testing intervals may be increased upon written approval by the engineer when the sand supplier demonstrates delivery of consistently graded materials.

Material Properties	Test Method	Recommended Maximum or Minimum
Primary Properties		
Gradation	See Table 1 and Table 2	Maximum 1 % passing No. 200 (0.075 or 0.080 mm) sieve
Micro-Deval Degradation	CSA A23.2-23A ASTM D7428	Maximum 8%
Constant Head Permeability	ASTM D2434	Minimum 2×10^{-3} cm/second (2.83 in/hr)
Secondary Properties		
Soundness – Sodium Sulfate or Magnesium Sulfate	ASTM C88	Maximum 7%
Silica (Quartz and Quartzite)/ Carbonate Ratio	MTO LS-616 ASTM C295	Minimum 80/20 ratio
Angularity and Particle Shape	ASTM D2488	Minimum 60% combined sub- angular and sub- rounded

Note 1: See "Recommended Material Properties" on page 5 of ICPI Tech Spec 17

Note 2: Bedding sand may also be selected based on field performance. Field performance is selected when the specifier or contractor assumes responsibility for the selection and performance of bedding sand not conforming to the properties in Table 4. Field performance as a selection criteria is suggested when the available local materials do not meet the primary material properties suggested in Table 4, but the specifier or contractor can demonstrate to the satisfaction of the owner (or owner's representative), successful historical field performance. In this case the owner should specify the class of vehicular traffic, and the contractor should verify past field performance of the bedding sand under similar vehicular traffic.

Table 3. Recommended Laboratory Material Properties for Bedding and Joint Sands in Vehicular Applications

2.4 Joint Sand Stabilizer

Stabilization materials for joint filling sand are optional and there are two categories of materials. These are liquid penetrating and dry mix formulas including materials mixed with joint sand and activated with water. Both categories of materials achieve early stabilization of joint sand. Liquid penetrating materials should have 24-hour cure time and be capable of penetrating the joint sand to a minimum depth of 1 in. (25 mm) prior to curing. Dry mix organic or polymer additives combine with joint sand prior to placing it in the joints. These materials typically cure in a few hours after activation with water. If the need for joint sand stabilization is determined, the application rate and method should be established on the mock-up area of paving.

3.0 PART 3 – EXECUTION

3.1 Examination

The elevations and surface tolerance of the base determine the final surface elevations of concrete pavers. ICPI recommends a base surface tolerance of +/- 3/8 in. over 10 ft. (+/- 8 mm over 3 m). The paver installation subcontractor cannot correct deficiencies in the base surface with additional bedding sand or by other means. Therefore, the surface elevations of the base should be checked and accepted by the GC or designated party, with written certification to the paving subcontractor, prior to placing bedding sand and concrete pavers.

The GC should inspect, accept and certify in writing to the subcontractor that site conditions meet specifications for the following items prior to installation of interlocking concrete pavers:

1. Subgrade preparation, compacted density and elevations conform to specified requirements.
2. Geotextiles or geogrids, if applicable, placed according to drawings and specifications.
3. Aggregate, cement-treated, asphalt-treated, concrete, or asphalt base materials, thicknesses, compacted density, plus surface tolerances and elevations that conform to specified finished surface requirements.

Heavy-duty paving will often have high strength base material such as cement stabilized base, concrete slabs or asphalt. Even though these materials are used as a base layer, the construction specification must require installation of the top layer of these materials to typical surface finish tolerances. Asphalt crews, for example, may use different elevation control methods for base lifts than they do for top lifts. The base lift methods often are not as tightly controlled for grade as variations can be made up by the top lift of asphalt. If a base lift is directly under the bedding sand, a top lift may not be present, nor close surface tolerances normally expected from a top lift. Compensation for variations in base lift elevations must not be from adding more bedding sand. Special care should also be taken at edge contacts to ensure that asphalt, or other materials are installed deeply enough to allow a complete paver and sand section above.

Edge restraints should be in place before pavers are installed. Some projects can have completed edge restraints with paving activity near them while the construction schedule dictates that the opposite side of the area may see ongoing construction of edge restraints. In such cases, the GC should propose an edge restraint installation schedule in writing for approval by the engineer. All bollards, lamp posts, utility covers, fire hydrants and like obstructions in the paved area should have a square or rectangular concrete collar. The location, type, and elevations of edge restraints, and any collars around utility structures, and drainage inlets should be verified with the drawings.

Likewise, verification of a clean surface of the base surface is required, including no standing water or obstructions prior to placing the bedding sand and concrete pavers. There will be a need to provide drainage during installation of the wearing course and joint sand by means of weep holes or other effective method per the drawings, temporary drains into slot drains, dikes, ditches, etc. to prevent standing water on the base and in the bedding sand. These may be indicated on the drawings. If not, they should be a bid item provided by the GC from the paver installation subcontractor. All locations of paver contact with other elements of the work should be inspected, including weep holes, drain inlets, edge restraints, concrete collars, utility boxes, manholes and foundations. Verify that all contact surfaces with concrete pavers are vertical.

Areas where clearances are not in compliance, or where the design or contact faces at adjacent pavements, edges, or structures are not vertical should be brought to the attention of the GC and engineer in writing with location information. The GC should propose remediation method(s) for approval by the engineer. All such areas shall be repaired prior to commencing paver installation. Alternately, the GC may propose a repair schedule in writing for approval by the engineer.

3.2 Installation

There are a variety of ways to install interlocking concrete pavements. The following methods are recommended by ICPI as best practices. Other methods vary mainly in the techniques used for compaction of the pavers and joint sand installation. ICPI recommends using a vibrating plate compactor on concrete pavers for consolidation of bedding and joint sands.

The bedding sand installation begins by screeding a uniform uncompacted layer to a nominal 1 in. (25 mm) thickness. When determining the surface elevation for the base allow for consolidation due to compaction of the pavers, typically 3/16 in. (5 mm), and an additional 3/16 in. (5 mm) for paver surfaces above curbs and utility structures. For example, if the pavers are 3 1/8 in. (80 mm) thick, the elevations of the base surface should be 3 3/4 in. (95 ± 5 mm) below the finish elevation of the pavement. The exact amount of consolidation will vary depending on local sands and this is determined in the mock-up. Do not fill depressions in the surface of the base with

Figure 7. Maintaining an angular laying face that resembles a saw-tooth pattern facilitates installation of paver clusters.

bedding sand, as they may reflect to the paver surface in a few months.

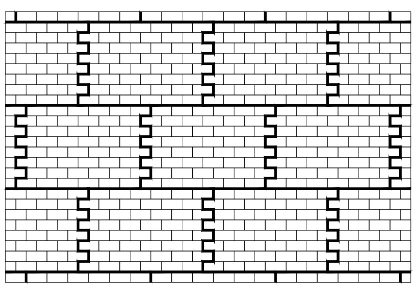
Variations in the surface of the base must be repaired prior to installation of the bedding sand. The screeded bedding course should not be exposed to foot or vehicular traffic. Fill voids created by removal of screed rails or other equipment with sand as the bedding proceeds. The screeded bedding sand course should not be damaged prior to installation of the pavers. Types of damage can include saturation, displacement, segregation or consolidation. The sand may require replacement should these types of damage occur.

Installation of the concrete pavers starts with securing string lines, laser lines or snapping chalk lines on the bedding course. These or other methods are acceptable to maintain dimensional control in the direction of paving. These lines are typically set at 50 ft. (15 m) intervals for establishing and maintaining joint lines at maximum allowable width of clusters. The installation subcontractor will determine exact intervals for lines.

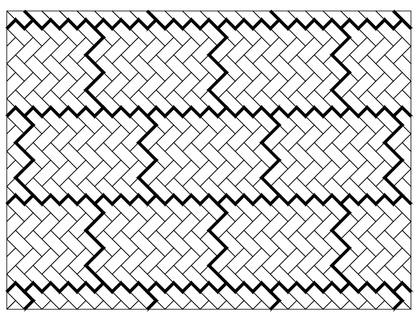
A starting area may need to be placed by hand against an existing curb. This will establish coursing, squareness of the pattern, and offset of the mechanical installed layers. Interlocking patterns such as herringbone patterns are recommended for port pavements. The orientation of the pattern is typically governed by the site operational layout and orientation should be included in the drawings. An angular laying face (or faces) should be maintained with the laid clusters creating a saw tooth pattern. This will facilitate rapid installation and adjustment of clusters as laying proceeds. Figure 7 illustrates this pattern for the laying face.

Bundles of pavers are positioned by the laying face and machines pick from them as laying proceeds. Pulling pavers from several cubes will help integrate the color variations between bundles. Straight joint lines are maintained by adjusting clusters and pavers with rubber hammers and alignment bars. Maximizing interlock among clusters and throughout the pavement surface is assisted by the placement pattern of the clusters. To help maximize the interlock between clusters, installations should avoid straight, continuous bond lines throughout the pavement surface. Rotating clamps on mechanical placement equipment facilitate easier clusters placement in patterns that do not create continuous joint lines.

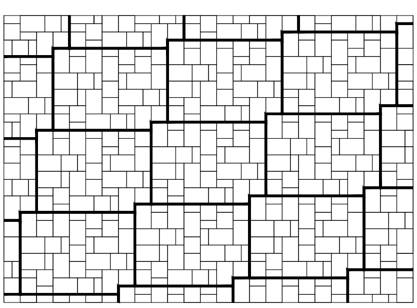
Paver cluster configuration determines stitching as well as possible cluster placement. Some pavers clusters created with dentated paving units mesh into each other and do not require stitching. If the cluster pattern has half-sized paver units, offset their locations when placing clusters or maintain their alignment, remove and fill openings with full-sized pavers, thereby stitching and interlocking each cluster with its neighbors. Just as the paving pattern can affect the pavement strength and stability under vehicular traffic, so can the placement pattern of clusters. Clusters placed in herringbone patterns offer increased stability over clusters placed



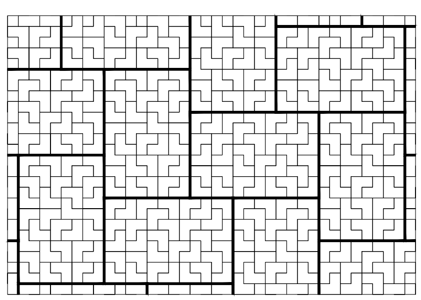
Clusters laid in running bond pattern create a running bond pattern in pavement.



Clusters laid in running bond pattern create a herringbone pattern in pavement.



Notched clusters create horizontal and vertical shifts in the cluster pattern that minimize long continuous bond lines.



Rectangular clusters laid in a herringbone pattern minimize long continuous bond lines.

Figure 8. Cluster patterns

Figure 9. Edge pavers are saw cut to fit against a drainage inlet.

Figure 10. Initial compaction sets the concrete pavers into the bedding sand.

Figure 11. During initial compaction, cracked pavers are removed and immediately replaced with whole units.

in a running bond patterns. This supports the recommended use of herringbone patterns in vehicular areas.

Different laying and cluster patterns are shown in Figure 8. The need to maximize interlock among clusters with stitching depends on expected vehicular loads. For lower load applications, stitching may not be needed. In some cases stitching is done more for aesthetic reasons. For higher load applications, herringbone patterns or stitching clusters together may be required. The cluster configuration pattern and stitching (if required) should be illustrated in the method statement in the Quality Control Plan. As paving proceeds, hand install a string course of pavers around all obstructions such as concrete collars, catch basins/drains, utility boxes, foundations and slabs.

Pavers are typically cut with powered saws. Cutting pavers with mechanical (non-powered) splitters for industrial pavement is an acceptable method as long as the resulting paver meets project tolerances for squareness and surface variations, as well as specified joint widths. Do not allow concrete materials emitted from cutting operations to collect or drain on the bedding sand, joint sand or in unfinished joints. Figure 9 shows a cutting with a dust collection system to prevent contamination of surfaces. If such contact occurs, remove and replace the affected materials.

Whenever possible cut pavers exposed to tire traffic should be no smaller than one-third of a full paver and all cut pavers should be placed in the laying pattern to provide a full and complete paver placement prior to initial compaction. Coursing can be modified along the edges to accommodate cut pavers. Joint lines are straightened and brought into conformance with this specification as laying proceeds and prior to initial compaction. Sometimes the pattern may need to be changed to ensure that this can be achieved. However, specifiers should note that some patterns cannot be changed because of the paver shape and some paver cuts will need to be less than one-third.

Remove debris from surface prior to initial compaction and then compact the pavers using a vibrating plate compactor with a plate area not less than 2 sf (0.2 m^2) that has a minimum compactive force of 5,000 lbs (22 kN) at 75 to 100 Hz (see Figure 10). After initial compaction, remove cracked or broken pavers, and replace with whole units. Figure 11 shows removal of a paver with an extraction tool. Initial compaction should occur within 6 ft. (2 m) of all unrestrained edges at the end of each day.

After initial compaction of the pavers, sweep and vibrate dry joint sand into the joints until all are completely filled with consolidated joint sand (see Figures 12 and 13). The number of passes and effort required to produce completely filled joints depends on many factors. Some of these include sand moisture, gradation and angularity, weather, plus the size, condition and adjustment of the vibrating plate, the thickness of the pavers, the configuration of the

Figure 12. Sweeping jointing sand across the pavers is done after the initial compaction of the concrete pavers.

Figure 13. Final compaction should consolidate the sand in the joints of the concrete pavers.

Figure 14. A simple test with a putty knife checks consolidation of the joint sand.

pavers and the skill of the vibrating plate operator.

Joint sand should be spread on the surface of the pavers in a dry state. If it is damp, it can be allowed to dry before sweeping and vibration so it can enter the joints readily. Vibrate and fill joints with sand to within 6 ft. (2 m) of any unconfined edge at the end of each day.

The various activities of the crews should be scheduled so that the paver surface is completed each day. This is the best practice. The surface should be placed to specified tolerances with all cut pavers in place before initial compaction, and the joints completely filled after the final compaction. This provides the maximum protection from weather and vehicles. Moreover, once an area is completed, inspected and accepted, it can be put to immediate use by the owner.

Coordination and Inspection—Large areas of paving are placed each day and often require inspection by the engineer or other owner's representative prior to initial and final compaction. Inspection should keep up with the paving so as to not delay its progress. There may be the occasional case where the inspection is not administered on a timely basis. In such unlikely cases, the engineer should decide the total allowable uncompacted area. It should be based on the daily production of the subcontractor, inspection schedules, and weather. Therefore, the engineer may establish a maximum distance from the laying face for uncompacted pavers that relates to the timing of inspection. For work in rainy weather, the 6 ft. (2 m) distance should be maintained, regardless of the timing of inspection. Rainfall will saturate the bedding sand under uncompacted pavers with no sand in the joints. This condition makes the bedding course impossible to compact.

3.2.1 Joint Sand Consolidation

After the final compaction of the sand in the joints, filling and consolidation of the joint sand should be checked by visually inspecting them. Consolidation is important to achieving interlock among the units. Consolidation also reduces infiltration of water into the sand and base. This can be done by dividing the project into areas of about 5,000 sf to 10,000 sf (500 to 1,000 m^2). Visually and physically inspect each area by taking at least 30 measurements of joint sand depth and consolidation. Take measurements by inserting a thin, rigid putty knife into the joint and pressing down. See Figure 14. It should not penetrate more than 1/4 in. (6 mm) when pressed firmly into the joint.

If areas are found deficient in consolidation and/or joint sand, make additional passes of a plate compactor. It should have a minimum compaction of 5,000 lbf (22 kN). Higher force compactors will be required on pavers thicker than 3 1/8 in. (80 mm). Inspect the joints again after refilling and compaction. Fill and compact until the joint sand has consolidated so that a putty knife moves less than 1/4 in. (6 mm) into the joint.

3.3 Tolerances on Completion

The minimum joint width is determined by the size of the spacer bar used for the project. This is typically 1/16 in. (2 mm). The maximum joint width depends on the paver shape and thickness. Generally, thicker pavers with more than four sides (dentated) will require slightly larger joints, often as much as 1/4 in. (6 mm).

Recommended tolerances are as follows:

1. Joint widths: This depends on the paver thickness. For 3 1/8 and 4 in. (80 and 100 mm) thick pavers, 1/16 to 3/16 in. (2 to 5 mm) is acceptable. No more than 10% of the joints should exceed 5 mm for the purposes of maintaining straight joint lines. For 4 3/4 in. (120 mm) thick dentated pavers, the maximum joint spacing can be increased to 1/4 in. (6 mm) with no more than 10% of the joints exceeding 6 mm for the purposes of maintaining straight joint lines and the designer might want to consider a coarser gradation of jointing sand.
2. Bond or joint lines: ±1/2 in. (±15 mm) from a 50 ft. (15 m) string line.
3. Surface tolerances: ±3/8 in. over a 10 ft. (±10 mm over a 3 m) straightedge. This may need to be smaller if the longitudinal and cross slopes of the pavement are 1%. Surface elevations should conform to drawings. The top surface of the pavers may be 1/8 to 1/4 in. (3 to 6 mm) above the final elevations after the second compaction. This helps compensate for possible minor settling normal to pavements. The surface elevation of pavers should be 1/8 to 1/4 in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels. Surface tolerances on flat slopes should be measured with a rigid straightedge. Tolerances on complex contoured slopes should be measured with a flexible straightedge capable of conforming to the complex curves in the pavement.

3.4 Protection and Clean Up

The GC should insure that no vehicles other than those from the subcontractor's work are permitted on any pavers until completion of paving. This requires close coordination of vehicular traffic with other contractors working in the area. After the paver installation subcontractor moves to another area of a large site, or completes the job and leaves, he has no control over protection of the pavement. Therefore the GC should assume responsibility for protecting the completed work from damage, fuel or chemical spills. If there is damage, it should be repaired to its original condition, or as directed by the engineer. When the job is completed, all equipment, debris and other materials are removed from the pavement.

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Figure 14. The Port of Oakland, California, is the largest mechanically installed project in the western hemisphere at 4.7 million sf (470,000 m^2).

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Tech Spec 17

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Bedding Sand Selection for Interlocking Concrete Pavements in Vehicular Applications

Bedding sands are a critical component of all sand-set segmental concrete paving systems. Especially for vehicular applications, specifiers and contractors need to consider bedding sand selection. While gradation is an important consideration, other characteristics should be assessed in order to ensure long-term pavement performance. This technical bulletin examines these characteristics and provides guidance to specifiers and contractors.

Background

Bedding sand provides four main functions. It beds the pavers during installation; helps initialize interlock among the pavers; provides a structural component for the system (as described in *ICPI Tech Spec 4 Structural Design of Interlocking Concrete Pavement for Roads and Parking Lots*) and facilitates drainage of water that infiltrates through the joints. Typical specifications require bedding sands to conform to ASTM C33 and CSA A23.1 FA1 gradation for concrete sands with additional limits on the allowable amount of material that passes the No. 200 (0.075 mm*) sieve (See Table 1). In vehicular applications, experience and research have shown that other factors besides gradation contribute to the successful function of the bedding layer in vehicular applications. Knapton (1994) notes that since 1980 the amount of material passing the No. 200 (0.075 mm) sieve has been reduced in the British Standard BS 7533-1 (2001) *Guide for the Structural Design of Heavy Duty Pavements Constructed of Clay or Concrete Pavers*. He notes that fines have reduced from 10% in 1980, to 3% in 1991, to 1% for heavily trafficked pavements, further reducing to 0.1% for bus stations. North American standards currently limit the amount of allowable material passing these sieves to 1%.

Other studies (Lilley and Dowson 1988) (Beaty 1996)

ASTM C33		CSA A23.1 FA1	
Sieve Size	Percent Passing	Sieve Size	Percent Passing
3/8 in.(9.5 mm)	100	10.0 mm	100
No. 4 (4.75 mm)	95 to 100	5.0 mm	95 to 100
No. 8 (2.36 mm)	80 to 100	2.5 mm	80 to 100
No. 16 (1.18 mm)	50 to 85	1.25 mm	50 to 90
No. 30 (0.6 mm)	25 to 60	630 μm	25 to 65
No. 50 (0.3 mm)	5 to 30	315 μm	10 to 35
No. 100 (0.15 mm)	0 to 10	160 μm	2 to 10
No. 200 (0.075 mm)	0 to 1[1]	80 μm	0 to 1[1]

Note 1: Bedding sands should conform to ASTM C33 or CSA A23.1 FA1 gradations for concrete sand. For ASTM C33, ICPI recommends the additional limitations on the No. 200 (0.075 mm) sieve as shown. For CSA A23.1 FA1, ICPI recommends reducing the maximum passing the 80 μm sieve from 3% to 1%.

Table 1. Gradation for Bedding Sand

**Although the ASTM equivalent for the No. 200 sieve size is 75 micron (.075 mm), CSA standards use the German (DIN) and French (ANFOR) standard equivalent sieve size of 80 micron (0.080 mm)* have investigated failures of segmental concrete pavements subjected to channelized vehicular traffic. They have also concluded that more comprehensive specifications are required. Lilley and Dowson (1988) suggested that bedding sands in segmental concrete pavements designed to carry more than 1.5 million equivalent standard axle loads, ESALs (18 kip/80 kN), should be subjected to grading and degradation tests. *For the purposes of this Tech Spec, vehicular traffic is defined as roads exposed to a minimum of 1.5 million lifetime ESALs and axle loads up to 24,250 lbs (11,000 kg).*

Failure Mechanisms

Failure of the bedding sand layer occurs in channelized vehicular loads from two main actions; structural failure through degradation and saturation due to inadequate drainage. Since bedding sands are located high in the pavement structure, they are subjected to repeated applications of high stress from the passage of vehicles over the pavement (Beaty 1996). This repeated action, particularly from higher bus and truck axle loads, will degrade the bedding sand and cause failure. For these applications sand should be selected based on their ability to withstand long-term degradation.

Bedding sand permeability also is a significant factor in the selection process. Wherever difficulties have been experienced with laying course materials in heavily trafficked pavements, water has been a major factor (Knapton 1994). As they approach higher moisture levels in service, bedding sands may become unstable. Smaller particle sizes (fines) become suspended in water, forming slurry that lubricates the entire bedding layer. Choosing bedding sand with a gradation as shown in Table 1 will help to reduce the risk of poor drainage and instability. However, these sands will be susceptible to drainage problems if they do not have the hardness to withstand long term degradation from vehicular wheel loads.

Figure 1. The Micro-Deval test apparatus.
Source: Gilson Company

Selection and Performance Design Principles—Going beyond gradation

Selecting Durable Bedding Sands—Durability of aggregates has long been understood to be a major factor in pavement performance. ASTM C88 *Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate* (ASTM 2005) is an example of a typical test method used by road agencies to assess aggregate durability. The test involves soaking an aggregate in a solution of magnesium or sulfate salts and oven drying. This is repeated for a number of cycles, with each cycle causing salt crystals to grow and degrade the aggregate. The test method takes a minimum of 6 days to complete. The percent loss is then calculated on individual size fractions. This test method, however, is considered highly variable. Jayawickrama, Hossain and Phillips (2006) note that when ASTM initially adopted this test method they recognized the lack of precision, saying, "it may not be suitable for outright rejection of aggregates without confirmation from other tests more closely related to the specific service intended." ICPI recommends using ASTM C88 as a measure of aggregate durability as long as other material properties described in this bulletin are also considered.

The Micro-Deval test is evolving as the test method of choice for evaluating durability of aggregates in North America. Defined by CSA A23.2-23A, *The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* (CSA 2004) and ASTM D7428-08 *Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus,* the test method involves subjecting aggregates to abrasive action from steel balls in a laboratory rolling jar mill. In the CSA test method a 1.1 lb (500 g) representative sample is obtained after washing to remove the No. 200 (0.080 mm) material. The sample is saturated for 24 hours and placed in the Micro-Deval stainless steel jar with 2.75 lb (1250 g) of steel balls and 750 mL of tap water (See Figure 1). The jar is rotated at 100 rotations per minute for 15 minutes. The sand is separated from the steel balls over a sieve and the sample of sand is then washed over an 80 micron (No. 200) sieve. The material retained on the 80 micron sieve is oven dried. The Micro-Deval loss is then calculated as the total loss of original sample mass expressed as a percentage. ASTM and the American Association of State Highway Transportation Officials have both adopted the coarse aggregate version of the Micro-Deval test, ASTM D6928 (2006) and AASHTO TP 58. Both are also considering a version for fine aggregates. Since the test apparatus uses the same size drum and rotates at the same speed, no modifications to the apparatus are required to perform the fine aggregate test in laboratories currently equipped to perform the coarse aggregate test procedure.

A study conducted by the Interlocking Concrete Pavement Institute (ICPI 2004) investigated nine sands from across the United States reported by contractors to have "good to excellent" serviceability in vehicular applications. The results of this study indicated that eight of these sands had Micro-Deval degradation losses less than 8% when measured according to CSA A23.2-23A (CSA 2000). The same study subjected these sands to the ASTM C88 soundness loss and found that no sample had greater than 6% loss. The Micro-Deval test is recommended as the primary means to characterize bedding sand durability (See Table 3) and the magnesium or sulfate soundness should be considered when the Micro-Deval test is not locally available. The variability of the soundness test method should always be a consideration unless measured in relation to other material properties.

A test method similar in nature to Micro-Deval is the Lilley and Dowson test (Lilley Dowson 1998). This test method specifically developed for bedding sands is recognized internationally and is referenced in ICPI manuals *Port and Industrial Pavement Design with Concrete Pavers* (ICPI 1997) and *Airfield Pavement Design with Concrete Pavers* (ICPI 1995). This test method is performed on 3 lbs (1.4 kg) randomly selected, oven-dried sand samples with two 1 in. (25 mm) diameter steel balls together weighing 0.3 lb (135 g). Three sub-samples each weighing 0.5 lbs (0.2 kg) are derived from the main sample. Each sub-sample is sieved according to ASTM C136 then re-mixed and placed in a nominal liter capacity porcelain jar with the two steel balls. The three jars are rotated at 50 rpm for six hours and sieved again. Sand durability is assessed from resulting increases in the percent passing the No. 50, 100 and 200 (0.300, 0.150, and 0.075 mm) sieves. Developed in the UK, the test is not readily available at laboratories in North America. The CSA and ASTM Micro-Deval tests may be more available.

Beaty (1996) demonstrated a correlation between the two tests with a correlation coefficient greater than 0.99. The relationship between the two tests is:

$L = 1.97 + 1.21\ M$

Where:

M = CSA Micro-Deval Degradation Loss (%)

L = Lilley and Dowson Degradation Loss (%)

Beaty's correlation involved a modification to the test procedure by reconstituting the test aggregates into a standard gradation shown in Table 2 and performing the Micro-Deval and Lilley Dowson tests on the re-graded aggregate. In this modified version of the Lilley Dowson test procedure the loss (L) is measured as the total increase in percentage of fines passing the No. 200 (0.075 mm) sieve at the completion of the test. Using the correlation described above, an 8% Micro Deval degradation (See Table 3) would have a corresponding Lilley and Dowson degradation of 12%.

Bedding Layer Drainage—Bedding layer drainage is important for early and long term performance of a pavement. One failure documented by Knapton (1993) describes a segmental pavement that was opened to bus traffic and within hours of construction subjected to continuous heavy rain. The bedding sand in this case had a high percentage of fines. As a result of the continuous rainfall, finer sieve fractions in the sand were transported into the drain holes of the underlying concrete slab. With the drainage compromised the bedding sand liquefied and was pumped through the joints of the pavement, resulting in immediate rutting and failure of the system. The pavement was subsequently reconstructed with bedding sand that had 0% material passing the No. 200 (0.075 mm) sieve and reported excellent performance. Although gradation is an important factor in drainage (since it affects permeability) eliminating all of the fines can sometimes be impractical. Therefore, ICPI recommends up to 1% passing the No. 200 (0.075 mm) sieve.

Another important material property is permeability. Even specifications that allow up to 3% of fines can result in a five fold decrease in permeability from the lowest to highest percentage passing (Bullen 1998). In research conducted by the Interlocking Concrete Pavement Institute (ICPI 2004) the permeability of "very good to excellent" bedding sands was measured. Using the test method described by ASTM D2434-68 *Standard Test Method for Permeability of Granular Soils (Constant Head)* (ASTM 2006) the permeabilities ranged from 2.8 in./hr (2.1×10^{-3} cm/second) to 15.6 in./hr (1.1×10^{-2} cm/second). These values correspond to fines that range from 2.5% to 0% passing the No. 200 (0.075 mm) sieve but, more

Sieve Size	Percent Passing
4.75 mm	100
2.36 mm	90
1.18 mm	70
0.600 mm	47
0.300 mm	20
0.150 mm	7
0.075 mm	0

Table 2. Modified Gradation or Reconstituted Aggregates According to Beaty (1996)

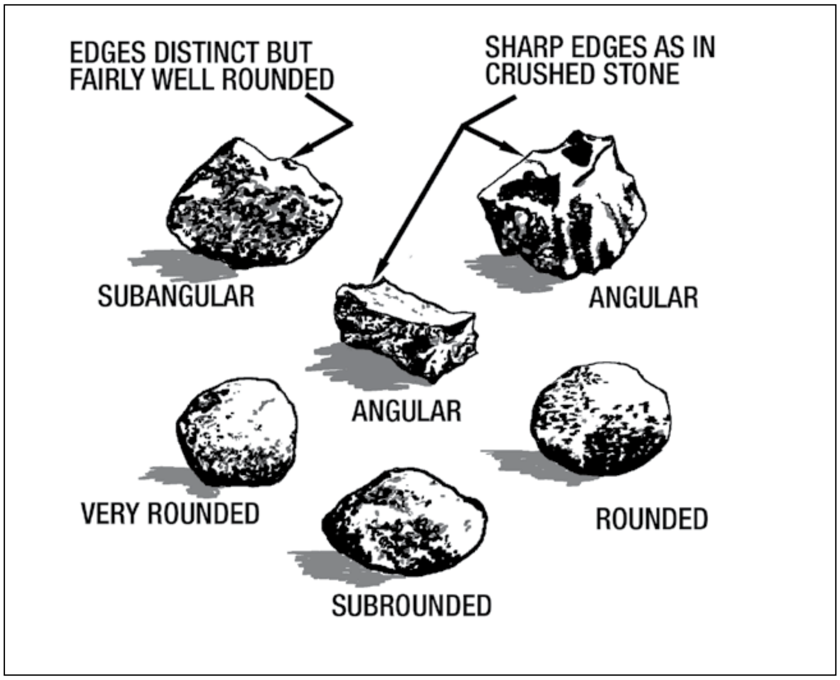

Figure 2. Typical description of coarse grains according to ASTM D2488

importantly they also are associated with Micro-Deval maximum degradation values of 8%. Table 3 indicates a minimum permeability of 2.8 in./hr (2.1 x 10^{-3} cm/second) that should also be considered at the same time as the other primary properties listed.

Other Material Properties—Studies have indicated that bedding sand shape plays a role in bedding sand performance. (Knapton 1993) notes that rounded or cubic grains lead to stable sands, whereas more angular grains are frequently associated with sands that fail. The sands tested by ICPI (ICPI 2004) showed that eight of the nine "good to excellent" performing sands were characterized by having a predominance of sub-angular to sub-rounded particle shapes when tested according to ASTM D2488 *Description and Identification of Soils (Visual-Manual Procedure)* (ASTM 2000). Specifiers and contractors should consider bedding sand angularity using Figure 2 as a guide. Figure 3 shows a photograph of one of the ICPI test sands at high magnification. Table 3 suggests that a combined percentage of sub-angular to sub-rounded particles should be a minimum of 60%.

Geology—Geology of bedding sands has been noted by a number of studies to play an important role in their performance. For example, bedding sand with quartz mineralogy is preferred over crushed sandstones (Knapton 1993). In the study by the Interlocking Concrete Pavement Institute (ICPI 2004), eight of the nine "good to excellent" performing sands were noted to consist predominately of silica minerals with over 80% of the material either quartz or quartzite. Table 3 recommends a minimum 80/20 ratio of silica/carbonate mineralogy. A tenth sample, included in the study (and noted as poor performing in the field) was characterized as having up to 50% carbonate content. Petrographic analysis was conducted according to the Ministry of Transportation of Ontario laboratory method MTO LS-616 P*rocedure for the Petrographic Analysis of Fine Aggregate* (MTO 1996). ASTM C295 *Standard Guide for Petrographic Examination of Aggregates for Concrete* (2003) offers an alternative test method.

Limestone screenings and stone dust are not recommended for bedding sand. In addition to being unevenly graded and having excessive material passing the No. 200 (0.075 mm) sieve, screenings and stone dust will break down over time from wetting and abrasion due to vehicular loads. Unlike soft limestone screenings and stone dust, hard, durable concrete sand meeting the requirements in Table 3 will not break down easily. Limestone screenings also tend to break down during pavement construction under initial paver compaction. Depressions will eventually appear in the pavement surface with limestone screenings or stone dust.

Recommended Material Properties—Table 3 lists the primary and secondary material properties that should be considered when selecting bedding sands for vehicular applications. Bedding sands may exceed the gradation requirement for the maximum amount passing the No. 200 (0.075 mm) sieve as long as the sand meets degradation and permeability recommendations in Table 3. Micro-Deval degradation testing can be replaced with sodium sulfate or magnesium soundness testing as long as this test is accompanied by the other primary material property tests listed in Table 3. Other material properties listed, such as petrography and angularity testing are at the discretion of the specifier and may offer additional insight into bedding sand performance.

Figure 3. Example of sand from the ICPI bedding sand test program with a total combined percentage of sub-angular and sub-rounded particles equal to 65% according to ASTM D2488

Figure 4. A two-man hand pulled screed

Figure 5. Mechanical screeding is the most efficient method of bedding sand installation

Role of Bedding Sand in Construction—Provided that the base was installed according to recommended construction practices and tolerances (See *ICPI Tech Spec 2—Construction of Interlocking Concrete Pavements*), the bedding sand ensures that the pavers have a uniform slope and meet surface tolerances without surface undulations or "waviness." Sand should be loosely screeded to a uniform thickness of 1 in. (25 mm) to 1$^1/_2$ in. (38 mm), which will compact to a thickness of $^3/_4$ in (19 mm) to 1$^1/_4$ in (31 mm). for vehicular applications. Screeds can either be pulled by hand or by machine (mechanical screed) as shown in Figures 4 and 5. Mechanical screeding provides the most efficient method. Pavers are placed on the loose uncompacted sand. Contractors should select sand that allows the pavers to be uniformly seated during their initial compaction with a minimum 5000 lb (22kN) force plate compactor.

The sand should have sufficient moisture content to allow for adequate compaction. At no times should bedding sand be either "bone dry" or saturated. A moisture content range of 6% to 8% has been shown to be optimal for most sands (Beaty 1992). Contractors can assess moisture content by squeezing a handful of sand in their hand. Sand at optimal moisture content will hold together when the hand is re-opened without shedding excess water. Although it can be difficult to control the exact moisture content on the job site, uniformity of moisture content can be maintained by covering stock piles with tarps. Digging into sand piles at mid-height to avoid saturated material that may be at the bottom of the pile is also recommended.

While on the job site, a contractor should check the hard-

Material Properties	Test Method	Recommended Maximum or Minimum
Primary Properties		
Gradation	ASTM C33 CSA A23.1 (FA1)	Maximum 1 % passing No. 200 (0.075 or 0.080 mm) sieve
Micro-Deval Degradation	CSA A23.2-23A ASTM D7428	Maximum 8%
Constant Head Permeability	ASTM D2434	Minimum 2×10^{-3} cm/second (2.83 in/hr)
Secondary Properties		
Soundness – Sodium Sulfate or Magnesium Sulfate	ASTM C88	Maximum 7%
Silica (Quartz and Quartzite)/ Carbonate Ratio	MTO LS-616 ASTM C295	Minimum 80/20 ratio
Angularity and Particle Shape	ASTM D2488	Minimum 60% combined sub- angular and sub- rounded

Note 1: See "Recommended Material Properties" on page 5 of ICPI Tech Spec 17

Note 2: Bedding sand may also be selected based on field performance. Field performance is selected when the specifier or contractor assumes responsibility for the selection and performance of bedding sand not conforming to the properties in Table 3. Field performance as a selection criteria is suggested when the available local materials do not meet the primary material properties suggested in Table 3, but the specifier or contractor can demonstrate to the satisfaction of the owner (or owner's representative), successful historical field performance. In this case the owner should specify the class of vehicular traffic, and the contractor should verify past field performance of the bedding sand under similar vehicular traffic.

Table 3. Recommended Laboratory Material Properties for Bedding and Joint Sands in Vehicular Applications [1,2]

Primary Properties	Test	Recommended Maximum or Minimum	Construction Tolerance	Frequency of Field Test
Gradation	ASTM C33 and CSA A23.1 (FA1)	See Table 1	Not Applicable	Provided by aggregate supplier every 25,000 sf (2,500 m^2)
Bedding Layer Thickness	Check with ruler	Nominal 1 in. (25 mm)	± 3/8 in. (10 mm)	By contractor every 5,000 to 10,000 sf (500 to 1000 m^2)
Hardness	Test with Swiss army pocket knife blade	No broken particles	Not Applicable	By contractor every 25,000 sf (2,500 m^2)
Secondary Properties	Test	Recommended Maximum or Minimum	Construction Tolerance	Frequency of Field Test
Moisture content at time of installation	Hand test	Holds together without shedding water	Not applicable	While screeding

Table 4. Recommended Installation Properties for Bedding Sands in Vehicular Applications

ness of the bedding sand particles. Particles of sufficient hardness will not break under the pressure of a Swiss Army pocket knife. This field test, although not recommended for pre-selection of bedding sands, helps assess a material at the time of delivery. Table 4 lists the recommended bedding sand properties that need to be considered by a contractor during installation.

Interlocking concrete pavements should also be designed and constructed such that the bedding sand should not be able to migrate into the base, or laterally through the edge restraints. Dense-graded base aggregates with 5% to 12% fines (the amount passing the No. 200 or 0.075 mm sieve), will ensure that the bedding sand does not migrate down into the base surface. For pavements built over asphalt or concrete bases, it is necessary to provide adequate drainage by providing 2 in. (50 mm) diameter weep holes around the perimeter on 10 ft (3 m) centers and at the low points in the concrete base to drain excess water from the bedding layer. Holes should be filled with washed pea gravel and covered with geotextile to prevent the loss of bedding sand. Figure 6 on the next page shows a detail. Specifiers can visit the ICPI website to download similar details for use in specifications from www.icpi.org. To control lateral loss of bedding sand, Figure 7 shows geotextile installed at the interface of a concrete curb. To ensure that the sand cannot migrate through the joints in the curb woven geotextile is placed on top of the aggregated base, extending approximately 1 ft. (300 mm) into the pavement and wrapped up the sides of the curb to fully contain the bedding sand.

Figure 7. Woven geotextile used to contain bedding sand from migrating laterally. Visit www.icpi.org for detail drawings.

Role of Jointing Sand

Jointing sand provides two primary functions in a segmental concrete pavement; it creates interlock and helps seal the pavement. ICPI recommends that the same material properties listed in Table 3 also apply to jointing sand. Panda and Ghosh (2002) describe laboratory research on pavements using fine and coarse joint sands. Simulated loading consisted of 11-kip (51 kN) over 80 mm pavers with varying joint widths and joint sand gradations. Deflection of the pavement was then measured with coarser sand exhibiting lower deflections. The study concluded that "the coarser the sand, the better the performance." The coarser sands used in the study correspond to the gradations for Joint Sand listed in Table 1 and the study recommended joint widths up to 3/16 in. (5mm). ICPI recommends joint widths of 1/16 to 3/16 (2 mm to 5 mm).

Contractors can benefit from using one sand source. There are advantages to using the bedding material for the jointing sand during construction. Using one material allows the contractor to monitor and control one sand product on the job site. Over time the joints become filled with detritus, providing some degree of sealing. Regardless of the sand used, segmental concrete pavements will always allow some water penetration through the joints.

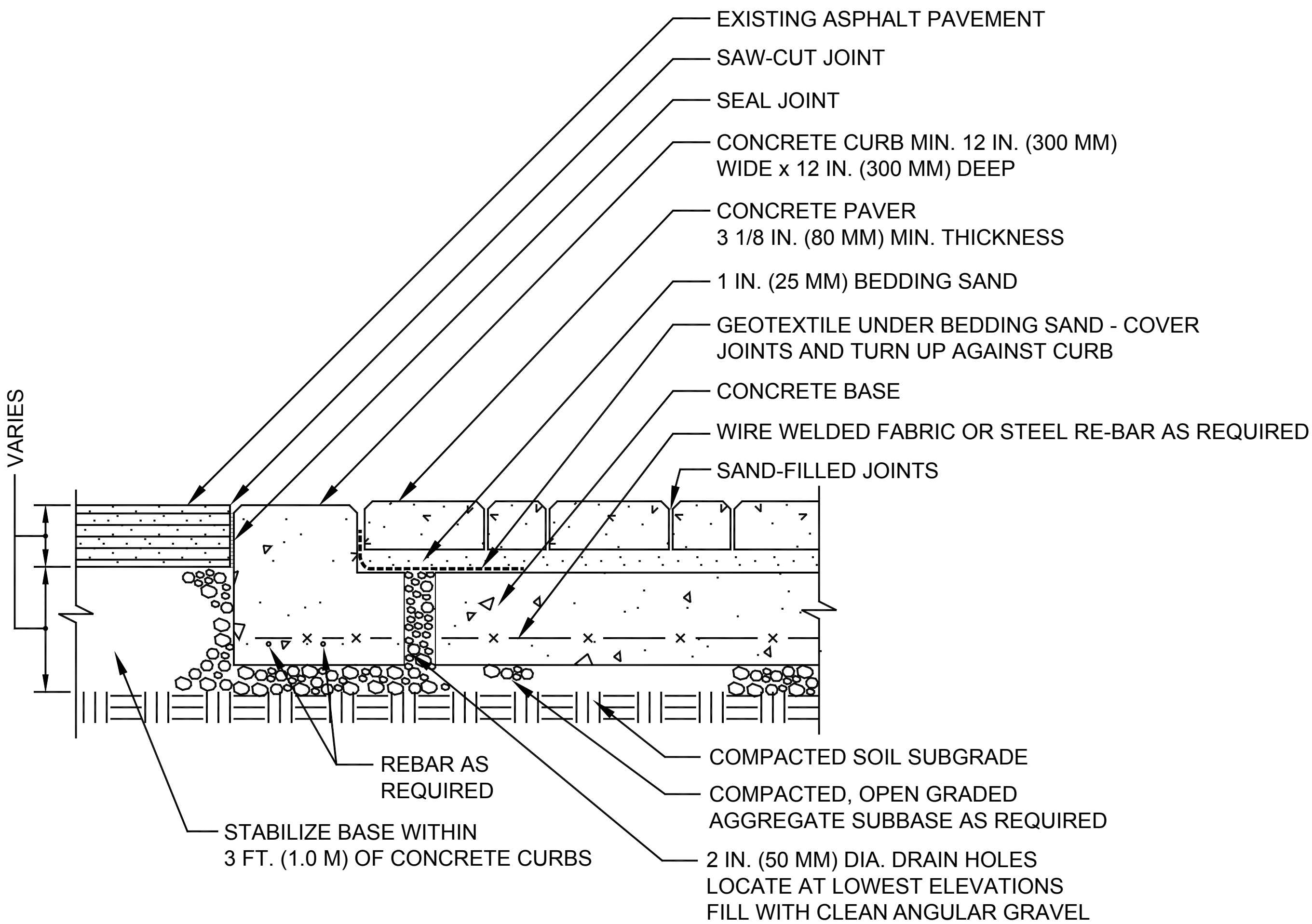

Figure 6. Recommended detail for sand set pavers over a concrete base. Drainage holes provide drainage for water that enters the bedding layer through the joints. The same detail applies for paver overlays on asphalt.

Coarse bedding sand may require additional effort in sweeping into the joints by the contractor. In some cases, smaller joint widths may require the use of finer graded sand. In this case, the use of mortar sand is recommended. Mortar sand should conform to the gradations of either ASTM C 144 or CSA A179 but should also meet the material property requirements of Table 3.

Although joint sand selection is an important factor, design and construction play a more important role. Considerations such as joint width, ensuring that the sand is swept in dry, degree of compaction, and ensuring the joints are completely filled, are just as critical to the long term success of pavement performance. Information on joint sand installation can be found in *ICPI Tech Spec 2—Construction of Interlocking Concrete Pavements* (ICPI 2004).

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