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16. ABSTRACT

The use of concrete block pavement (CBP) is limited in the U.S. This report examines CBPs from several perspectives to provide an overview of this alternative pavement type. First, the CBP system is described. The importance of using the proper bedding sand gradations is stressed, and the phenomenon of lock-up, or interlock, is explained. The various design methods for CBPs are also presented, and the concept of equivalency factors is discussed. Next, the structural performance of several CBP projects varying from 1 to 10 years is reviewed. Finally, the range of CBP costs in the Puget Sound area are provided and compared to recent WSDOT costs for flexible and rigid pavement.

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CONCRETE PAVING BLOCKS: AN OVERVIEW

by

Lt. Michael K. Abate
CEC, USN

Washington State Transportation Center (TRAC)
University of Washington, JD-10
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Newton C. Jackson
Pavement & Soils Engineer, Materials Laboratory

Prepared for

Washington State Transportation Commission
Department of Transportation

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ASTM	American Society for Testing and Materials
ATB	Asphalt Treated Base
BPF	British Ports Federation
CBP	Concrete Block Pavement
CBR	California Bearing Ratio
COE	Corps of Engineers
CPI	Concrete Paver Institute
CTB	Cement Treated Base
ESAL	Equivalent Single Axle Loads
FAA	Federal Aviation Administration
FWD	Falling Weight Deflectometer
LCC	Life Cycle Costs
LCI	Load Classification Index
LCN	Load Classification Number
NCMA	National Concrete Masonry Association
PAWL	Port Area Wheel Load
PCC	Portland Cement Concrete
WES	Waterways Experiment Station
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

INTRODUCTION

Concrete block pavements (CBPs) have been used to a greater extent, proportionally, in other countries than in the U.S. The use of CBP is increasing in the United States, but it is still a relatively "unknown" paving system. This report examines CBP from several perspectives in order to develop an overview. This overview may encourage the Washington State Department of Transportation (WSDOT) to try some initial applications. The following sections overview the chapters in this report. According to Knapton, the estimated paver usage worldwide is 288,000,000 square yards per year (240,000,000 m^2/year). This usage represents a $5.7 billion industry, which is growing between 5 and 40 percent annually in each market. [3]

THE CBP SYSTEM

A concrete block pavement (CBP) is made up of precisely dimensioned, individual concrete blocks that fit closely together to form a segmented pavement surface, which performs similarly to a flexible pavement. [2,3,4,5] Common names for the concrete blocks include pavers, paving blocks, paving stones, interlocking paving blocks, and road stones. Paver sizes are a nominal 4 x 8 inches (100 x 200 mm), with thicknesses from 2 1/2 to 4 inches (60 to 100 mm). They are usually laid manually, but mechanical installation methods are also available. A 1- to 2- inch (25- to 50- mm) bedding sand layer is used under the pavers. They are set into the sand and then vibrated into place, which forces some sand into the joints between the pavers. Jointing sand is then swept into the joints between the pavers, and they are again vibrated to wedge the jointing sand into place. Even though there is no consensus about which type is best, it is generally accepted that the paver should be in a shape that can be laid in an interlocking pattern (e.g., a herringbone). The requirement for suitable edge restraints to provide lateral resistance to the pavement is also discussed. Bedding sand is used to seat the pavers, and the gradation must meet the requirements of ASTM C33 and must not be easily degradable. A variety of bedding sand gradations were identified in the literature. The importance of using the proper gradation and type of bedding sand is highlighted by the example of the Pine Street failure in Seattle. To provide the avenue for shear transfer between the individual pavers, a jointing sand is used. The gradation is finer than that for bedding sand and must meet ASTM C144 requirements.

Installation of a CBP is relatively straightforward and may be done either manually or mechanically. Mechanical installation can increase productivity up to threefold over manual installation. The final step involves proof rolling the finished pavement with a pneumatic roller. This increases the overall stiffness by accelerating the onset of interlock at the paver joints.

In certain applications erosion of the jointing sand is a concern that, if not prevented, will lead to pavement failure. In addition, penetration of water through the joints can create problems with moisture susceptible subgrades. To avoid these problems, the use of flexible joint sealers, which must also be heat and solvent resistant, depending on the application, is recommended.

The ability of CBP to carry loads is a result of the friction of the jointing sand between the pavers, which provides a medium through which shear is transferred. The sand filled joints gradually develop postcompressive forces as a result of initial compaction and then trafficking, stiffening the CBP over time. This is analogous to post-tensioning and is referred to as interlock or lock-up. As a result of lock-up, an effective modulus of the paver/sand composite layer can be measured. The measured moduli of in-place CBPs have varied between 60 and 630 ksi (410 to 4,330 MPa), and modulus values for design vary between 145 and 1,088 ksi (1,000 to 7,500 MPa). This variation for the measured moduli can probably be best explained by different degrees of lock-up in each of the pavements. Unfortunately, a theoretical model that can accurately predict the ultimate stiffness of the composite paver/sand layer does not exist. Overall, this range of moduli is similar to traditional flexible pavements surfaced with asphalt concrete.

CBP DESIGN

Recently installed CBPs are designed with either modified existing pavement design procedures for flexible pavements, or mechanistic designs based on specific design parameters. Some design methods use equivalency factors that transform the thickness of the concrete paver and sand layer into an equivalent thickness of asphalt or concrete. Various equivalency factors were reported, but no specific ratio for any pavement material was apparent.

Rada et al made modifications to the American Association of State Highway and Transportation Officials (AASHTO) flexible design method and used layered elastic analysis to develop the paver/sand layer coefficient. This design also accounts for the progressive stiffening of the composite layer over time.

Pavers are also used as overlays to strengthen existing pavements, as demonstrated at Luton airport in the United Kingdom. The use of CBP as overlays may be of extra interest to WSDOT.

CBP PERFORMANCE

Rutting caused by repetitive shear deformations is the primary failure mode for CBP. Paver breakage and spalling are considered secondary problems and are usually a result of rutting. Evaluation of the in-place structural capacity of CBPs with a mechanistic elastic layer computer program revealed that the composite paver/sand layer effective modulus is roughly similar to that of AC. The characteristics that adversely affect the load carrying capacity of a CBP or that require maintenance include loss of jointing/bedding sand, edge/corner spalling, cracking, and rutting.

Generally, the performance of CBP installations reported in the literature has been satisfactory. The reviewed projects varied in age from one to ten years. Up to five years after construction, the majority of these projects were performing well. The magnitudes of the minor problems of rutting, spalling, and cracking appeared to be the similar to those of conventional pavements.

In addition to the structural performance characteristics, adequate site investigation, proper selection and/or specification of materials, maintenance, and competent, experienced supervision also contribute to CBP performance.

CBP COSTS

Acquiring accurate cost data for the supply and installation of pavers and bedding sand is difficult. Currently, in the U.S. a CBP is more expensive, on a first cost basis, than either AC or PCC. For many of the installations overseas, a comparative cost analysis determined pavers to be less expensive than either AC or PCC. In the Puget Sound area, costs for supply and installation of 3 1/8-inch (80-mm) pavers and 1 inch (25 mm) of bedding sand varies between \$3.25 and \$5.00 per square foot for hand installation. Use of machine installation can reduce this cost by as much as 15 percent for areas that are larger than 15,000 square feet (1,400 m^2). Life cycle cost (LCC) analysis is the best way to evaluate the overall cost of different pavement options; however, because of insufficient information regarding actual maintenance costs, lack of long-term performance data in the U.S., and the subjectiveness surrounding the assignment of user costs, making such an analysis is tentative at best.

A review of WSDOT's conventional pavement installed costs revealed that conventional pavements that represent a small percentage of the overall project typically have a high unit cost. In places where the cost of pavement is skewed by high mobilization costs, a CBP may be cost competitive, on a first cost basis.

CONCLUSIONS

In general, concrete pavers can be a viable alternative to conventional pavement materials. A CBP has a structural behavior and load spreading ability similar to those of AC; can support heavy loads; may have potentially fewer maintenance requirements; and may provide less expensive access to utilities because no saw cutting equipment or jackhammers are required for its removal, and because, unlike conventional pavements, excavation does not destroy the continuity of materials on which the pavement relies for strength. Several design methods are available. CBPs have demonstrated their use as an alternative pavement for heavy industrial and airport areas in several successful applications worldwide. Successful performance is not only dependent on sound design but also on strict adherence to material and construction specifications.

A CBP is usually more expensive than conventional pavements on a first cost basis. However, consideration of the various advantages of this pavement may make it economically attractive. For projects in which the pavement represents only a small percentage of the overall project cost, pavers can be competitive, on a first cost basis, with AC or PCC.

CHAPTER 1

INTRODUCTION

Concrete paving blocks (pavers) have been used in pavements for more than 50 years in Europe and have been used in the United States since the 1970s. [1,2] Many successful applications of pavers exist in heavy industrial, port, and airfield pavements.

According to Knapton, the estimated paver usage worldwide is 288,000,000 square yards per year (240,000,000 m^2/year) and represents a $5.7 billion industry, which is growing between 5 and 40 percent annually in each market. [3] Major markets are listed below:

Germany	90,000,000 sy/year
Misc. Europe	48,000,000 sy/year
Central America	48,000,000 sy/year
Middle East	36,000,000 sy/year
Africa	30,000,000 sy/year
South America	30,000,000 sy/year
U.S./Canada	22,000,000 sy/year
Netherlands	18,000,000 sy/year
United Kingdom	14,000,000 sy/year
France	11,000,000 sy/year
Japan	11,000,000 sy/year
N.Z. and Australia	10,000,000 sy/year

A concrete block pavement (CBP) is made up of precisely dimensioned, individual concrete blocks that fit closely together to form a segmented pavement surface, which performs similarly to a flexible pavement. [2,3,4,5] Common names for the concrete blocks include pavers, paving blocks, paving stones, interlocking paving blocks, and road stones. Paver sizes are a nominal 4 x 8 inches (100 x 200 mm), with thicknesses from 2 1/2 to 4 inches (60 to 100 mm). They are usually laid manually, but mechanical installation methods are also available. A 1- to 2- inch (25- to 50- mm) bedding sand layer is used under the pavers. They are set into the sand and then vibrated into place, which forces some sand into the joints between the pavers. Jointing sand is then swept into the joints between the pavers, and they are again vibrated to wedge the jointing sand into place.

Although the pavers are not bonded together with mortar, they are nevertheless able to transfer loads sideways from one paver to the next. The friction of the sand in the joints provides an avenue for shear transfer between the individual blocks. However, this shear transfer is only possible with narrow joints 1/16- to 1/8-inch (1.5 to 3 mm) wide. [6,7,8] According to ASTM C 936, paver length and width dimensions must be accurate to within 1/16 inch (1.6 mm). [9]

From the constructibility perspective, CBP is similar to other pavements with two exceptions. First is the sand bedding layer, which can be dumped and then screened manually, or can be placed with a modified asphalt concrete spreader. Second is the paver, which is usually laid manually but can also be placed with various machines specifically designed for laying pavers. Although placement by either method is slow, completed and compacted sections can be used immediately.

From the design perspective, CBP presents problems because it is difficult to model with analytical techniques such as layered elastic analysis. Layered elastic pavement theory can be used to design block pavements if an effective modulus of elasticity for the composite system (pavers and sand bedding) can be determined.

From the performance perspective, a CBP may be preferable to conventional pavements for some applications (e.g., ports and aircraft aprons). Measurement of a CBP's performance is similar to that of either asphalt concrete (AC) or portland cement concrete (PCC). In addition, strict adherence to construction specifications and an experienced supervisor is important in achieving a successful CBP project.

From the cost perspective, installation of CBP varies greatly and depends on several factors: local labor cost, bedding sand thickness, paver size and shape, distance pavers must be shipped from the manufacturer, amount of cutting required, and the size of the pavement. In the United States, pavers are usually more expensive than conventional pavements. Under some conditions, consideration of maintenance cost savings may give pavers an economic advantage.

The goal of this report is twofold. One is to assess the use of pavers as an effective alternative paving method to either AC or PCC when used for specific applications. The other is to investigate local costs for CBP and compare them with those of AC and PCC.

CHAPTER 2

THE CONCRETE PAVING BLOCK SYSTEM

2.1 CHAPTER SUMMARY

This chapter describes the concrete paving block system. The importance of the proper gradation of both the bedding and jointing sand is mentioned, as is the necessity in some applications of a joint sealer to prevent the erosion of the jointing sand or to reduce water penetration. The phenomenon of lock-up or interlock, which gives the segmental block pavement its stiffness, is also discussed. Unfortunately, this phenomenon is not fully understood, and a theoretical model for predicting the ultimate stiffness of the paver/sand composite layer does not exist.

2.2 PAVER DESCRIPTION

Pavers are manufactured from portland cement and a fine sand aggregate and must meet or exceed the minimum values of the American Society for Testing and Materials (ASTM) Specification C936, "Standard Specification for Solid Interlocking Concrete Paving Units."

The average compressive strength of pavers is not less than 8,000 psi (55 MPa), with no individual unit less than 7,200 psi (50 MPa). The average absorption of pavers is not greater than 5 percent, with no individual unit greater than 7 percent. Pavers must be able to withstand a minimum of 50 freeze-thaw cycles without breakage and with a loss of less than or equal to 1 percent in the dry weight of any individual unit. The typical components of a CBP are illustrated in Figure 2.1.

2.3 SHAPES, SIZES, AND LAYING PATTERN

Pavers are available in a variety of shapes and thicknesses. The most common shapes include rectangular (dentated and non-dentated) and "L" shaped. A dentated paver has indentations on all sides that key into each other. A non-dentated paver has smooth sides that do not mechanically interlock with each other. These are illustrated in Figure 2.2. Some researchers claim that dentated pavers provide a better distribution of stresses under dynamic horizontal forces, which reduces creep and shoving under traffic (e.g., ref. 1). Other researchers believe there is no significant difference between the two (e.g., ref. 3). However, more important than the paver shape selected, may be the pattern in which the pavers are laid.

Pavers are commonly laid in either of two ways, stretcher bond or herringbone. These patterns are illustrated in Figure 2.3. Accelerated trafficking tests conducted by Shackel indicated superior performance with the herringbone pattern in resisting horizontal creep caused by turning, braking, and accelerating vehicles. [1] As shown in Figure 2.4, use of the herringbone pattern obviates joint width adjustments and construction joint requirements when changes in pavement alignment are encountered.

Available thicknesses are 2 1/2 inches (60 mm), 3 1/8 inches (80 mm), and 4 inches (100 mm). For heavy industrial uses (ports, airports, bus lanes) both 3 1/8-inch [13,14,15,16,17,18,19] and 4-inch [4,13,14,19,20,21] pavers have been recommended or used. However, no justification for using pavers thicker than 3 1/8 inches has been established. [3] In fact, recent publications specifying 3-1/8 inch (80-mm) pavers supports this. [17,18] Although Shackel has shown that increased block thickness will reduce the permanent deformations and elastic deflections of the pavement, as well as the stresses transmitted to the subgrade, similar results are more economically achieved by increasing the base course thickness. [1]

2.4 EDGE RESTRAINTS

Edge restraints are required to provide lateral resistance to the pavement, restraining its spreading from the force of traffic. Several materials, such as wood, steel, aluminum, plastic, and concrete (both precast and poured-in-place), are available. However, for heavy, industrial pavements, concrete edge restraints are normally used. [22] The compacted base should extend to the rear of the edge restraint at a minimum, but it is preferable to extend the base beyond the edge restraint for added stability. The edge restraint should be 1/4 inch (6 mm) below the top of the pavers to reduce potential tripping hazard, prevent extensive wear on edge restraint, allow for minor paver settlement, and allow for drainage runoff. All utility covers in the pavement should have rectangular concrete collars. These collars should be the same elevation as the edge restraint to avoid catching snow plow blades. It is also recommended that rubber edged snow plow blades be used to avoid damaging the pavers.

2.5 BASE/SUBBASE CONSTRUCTION

CBP base and subbase construction requirements, as well as their function, are the same as those of conventional flexible pavements. [4,6,10] Use of a geosynthetic fabric may be required if the compacted base course is not "tight" to prevent migration of the bedding sand into the base. [6] A geosynthetic is also recommended with cement treated bases to prevent bedding sand migration into the shrinkage cracks that normally develop as the cement treated base cures. [18]

2.6 BEDDING SAND

The bedding sand layer not only acts as a laying course for the pavers, it also provides the sand that fills the lower portions of the joints. [1] The bedding sand thickness, as well as the sand gradation and angularity, affect the finished CBP. [1,21,23]

2.6.1 Bedding Sand Thickness

The proper thickness for bedding sand is typically 1 inch to 1.5 inches (25 to 40 mm). [6,7,18] As the sand thickness is reduced, rutting deformations decrease [1] and overall pavement performance improves. [2,24] However, sand layers less than 1 inch (25 mm) after compaction will not produce the lock-up (discussed later) required by the upward migration of sand into the joints. [2,24] The sand bedding should not be used to compensate for uneven elevations in the base, whether or not they are due to improper compaction. [1,6,7] Thickness variations lead to variations in the compacted density of the bedding sand, which in turn create a tendency for the CBP to deform unevenly under traffic. [1,23]

2.6.2 Bedding Sand Gradation

Table 2.1 lists some of the bedding sand gradations specified in the literature. As can be seen, there are significant differences in the gradations. Typically, bedding sand that meets the requirements of ASTM C33 is recommended. The bedding sand may be crushed or natural, should be essentially equidimensional without any flat and elongated particles, and should not degrade under traffic. Under no conditions should masonry mortar sand or any other sand not meeting ASTM C33 requirements be used. [6] Cook and Knapton have shown that the failure of Pine Street in Seattle, Wash., was due to use of an improper bedding sand. [21] The Pine Street pavers were made of granite and not concrete, the dimensional tolerances were equal to those of concrete pavers, and the project was designed as a CBP. The authors inferred that the bedding sand had a high percentage of fines that passed the No. 200 sieve, though they did not support their findings with evidence of the in-place bedding sand gradation, moisture content, and density. The sand was replaced with a naturally occurring silica, of which virtually no material passed the No. 200 sieve, and the pavement has since performed satisfactorily.

Cook and Knapton also showed that in Northwest England crushed rock sands have sharp features that are degraded through interaction with other sand particles. This degradation produces a fine dust which, when mixed with water, forms a "lubricating slurry" and results in pavement failure. Therefore, an easily degradable sand will increase the percentage of material that passes the No. 200 sieve, which in turn will lead to premature pavement failure.

In the United States, guide specifications written by the Army Corps of Engineers (COE) Waterways Experiment Station (WES) and the Concrete Paver Institute (CPI) address this problem. WES requires the bedding sand to have a minimum Los Angeles (L.A.) Abrasion of 40 percent when tested in accordance with ASTM C131. [25] This test is for sand that passes the No. 4 sieve and is retained on the No. 8 sieve. Presumably, if a sample of the parent sand source can be obtained for sand that passes the No. 8 sieve, the test can be run and the degradation checked. CPI requires that manufactured bedding sands be produced from rock that has an L.A. Abrasion of 20 percent or less when tested in accordance with ASTM C131. [18] Also, CPI requires the bedding sand to conform to the Micro Deval degradation test. This test measures degradation of the sand in a manner similar to the L.A. Abrasion test except that the sand sample is placed in a porcelain jar with two 1-inch (25-mm) diameter steel ball bearings weighing 60 to 75 grams each, and the jar is rotated at 50 rpm for six hours. The maximum increase in the percentages that pass each sieve and the maximum individual percentage that passes must be as shown below:

Sieve Size	Maximum Increase	Maximum Passing
No. 200	2 %	2 %
No. 100	5 %	15 %
No. 50	5 %	35 %

2.7 JOINTING SAND

The jointing sand fills the area between the individual pavers, providing the medium through which shear forces are transferred. Table 2.2 lists some of the jointing sand gradations specified in the literature. As can be seen, there are differences in the gradations. Typically, a grading that is finer than that of the bedding sand and that meets ASTM C144 requirements is recommended. All other physical properties of the jointing sand, including resistance to degradation, are identical to those for the bedding sand.

2.8 INSTALLATION

As mentioned earlier, construction of the subgrade, subbase, and base layers is the same as for any conventional flexible pavement. However, it is important that an even base course of the proper grade be attained so that a uniform thickness of bedding sand can be placed.

The bedding sand layer is placed on top of the compacted base course. For very large projects asphalt laydown machines modified for screed sand have proven successful. [1,6,25] More commonly, however, the bedding sand is placed by hand, and screeding is done with pipes and a screed board. [6] Regardless of the method chosen, the sand is normally placed in an uncompacted state and the pavers are placed immediately. Note that at the Port of Lyttelton, the bedding sand was placed by machine and then rolled. This was done for two reasons: hand screeding could not keep up with the speed of mechanized laying, and the large surface area of exposed bedding sand was subject to high velocity winds and potential sand loss. [26] To maximize the density of the bedding sand after compaction, a moisture content is specified. The literature varies in this specification from a low of 6 to 8 percent [1] to a high of 10 to 15 percent

[25]. The most current guide specification for using pavers in airport pavement requires a bedding sand moisture content within 2 percent of optimum. [18]

Pavers are most often installed manually, but manual installation is both time consuming and labor intensive. Mechanical installation equipment is also available and can increase productivity by a factor of two to three. [13,27] The pavers are placed with a joint spacing of 1/8 inch (3 mm) and a tolerance of 1/16 inch (1.6 mm). [1,6,7,8] To ensure proper joint spacing, some pavers are manufactured with nubs on the vertical faces so the installer simply has to set one paver up against another. Experience gained during paver installation at Cairns airport indicated that these nubs are necessary to avoid placing pavers too close to one another. [28] Once an area has been installed, the pavers are compacted into place with a plate vibrator capable of 3,000 to 5,000 pounds (13 to 22 kN) of centrifugal compaction force. At least two passes are required to adequately compact the pavers and bedding sand. No compaction within 3 feet (1 m) of an unrestrained edge should be attempted to avoid outward shoving and separation of the set pavers.

The next step is to spread the dry jointing sand over the compacted pavers. No particular method is specified, and any convenient technique is allowable. Typically, the jointing sand is thrown over the pavement surface with shovels and then swept into joints with brooms. The sand is compacted in the joints in the same manner as previously described for setting the pavers in the bedding sand. Several repetitions may be required until the joints are completely filled, at which point any remaining sand on the CBP surface is removed. Experience with the Webb Dock Container Terminal demonstrated that jointing sand must continue to be topped off for up to one year. [15] At the Port of Lyttelton, repeated joint sandings were also found to be necessary, and continuation for at least three months was recommended. [26]

Years ago, the CBP would be opened to traffic once the joints had been filled and the sand had been vibrated into place. Work by Shackel in 1980 showed that further compaction with a roller can benefit CBP performance by increasing the overall pavement stiffness, but additional study is needed. [1] It is interesting to note that despite the use of rollers to supplement paver compaction, there appears to be no consensus on the type and weight of the roller or the number of passes required. Lary et al [16], Knowles [26], and Vroombout et al [28] refer to the use of rollers at the Dallas-Forth Worth airport, the Port of Lyttelton, and the Cairns airport, respectively, but no details of the compaction procedures or roller specifications are provided. Emery [13] refers to the use of an 8-ton (70-kN) pneumatic tired vibrating roller at Luton airport, and Oldfield [15] refers to a requirement of five passes or more of a 35-ton (311-kN) pneumatic tired roller at Webb dock container terminal. More recently, proof rolling with several passes of a 10,000-pound (45-kN) or greater pneumatic roller to seat the pavers is being recommended for U.S. airport applications. [18]

2.9 JOINT SEALING

Sand joints between pavers are widely assumed to seal as they become filled with detritus. However, this process takes time, and during this period the jointing sand is susceptible to erosion. Erosion of the jointing sand is a serious problem that can ultimately lead to pavement failure. The most common causes of erosion are jet blast and propeller wash from aircraft engines, water runoff in large volumes, and the use of vacuum sweepers. [29]

Clark found that for subgrades susceptible to moisture, penetration of water through the joints is undesirable. [30] Observations by Knapton confirmed this finding. [31] It would be beneficial if the natural sealing process of the CBP could be accelerated. The addition of several materials to the jointing sand to improve joint sealing was tried at Luton airport [29], but although it was initially successful, the results were only temporary. Another attempt to seal the joints using an acrylic and urethane polymer was also unsuccessful, as the resulting sand/polymer matrix shrunk, thereby permitting water infiltration. In yet a third attempt to seal the joints, a low viscosity urethane pre-polymer was tested and found to be satisfactory. The advantage of this last sealer was that it cured into a flexible bond that was also more heat and solvent resistant. The most recent guide specification published by CPI for use of pavers at U.S. airports requires a urethane sealer that is capable of 100 percent elongation and that is resistant to fuels, hydraulic fluids, and deicing chemicals. [18] One other method of sealing joints is to mix a hydrated polymer with the jointing sand prior to placement. This method was used at Cairns airport and proved successful. Table 2.3 summarizes the discussed sealing methods and their performance. Interestingly, Shackel [1] recommends not sealing the joints from water infiltration, but ensuring that proper precautions are taken to reduce the effect of water on the pavement layers.

2.10 PAVER LOCK-UP

A CBP tends to stiffen with time as it withstands traffic. Over time, the rate of pavement deformation decreases, the effective elastic modulus of the CBP increases, and the load carrying capacity of CBP increases. [1,24] The primary factor related to the load carrying capacity of CBP is shear transfer in the joints, which results in less stress on the base. As stated earlier, shear transfer between pavers is made possible by narrow, sand filled joints. According to Kuipers, resistance of the CBP to bending is only possible if the paver/sand composite layer is prestressed or postcompressed, enabling the composite layer to transfer shear through the joints and providing some rigidity, which results in smaller rotations and deflections. [32] The development of these postcompressive forces is a result of the progressive stiffening of the CBP under traffic and is referred to as "lock-up" or "interlock." This progressive increase in postcompressive forces, which is developed by initial paver deformations/rotations caused by lateral traffic forces and rolling traffic that further compacts the sand in the joints, is analogous to post-tensioning. Kuipers also showed that a compressive force of 72.5 psi (0.5 MPa) can be developed through temperature variations alone. The lock-up condition is influenced by the laying pattern (herringbone is best) and bedding sand thickness (1 to 1.5 inches is best).

The literature shows that as interlock develops, a broad range of effective modulus values are possible for CBP. The composite paver/sand layer modulus is assumed to be made up of only one combined material. Considered separately, the modulus of pavers is around 5,000,000 psi (35,000 MPa), and the modulus of the sanded joints is between about 1,450 psi (10 MPa) when first placed and as much as 14,500 psi (100 MPa) after lock-up. [32] When combined, the effective modulus of the composite layer varies greatly. Rollings et al [12] and

Rada et al [5] have reported on this variation in moduli values. Their findings, and those of other researchers, are summarized in Table 2.4. Although modulus values of 145,000 psi to 1,088,000 psi (1,000 MPa to 7,500 MPa) have been used for design [5,15,33], Table 2.4 shows clearly that no consensus exists on an appropriate effective modulus value. This variation can be partially explained by the different degrees of lock-up in each of the pavements measured. In fact, Rada et al [24] identified a clear relationship between the amount of traffic the CBP received and the effective modulus of the composite paver/sand layer. In all cases, the stiffness of the composite layer increased with increasing traffic.

Many potential users of pavers may be uncomfortable with this variation in effective modulus and may question the ability of pavers to carry expected loadings. This is a valid concern in light of the inability to identify a tighter and reproducible range of effective modulus values. The major difficulty facing designers is that there is still no way to predict the ultimate effective modulus that will be reached when a pavement fully develops interlock. Although the pavement is able to withstand traffic immediately after it has been compacted the maximum load carrying capability of the pavement is not reached until full lock-up develops. In this respect a CBP is not unlike AC or PCC, which also do not develop their maximum load carrying capability until the new AC cools to ambient temperature or the PCC cures to a desirable strength. Additional study is needed to identify the primary parameters that affect interlock and their allowable ranges. These parameters will in turn provide a more consistent and reproducible effective modulus.

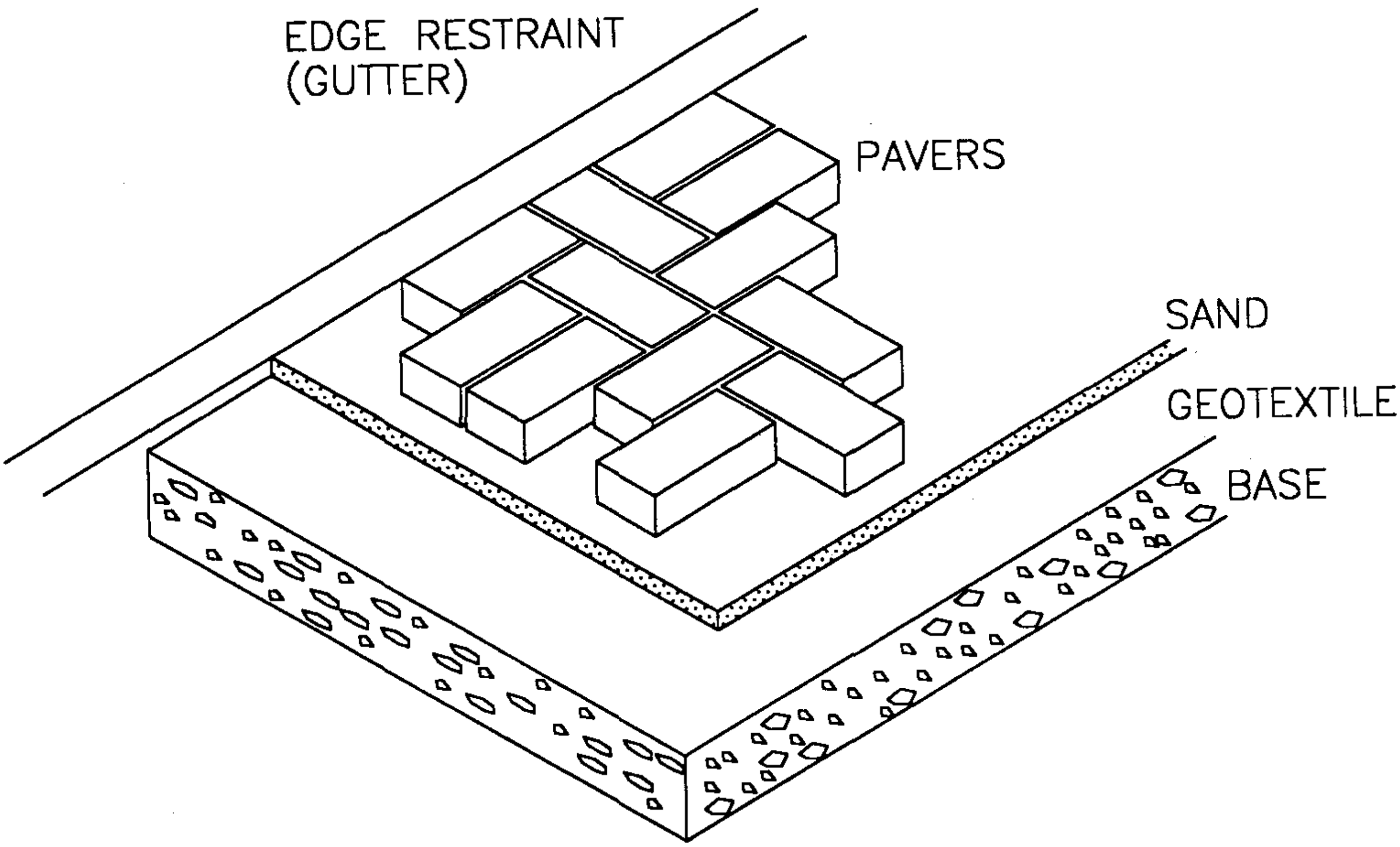


Figure 2.1. Typical Components of a Concrete Block Pavement
(After CPI TR-98, Airfield Pavement Design with Concrete Pavers [18])

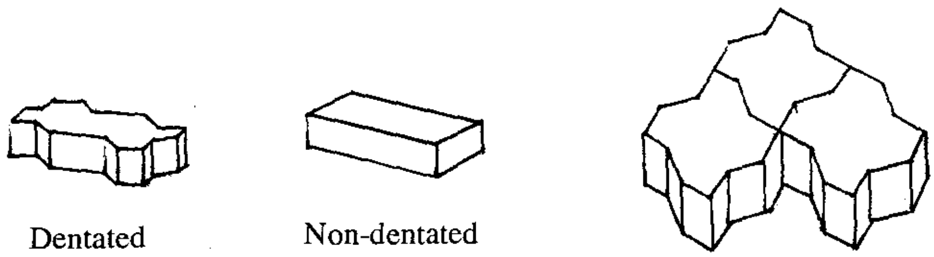
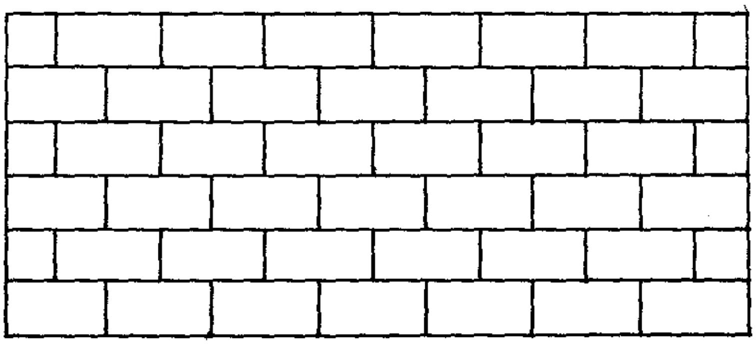
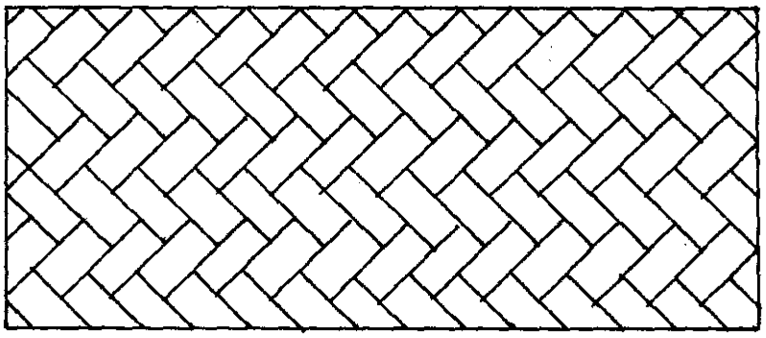


Figure 2.2. Common Paver Shapes



(a) Stretcher Bond



(b) Herringbone

Figure 2.3. Common Placement Patterns

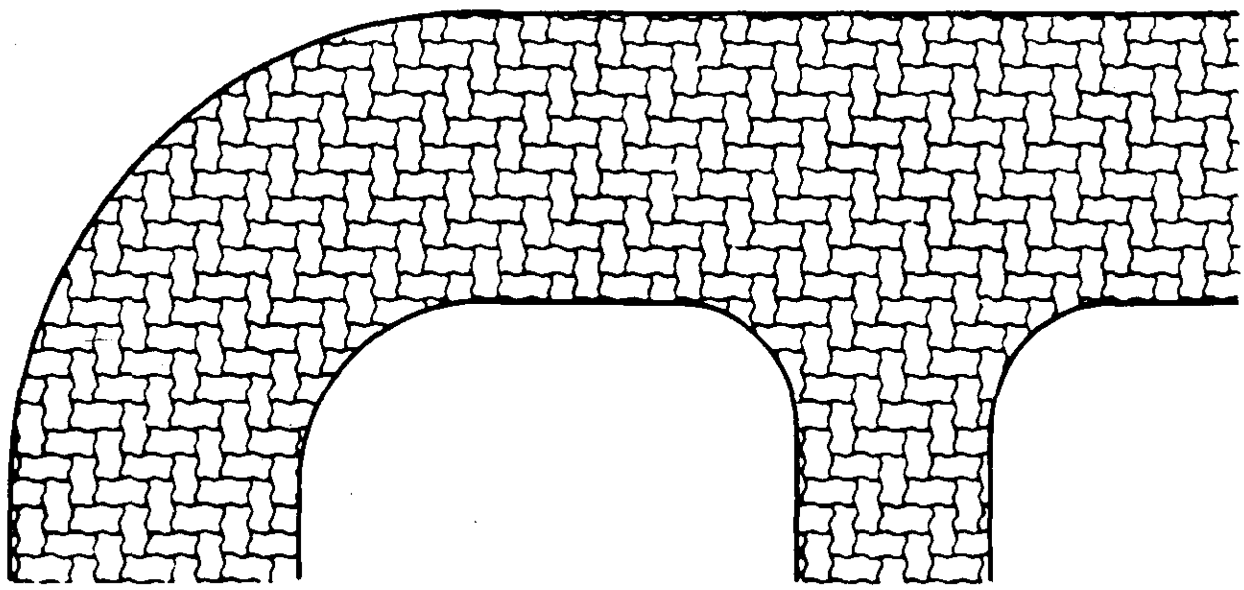


Figure 2.4. Herringbone Pattern with Changes in Alignment
(From Shackel [1])

Table 2.1. Bedding Sand Gradation

Sieve Size	3/8	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Source
% Passing	100	95 - 100	80 - 100	50 - 85		10 - 30	5 - 15	0 - 10	[4]
% Passing	100	95 - 100	80 - 100	50 - 85	25 - 60	10 - 30	2 - 10	0	ASTM C33 V. 04.02
% Passing	100	70 - 100	40 - 90	25 - 70	10 - 35	5 - 20	0 - 10	-	[34]
% Passing	100	80 - 100	60 - 90	25 - 70	10 - 35	5 - 20	0 - 10	0 - 5	[1,25]
% Passing	100	95 - 100	80 - 100	50 - 85	25 - 60	10 - 30	2 - 10	0 - 2	[18]
% Passing	100	95 - 100	80 - 100	50 - 85	25 - 60	10 - 30	5 - 15	-	[1]
% Passing	100	90 - 100	75 - 100	55 - 90	35 - 59	8 - 30	0 - 10	0 - 3	[1]
% Passing	100	90 - 100	75 - 100	55 - 90	35 - 70	8 - 35	0 - 10	0 - 3	[1]
% Passing	100	95 - 100	80 - 100	50 - 85	25 - 60	10 - 30	2 - 10	0	[16]
% Passing	-	90 - 100	75 - 100	55 - 90	35 - 59	8 - 30	0 - 10	-	[20]
% Passing	100	95 - 100	80 - 100	50 - 95	25 - 60	10 - 30	0 - 15	0 - 10	[26], NZS 3116:1981*

* New Zealand Standard

Table 2.2. Jointing Sand Gradation

Sieve Size	3/8	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Source
% Passing	100	100	100	100				10	[4]
% Passing (natural)	-	100	95 - 100	70 - 100	40 - 75	10 - 35	2 - 15	-	ASTM C144 V. 04.02
% Passing (manufactured)	-	100	95 - 100	70 - 100	40 - 75	20 - 40	10 - 25	0 - 10	ASTM C144 V. 04.02
% Passing	-	100	100	100	40 - 75	10 - 35	2 - 15	-	[18]
% Passing	-	-	100	90 - 100	60 - 90	30 - 60	15 - 30	5 - 10	[1]
% Passing	-	-	-	100	25 - 60	10 - 30	2 - 10	0	[16]
% Passing	100	100	95 - 100	70 - 100	40 - 75	10 - 40	2 - 25	0 - 10	[1,25]

Note: One reference [8] recommended 100% passing the No. 10 sieve. No other gradation information provided.

Table 2.3. Joint Sealer Alternatives

Sealing Method	Type Seal	Performance	Ref
Single sized fine sand mixed with polymer glue	Flexible	Successful	[28]
Lime dust (10:1 sand:lime mix)	-	Temporarily decreased permeability, weak bond resulted in eventual erosion	[29]
Cement	-	Temporarily decreased permeability, weak bond resulted in eventual erosion	
Pulverised fuel ash	-	Temporarily decreased permeability, weak bond resulted in eventual erosion	
Bentonite	-	Temporarily decreased permeability, eroded after repeated wet/dry cycles	
Liquid polymers (acrylic and urethane)	Rigid	Unacceptable joint matrix shrinkage increased permeability of joints	
Low viscosiity urethane pre-polymer	Flexible	Satisfactory after 5 years, most resistant to heat and solvents	

Table 2.4. Various Reported Effective Moduli for Composite Paver/Sand Layer

Project Site	Pavement Category	Paver Thickness, in.	Bedding Sand Thickness, in.	Effective Modulus, ksi*		Basis for Determination	Ref
				Range	Mean		
U.K.	Test	3 1/8	2	-	130.5	For Design	[35]
Japan?	-	3 1/8	-	-	234.9	Deflection	[12]
Japan?	Roadways	3 1/8	-	-	627.9	Deflection	[12]
N.Z.	-	3 1/8	-	-	59.4	Deflection Bowl	[12]
U.K.	Port Areas	-	-	-	1,102	For Design	[33]
-	Industrial	-	-	42.1-168.2	-	Deflection	[12]
-	Industrial	-	-	8.4-42.1	-	For Design	[12]
U.K.	Port Area	4	2	91.4-97.9	-	FWD	[36]
U.K.	-	4	2	65.3-137.8	-	FWD	[36]
U.K.	-	3 1/8	1 9/16	-	116	FWD	[36]
-	-	-	-	227.7-1811.8	493	FWD	[12]
-	-	-	-	72.5-1015	431.4	FWD	[12]
-	-	-	-	406-493	-	Traffic Tests	[12]
Japan	Roadway	3 1/8	3/4	14.5-90	-	FWD	[11]
-	Port Areas	3 1/8	1	-	650	For Design	[17]
Several	-	-	-	31-375	169.9	Traffic Tests	[12]
Austrailia	-	-	-	50.8-464	-	-	[24]
Netherlands	-	-	-	92.7-402.1	-	-	[24]
USA	Airports	3 1/8	1 1/4	-	450	For Design	[18]
Ontario	Roadways	3 1/8	1.2	-	377	FWD	[24]
(North Bay)	Intersections	3 1/8	1.2	-	559.9	FWD	[24]
	Others**	3 1/8	1.2	-	118.3	FWD	[24]
Ontario	Roadways	3 1/8	1.2	-	300.3	FWD	[24]
(Timmins)	Intersections	3 1/8	1.2	-	420.6	FWD	[24]
Fayetteville	Transit Mall	3 1/8	1.5	-	344.5	FWD	[24]
(N.C.)	Others	3 1/8	1.5	-	206.6	FWD	[24]

* MPa equivalencies may be determined by dividing ksi values by .145 ksi/MPa.
** This includes parking lanes, sidewalks, and bus stops.

CHAPTER 3

CONCRETE BLOCK PAVEMENT DESIGN

3.1 CHAPTER SUMMARY

Several design methods are available for CBP, and each may yield different results for similar traffic loadings and subgrade conditions.

3.2 INTRODUCTION

As a result of interlock and the segmented construction of CBP, most of the information in the literature suggests that a CBP behaves in a manner somewhat similar to a flexible pavement in that they both can fail as a result of rutting caused by repetitive shear deformations. [1,3,12,24,35]

However, there are differences in how the ruts occur. A CBP shows an increase in permanent deformation early in its pavement life. As lock-up in the CBP develops, the elastic modulus increases and permanent deformations cease. [35] On the other hand, a flexible pavement that ruts continues to rut with increasing load applications.

According to Armitage, a CBP with an unbound base will result in significantly greater deformations and deflections under traffic than one with an asphalt or cement treated base. [36] This confirms, in part, similar results summarized by Shackel and reproduced in Figure 3.1. [1]

3.3 CBP DESIGN METHODS

CBP design methods can be divided into four categories:

1) design based on experience,
2) empirical designs based on full-scale trafficking tests,
3) modifications of existing design procedures for flexible pavements, and
4) mechanistic designs based on specific design parameters.

3.3.1 Experience Based Designs

Experience based designs have been used successfully in Europe, where concrete pavers have been used since the early 1900s. However, these designs are based on local conditions only and do not lend themselves to locations where subgrade strengths and traffic loadings can be significantly different. Further, experience based designs require judgment, and judgment is difficult to transfer. For this reason, this type of design will not be discussed further.

3.3.2 Empirical Designs

Shackel attempted to develop an empirically based design but abandoned his efforts because of the complexity, cost, and length of time necessary to test the many prototype pavements required. [1] No other purely empirical designs or attempts were found in the literature, and this type of design will not be discussed further.

3.3.3 Modified Existing Flexible Pavement Designs

Some CBP design methods modify existing flexible pavement design procedures. They use equivalency factors that transform the thickness of the concrete paver plus bedding sand composite layer into an equivalent thickness of asphalt, concrete, gravel, and other materials. With the equivalency approach, a pavement is first designed conventionally. Then the pavers and sand composite layer are converted to an equivalent thickness of conventional pavement material. The required thickness of the pavement under the pavers is the difference between the conventional design thickness and the paver/sand composite system equivalent thickness.

Table 3.1 shows several equivalency factors reported in the literature. Rada et al used layer coefficients to represent the relative load carrying strength of the various construction materials in the pavement. [5] The paver and bedding sand thickness/material thickness ratios were obtained from the ratio of the respective layer coefficients. Vertical stress measurements taken just below the bedding sand during static loading tests were the basis for equivalency factors reported by Knapton et al. [3] Accelerated trafficking tests conducted by Shackel were the basis for his equivalency factors. [1] Rollings' equivalency factor followed from the Corps of Engineers' (COE) current design method, which equates the paver/sand layer with 6.5 inches of asphalt concrete for an equivalency factor of 0.635 ($3^1/_8$-inch paver plus 1-inch sand bed/ 6.5-inches of asphalt concrete). [10] The remaining factors listed in Table 3.1 were developed by others and reported by Rollings et al. [12]

Table 3.1 shows clearly that there is no specific ratio for any of the pavement materials. Despite this lack of absolutes, the equivalency factor approach can be used to design CBP for virtually any use. [3] In fact, the Federal Aviation Administration (FAA) has approved the equivalency factor approach of designing the pavement as a flexible pavement and replacing the AC wearing course with pavers and bedding sand. [18] However, according to Rollings et al, "While this is a convenient design expedient, it is not a theoretically rigorous approach." [12] What this means is that such designs fail to account for the interlock and large deflection tolerance peculiar to CBP.

For roadway pavement applications, the National Concrete Masonry Association (NCMA) bases its design on equivalent 18-kip (80-kN) single axle loads (ESALs) and a series of base thickness design curves that use conventional CBR flexible pavement relationships. [4] The design curves are for six traffic categories and three base types, granular, asphalt treated, and cement treated. The subgrade CBR and the design traffic category or number of ESALs are used to take off a base thickness. These curves are reproduced in Figure 3.2. The thickness shown on these curves does not include the 2-inch (50-mm) bedding sand layer nor the paver thickness. Recommended thicknesses are shown below.

Traffic Curve	A	B	C	D(E)
18-Kip ESAL Repetitions	50K	150K	500K	1,500K
Paver Thickness (in.)	2 1/2	3 1/8	3 3/4	4

The Corps of Engineers uses its CBR flexible pavement design method. [37] The thickness requirements of the base and surface layers are determined on the basis of the in-situ soil properties and in accordance with the provisions given in Technical Manual TM 5-825-2/ AFM 88-6, Chapter 2 ("Flexible Pavement Design for Airfields"). Then the 3 1/8-inch (80-mm) pavers and 1 1/4-inch (32-mm) bedding sand layer is substituted for the top 6.5 inches (163 mm) of base and surface thickness.

In heavy industrial and port areas, pavements are subjected to large vehicle traffic with single wheel loads of 30,000 pounds (134 kN) or greater. The National Concrete Masonry Association has published design curves based on either 18-kip (80-kN) ESALs or on the movements of a design vehicle (Hyster 620 forklift) that has a single wheel load of 33,410 pounds (1486 kN). [19] The subgrade CBR and the number of ESALs for normal industrial areas or number of passes of the Hyster 620 forklift (for heavily loaded port areas) are used to take off a combined unstabilized base/subbase thickness. The subbase CBR must not be less than 20. The base CBR for normal industrial pavements cannot have less than a CBR of 80, and the minimum thickness is 4 inches (100 mm). For port area pavements, the minimum CBR is 100 with a minimum thickness of 6 inches (150 mm). The base thickness is then determined by again entering the curve with the subbase CBR and taking off the base thickness. The subbase thickness is the difference between the combined unstabilized base/subbase thickness and the base thickness. With stabilized bases an equivalency factor is used. One inch (25 mm) of high quality, densely graded, well compacted asphalt or 1 inch (25 mm) of 750-psi (5-MPa) cement stabilized material is equivalent to 1.15 inches (29 mm) of unstabilized granular material. The minimum thicknesses stated above must still be met. The NCMA recommended paver thicknesses listed earlier also apply here. However, the minimum paver thickness is 3 1/8 inches (80 mm) with a 1- to 2-inch (25- to 50-mm) bedding sand layer. For very heavy loads, 4-inch (100-mm) pavers are used. These curves are reproduced in Figure 3.3.

Recently, a more comprehensive design procedure for CBP was developed by Rada et al. [5] This design was based on the empirically developed American Association of State Highway and Transportation Officials (AASHTO) flexible pavement design method. With this design, layered elastic analysis that models the paver/sand combination as a composite layer was used to develop the layer coefficient. Essentially, all aspects of the design are the same as for AC, with the exception of the design layer coefficient. The coefficient is considered equal to that of AC only after 10,000 ESALs, at which point lock-up is considered to have occurred. Interestingly, the 10,000 ESALs deemed necessary to achieve full lock-up is the same number Shackel found after his South African accelerated road trafficking tests. [1] (Refer to Appendix C for a design example using Rada's approach.)

The design assumes the use of 3 1/8-inch (80-mm) pavers, a 1-inch (25-mm) minimum bedding sand layer, and a herringbone pattern for ESALs of 2,000,000 or less. For ESALs greater than this, either 4-inch (100-mm) pavers are needed, or 3 1/8-inch (80-mm) pavers can still be used but the base must be stiffer. The subgrade modulus and number of ESALs are used to obtain the base thickness. These curves are reproduced in Figure 3.4. The stiffness characterization model accounts for the progressive stiffening of the composite system over time. This design procedure is available in a computer program called PAVECHECK, which is available from the Concrete Paver Institute.

3.3.4 Mechanistic Designs

Mechanistic design procedures are based on structural theory and the behavior of construction materials under repeated stress. This type of design is premised on reducing strains at critical pavement locations so that they do not exceed the strains the construction materials can withstand. One such design method is an updated version of the British Ports Federation (BPF) design published by NCMA. This design uses the Port Area Wheel Load (PAWL) unit to quantify the damaging effect, the Load Classification Index (LCI) to classify the PAWLs of cargo handling equipment, and the Design Life (L), which is the maximum number of movements of the critical load. [17] On the basis of the design life, permissible tensile (CTB) or compressive strains (granular base) are taken from design charts. The permissible strain and LCI are then used to take off the required base thickness. This design procedure assumes 3 1/8-inch (80-mm) pavers, 1 inch (25 mm) of bedding sand, and a minimum subbase CBR of 20. The curves on the charts apply to four types of cement treated base. Once the lean concrete base thickness has been found, an equivalency equation can be used to determine alternative material thicknesses. Some of these charts are reproduced in Figure 3.5.

Another mechanistic design is in the form of a computer program called LOCKPAVE, which is available from the National Precast Concrete Association. The premise behind design with a granular base is to place successively stronger material layers of adequate thickness above the subgrade to limit rutting deformation due to shear (inadequate layer thickness) or densification (inadequate compaction). With an ATB or CTB, the thickness is chosen to limit traffic-induced tensile stresses to values that will not cause fatigue cracking in the layers within the pavement's design life.

3.4 OVERLAY DESIGNS

Pavers can also be overlaid on existing AC and PCC. [17,18,38] This was successfully done at Luton airport in the U.K., where deteriorated AC overlays were removed and replaced with pavers. In fact, the resulting CBP overlay at Luton increased the pavement strength 14 percent over that of the original 5-inch (125-mm) AC overlay and 21.7 percent over that of the original 10-inch (250-mm) PCC pavement. [13,14] Pavement strength was measured with plate bearing tests to assess the Load Classification Number (LCN) at three stages of reconstruction. The first stage was the original pavement, which consisted of 1 1/2 inches (40 mm) of grouted bitumen over 3 1/2 inches (90 mm) of AC, 10 inches (250 mm) of 4,500-psi (30-MPa) PCC, and 4 inches (100 mm) of cement stabilized base. In the second stage, the grouted bitumen and AC surfacing were removed from the PCC. In the third stage, 3 1/8-inch (80-mm) pavers and 2 1/2 inches (65 mm) of bedding sand were placed on the PCC. Resulting LCNs for stages 1, 2, and 3 were 64, 60, and 73, respectively. Although these results indicate superior pavement strengthening from the pavers, Emery [13,14] felt that the Stage 1 LCN was artificially low, as the top 1 1/2 inches (40 mm) consisted of only a grouted bitumen and were most likely weaker than the underlying AC. Unfortunately, no specific information describing the mixture design of a grouted bitumen was provided.

Overlays are usually considered when the pavement shows visible deterioration or a structural analysis indicates an inability to carry expected loads. Strengthening the pavement with an overlay is more economical before the deterioration becomes too severe; otherwise, total pavement replacement may be needed. A version of the component analysis method similar to the Asphalt Institute method is used to transform pavement layers into an equivalent thickness of

1,800-psi (12-MPa) concrete. [29,38] The reason for this is that the design charts originally developed by Knapton for the British Ports Federation already exist. [17] Conversion factors are listed in Table 3.2. The transformed thickness of each layer is multiplied by control factors that take into account the degree of cracking and spalling, C.F. 1 (Table 3.3), and the degree of rutting and localized settlement, C.F. 2 (Table 3.4). All other aspects of the Asphalt Institute's component analysis remain the same.

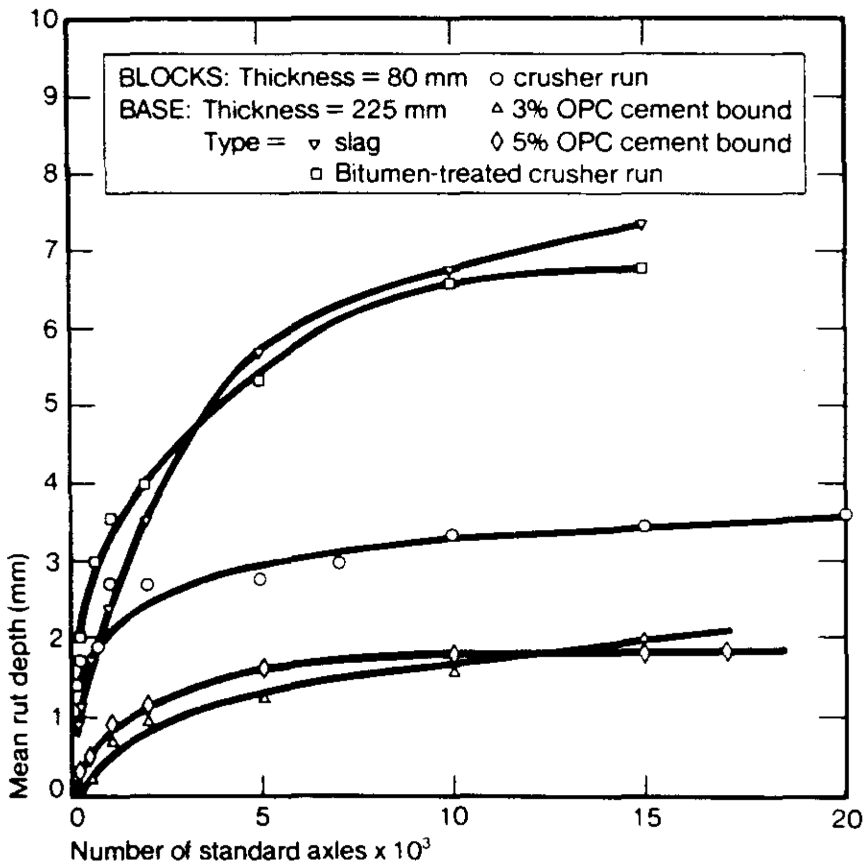
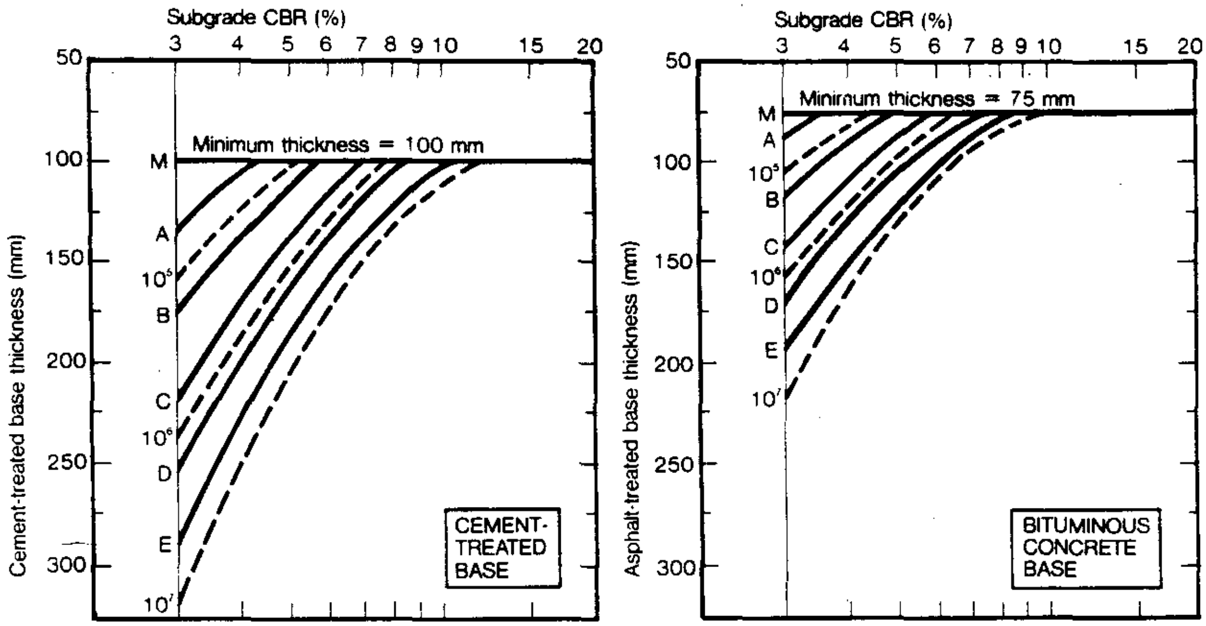
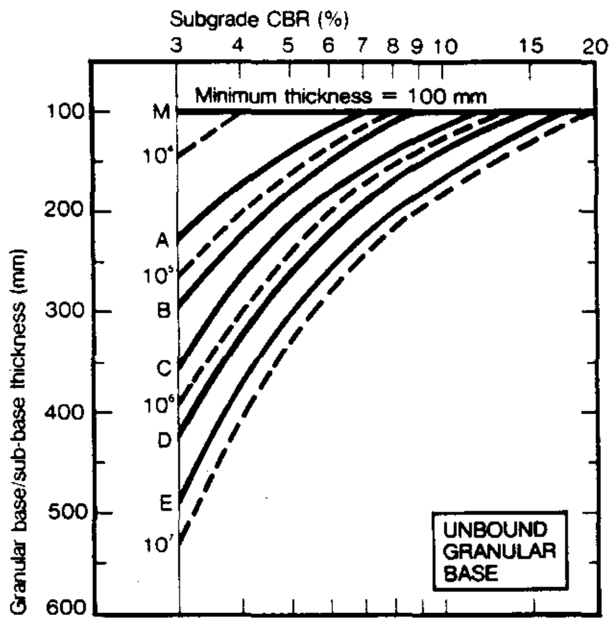


Figure 3.1. The Effects of the Type of Base Course on the Performance of CBP Under Traffic, OPC = Ordinary Portland Cement (Shackel [1])



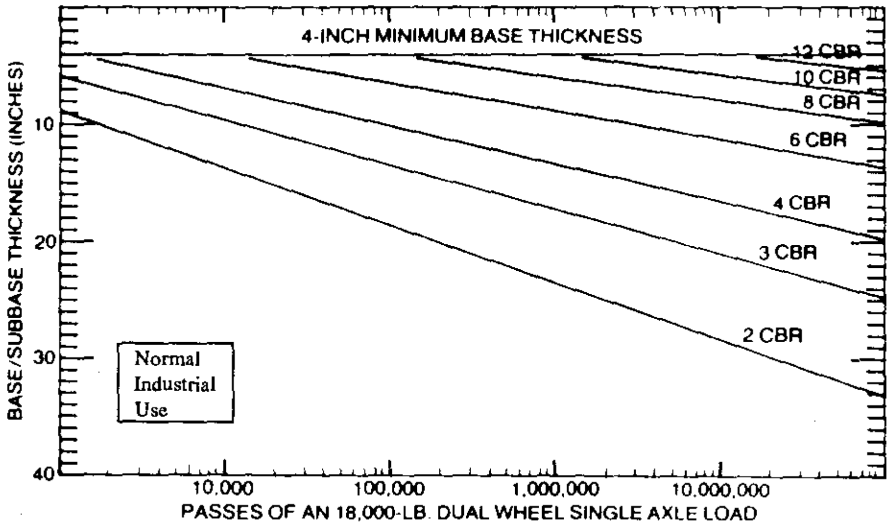


TYPICAL DESIGN TRAFFIC CATEGORIES

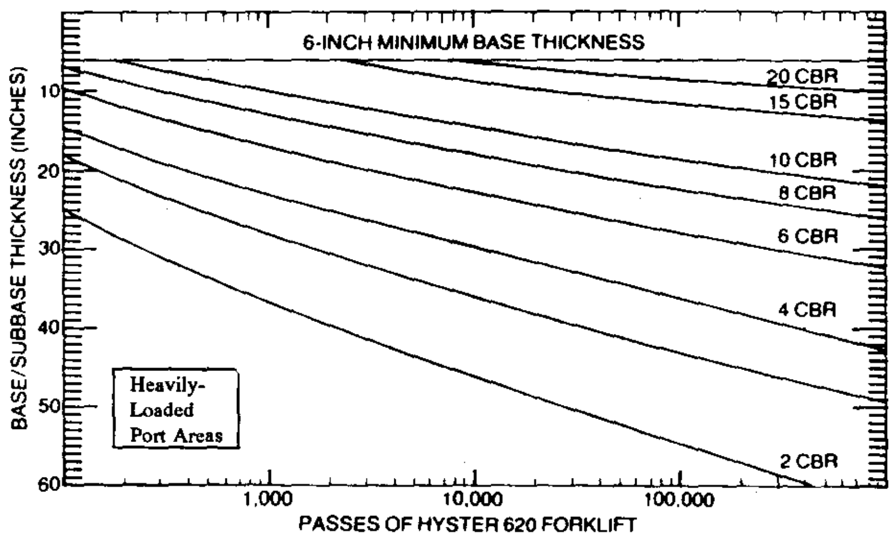
Traffic Curve	Design Traffic Description
M	Pedestrian paths, bicycle pathways
A	Multi-dwelling driveways, car parking areas, residential cul-de sacs (<15 commercial vpd)
B	Minor residential streets (15 to 50 commercial vpd), service station areas
C	Truck terminals and storage areas, light industrial floors(1), residential streets (50 to 150 commercial vpd), bus stops
D	Urban through roads(2) (150 to 500 commercial vpd), medium to heavy industrial floors and hardstands(1), industrial access (trucks only)
E	Urban through roads(2) (500 to 1500 commercial vpd), heavy industrial floors and hardstands

(1) If traffic channelised, use next traffic curve
(2) Vehicle speed not to exceed 60 km/hr

Figure 3.2. NCMA CBP Structural Design Curves (Shackel [1])



(a) Design Curves for 18 kip ESAL's



(b) Design Curves for Hyster 620 Forklift

Figure 3.3. Base Thickness Design Curves (NCMA [19])

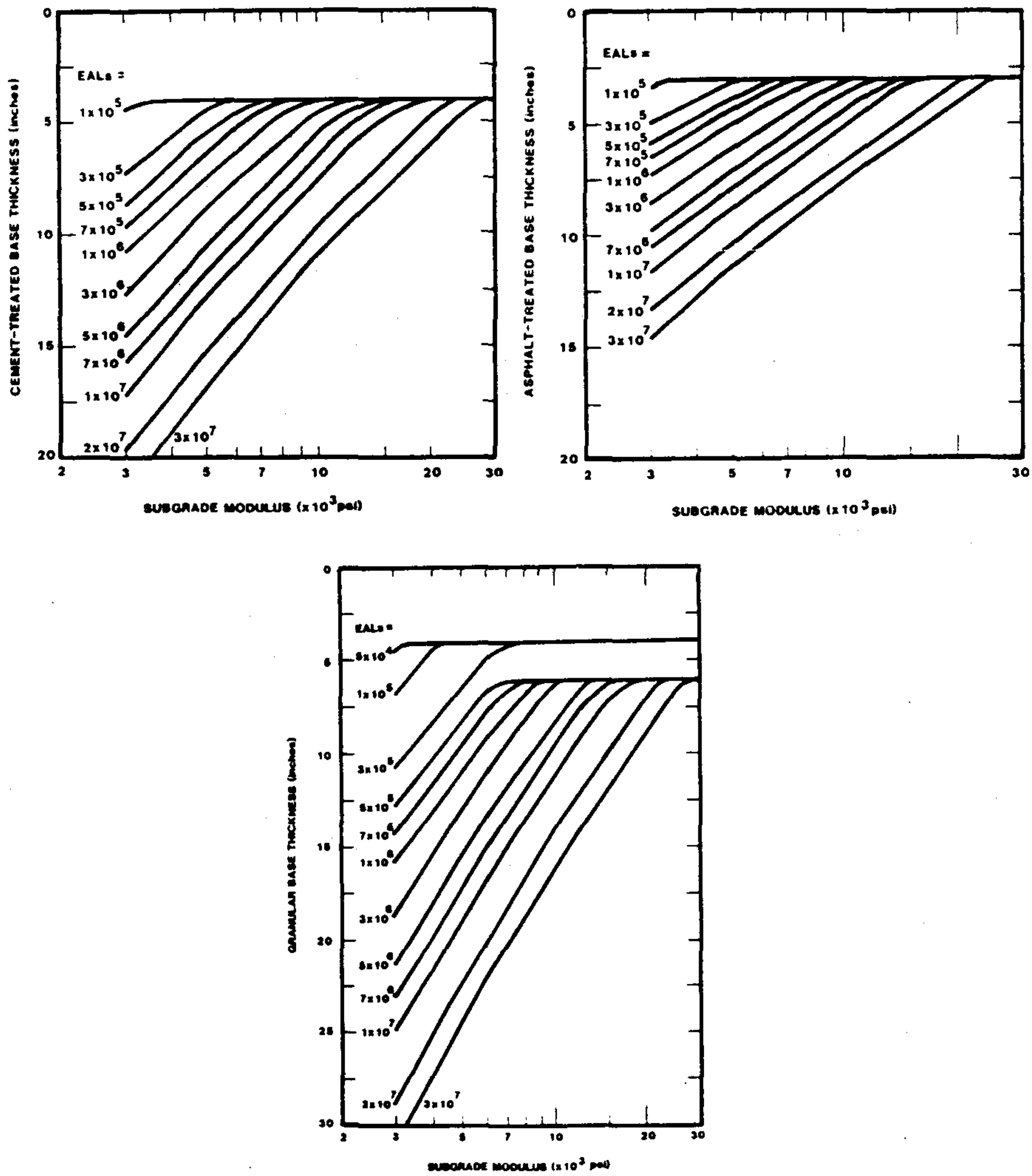


Figure 3.4. Base Thickness Design Curves (Rada [5])

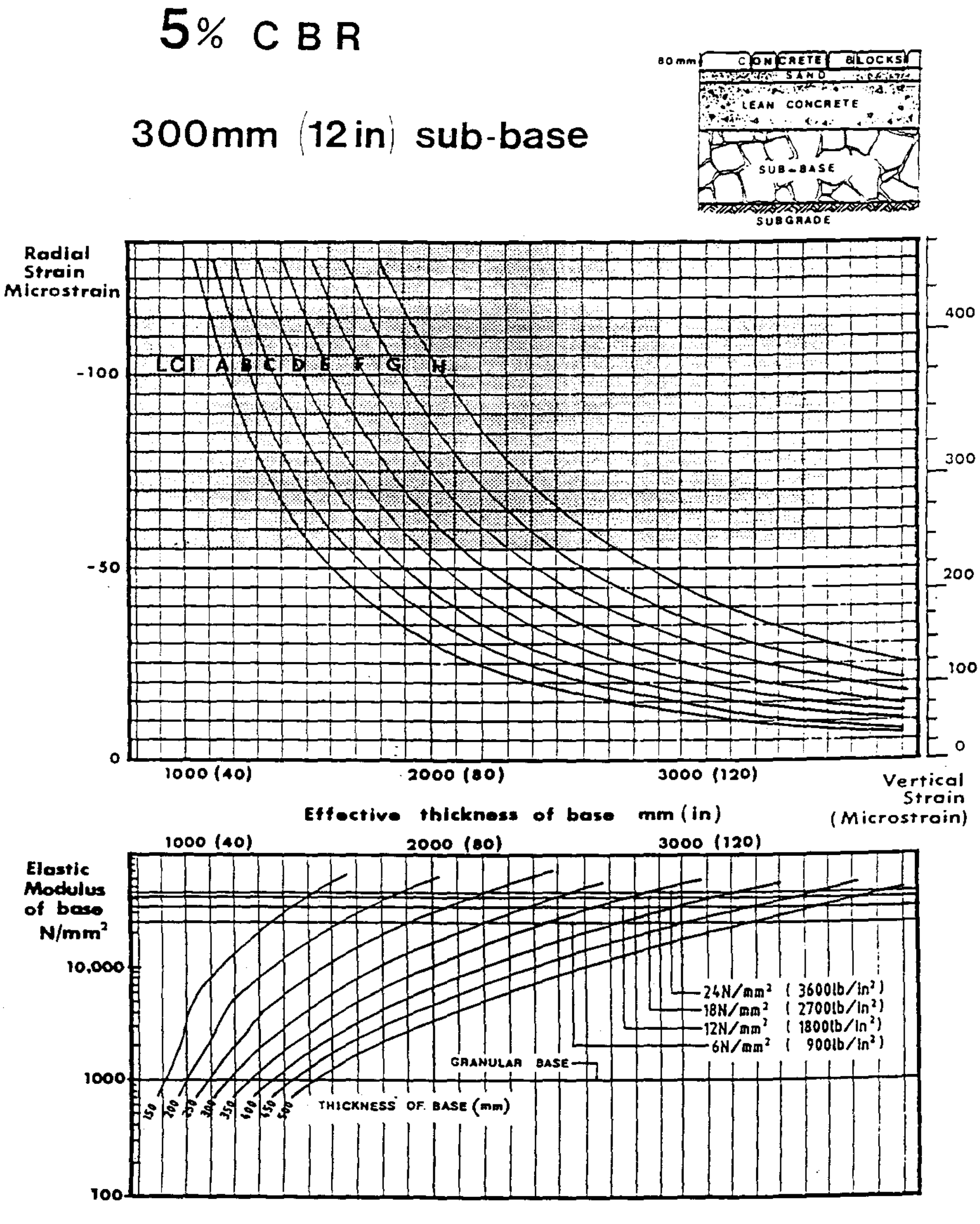


Figure 3.5(a). Design Curves for 5% CBR Subgrade and 12 inch Subbase (CPI [17])

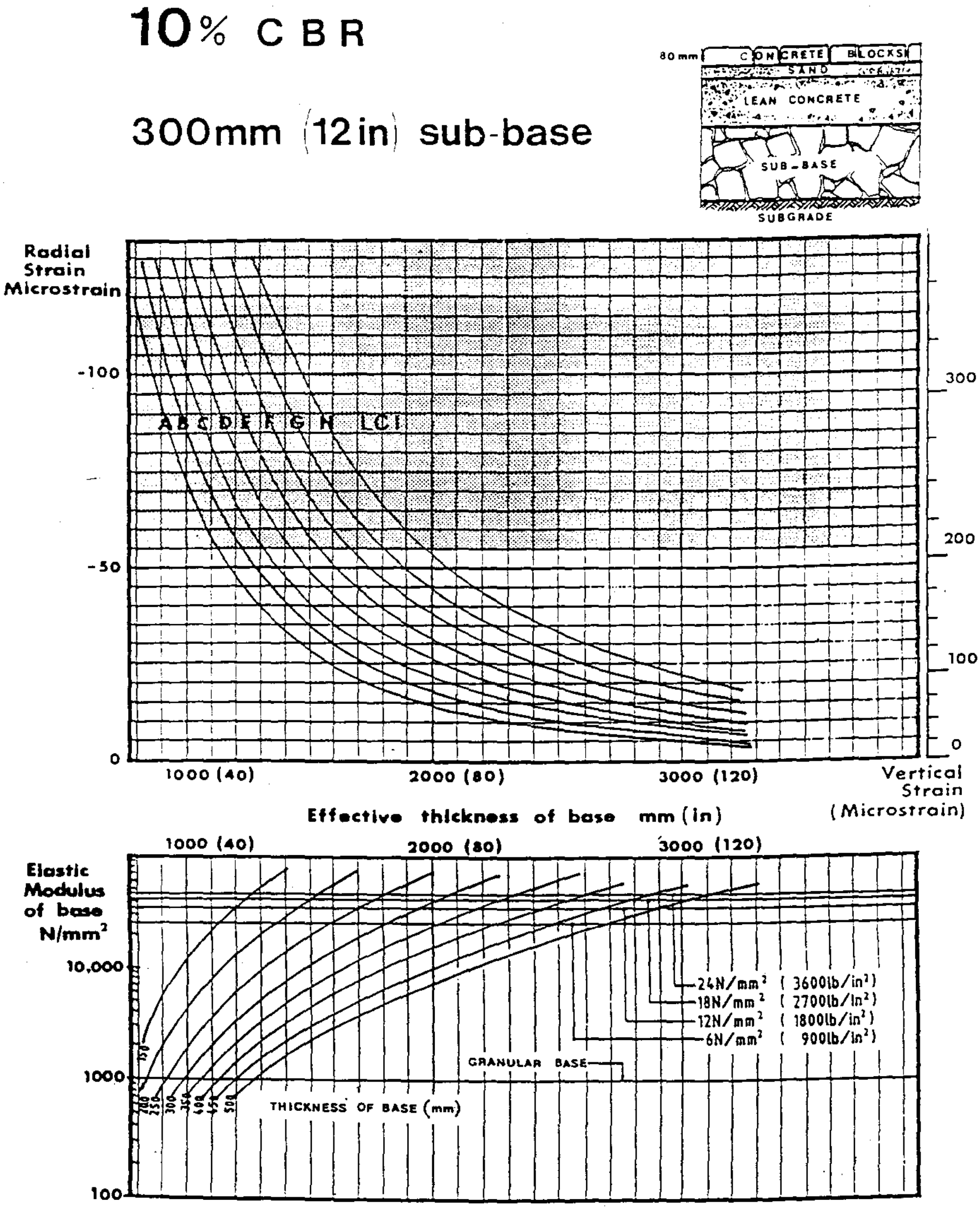
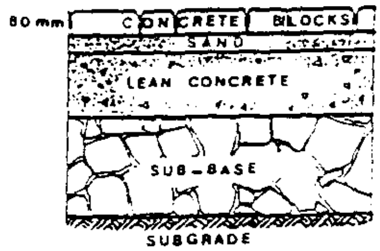


Figure 3.5(b). Design Curves for 10% CBR Subgrade and 12 inch Subbase (CPI [17])

30% C B R

300mm (12in) sub-base



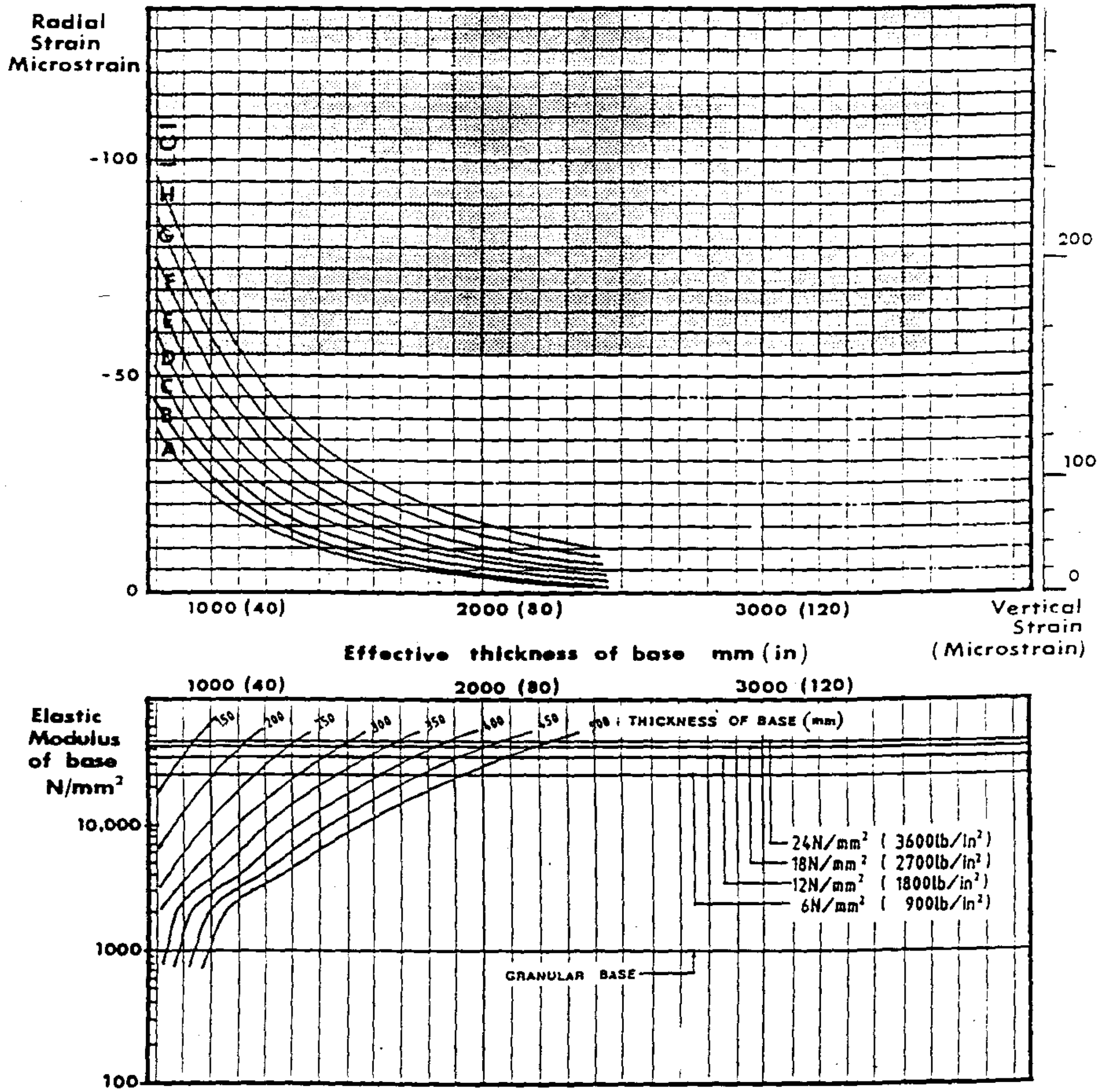


Figure 3.5(c). Design Curves for 30% CBR Subgrade and 12 inch Subbase (CPI [17])

Table 3.1. Paver Equivalent Material Factors

Material	Paver (in.)	Sand (in.)	Equivalency Ratio (paver & sand thick./matl. thick.)	Ref
Asphalt concrete Asphalt treated base Cement treated base Unbound base	3 1/8 (min)	1 (min)	1.0 0.68 - 0.91 0.5 - 0.68 0.32 - 0.57	[5]
Asphalt concrete Concrete Unbound base Cement treated base	2 1/2 - 3 1/8	1.2 - 2	1.0 1.7 0.45 0.4 - 0.7	[3]
Asphalt concrete Crushed rock base	3 1/8	2	0.67 - 0.91 0.34 - 0.48	[1]
Asphalt Concrete with base	3 1/8	1	0.635	[10]
Asphalt concrete	-	-	0.93 - 0.98	[12]
Asphalt concrete	3 1/8	-	0.67	[12]

Table 3.2. Material Conversion Factors for the Component Analysis Method (From CPI TR-97, Port and Industrial Pavement Design with Concrete Pavers [17])

Type of Material	Material Conversion Factors*
3 1/8 " concrete pavers including 1" sand	1.1
4500 psi pavement quality concrete	1.7
1800 psi lean concrete	1.0
2700 psi lean concrete	1.3
Cement-bound granular material	0.7
600 psi soil-cement	0.5
900 psi soil-cement	0.6
Open-textured bituminous material stiffened with latex slurry	1.5
Dense bituminous macadam	1.0
Rolled asphalt	0.8
Type 1 sub-base material over subgrades with CBR > 5%	0.3
Type 1 sub-base material over subgrades with CBR < 5%	0.2
Type 2 sub-base material over subgrades with CBR > 5%	0.2
Type 2 sub-base material over subgrades with CBR < 5%	0.1
Subgrade	0.0

Type 1 - Gravel base material that is free draining, non-plastic.
Type 2 - Gravel base material that may have a plasticity index and often has fines passing the 200 sieve.
* Transforms pavement into an equivalent thickness of 1800 psi lean concrete.

Table 3.3. Condition Factors for Cracking and Spalling (From CPI TR-97, Port and Industrial Pavement Design with Concrete Pavers [17])

Condition of Material	Condition Factor 1
As new	1.0
Slight cracking	0.8
Substantial cracking	0.5
Fully cracked or crazed and spalled	0.2

Table 3.4. Condition Factors for Maximum Degree of Localized Rutting and Localized Settlement (From CPI TR-97, Port and Industrial Pavement Design with Concrete Pavers [17])

Degree of localized rutting or localized settlement (mm)	Condition Factor 2
0-10	1.0
11-20	0.9
21-40	0.6
40+	0.3

CHAPTER 4

CONCRETE BLOCK PAVEMENT PERFORMANCE

4.1 CHAPTER SUMMARY

Concrete pavers can indeed be used for heavy industrial, airport, and city roadway pavements, as shown by various successful applications. Aside from a few distress types that are slightly different than those of AC or PCC, a CBP's performance is determined similarly. The key to a successful CBP application is proper assessment of the in-situ soil properties, strict adherence to design specifications, and competent, experienced supervision. Although most researchers have not reported on failures, those that have stressed problems with materials and construction and not with the paver system.

4.2 INTRODUCTION

A straightforward way to determine pavement performance is to compare other pavements in the immediate area that are subject to similar loading and environmental conditions. However, some objective way to evaluate this performance is needed. The most important issues concerning CBP involve load-carrying capacity or structural adequacy, and serviceability or functional adequacy, of which safety and aesthetics are a part. CBP structural performance may be evaluated with surface deflection measurement using static, steady-state, or impact load devices. Armitage [36] and Rada et al [24] successfully used impact load devices (Falling Weight Deflectometer [FWD]) to backcalculate the effective modulus of elasticity of the layers in a CBP to evaluate their structural integrity. Functional performance, which is a measure of how well the pavement performs as a riding surface for the user, is not as easily evaluated. Significant errors in the subjective evaluation of the rating criteria are possible. This chapter is primarily concerned with CBP structural performance.

Evaluation of structural performance is enhanced by the use of pavement condition surveys. Unlike conventional pavements, for which a wealth of information is available regarding major distress factors and their measurement, until recently no distress factor information could be found for a CBP. Rada et al. were faced with this problem and established a list of distress types for use with an interim condition survey procedure. [24]

Abrasion resistance, absorption, compressive strength, and freeze-thaw durability are additional performance concerns. Normally they are not a problem because these physical requirements apply directly to the pavers instead of the finished pavement and can be evaluated before installation.

The primary failure mode for CBP is rutting caused by repetitive shear deformations. [2,4,5,12,24] Paver breakage and spalling are considered secondary problems and are usually a result of rutting.

4.3 CBP STRUCTURAL PERFORMANCE

Structural performance is simply a measure of the load carrying capacity of a pavement today and its ability to meet future loadings. Installation of a CBP that is designed in accordance with any of the established methods and that adheres to material and construction specifications results in a pavement capable of meeting the loads expected during its design life. In some cases, as a result of a conservative design, the pavement may exceed the originally planned load carrying requirements. [15] Elastic layer computer programs such as CIRCLY [28] and ELSYM [15] have been used to model the response of CBP for specified loads. Rada et al used the MODULUS back-calculation program (which is based on layered elastic theory) to evaluate the in-place structural capacity of a CBP at three sites in North America. [24] The results showed that the paver/sand composite modulus correlated well with values found in the literature and that these modulus values are similar to those of AC.

The determination of CBP structural performance for the majority of applications reviewed appears to rely on visual inspection and the evaluation of various physical distress criteria. The more important characteristics for a CBP include loss of jointing/bedding sand, edge/corner spalling, cracking, and rutting which adversely affect the load carrying capability of the pavement or require maintenance.

As discussed in Chapter 2, loss of jointing sand results in total failure of the CBP because it removes the medium that provides interlock and transfers shear loads. The joint sand may be washed away, blown away, or may further compact as interlock develops, making the sand appear to be lost. Bedding sand loss is no less severe. The bedding sand may migrate into an "open" base material, into cracks of a CTB, or under an edge restraint. Edge/corner spalling and cracking are normally more of an aesthetic concern, but they can lead to pavement failure if excessively spalled and cracked pavers are not replaced. [8] Some cracking is acceptable because interlock compressive forces maintain tight joints and do not interfere with shear transfer. Rutting may be an indication of the use of the wrong bedding sand, subgrade/fill settlement as a result of insufficient compaction, or failure to adequately assess the subgrade strength during design. As with conventional flexible pavements, rutting of 0.50 to 0.75 inches (13 to 19 mm) in the wheel paths is also considered failure for CBP. The effect of rutting on the pavement's ability to carry future loadings must be evaluated along with surface deflection measurements to determine whether the underlying layer(s) have experienced shear failure, causing the rutting.

4.4 CBP DISTRESS TYPES

Measurement of a pavement's physical condition is often accomplished by conducting a condition survey. This survey not only identifies maintenance requirements but complements the FWD layered elastic analysis by identifying distress types that, if left uncorrected, could cause additional distress and ultimately failure. The distress types developed by Rada et al [24] are shown below.

<table>
<tr><th colspan="2">Distress Types</th></tr>
<tr><th>Surface Irregularities</th><th>Paver Distress</th></tr>
<tr><td>Rutting
Swell/Heave
Depression
Transition to Utility
Transition to Curb</td><td>Corner/edge Spalling
Cracked Pavers
Polished Aggregate
Stained Surface
Horizontal Creep</td></tr>
<tr><th>Joint Distress</th><th>Miscellaneous</th></tr>
<tr><td>Deformed Joint Width
Loss of Joint Sand</td><td>Snow Plow Damage</td></tr>
</table>

The distress types used by Iskandar et al [20] to evaluate the use of CBP at container handling areas are shown below.

Distress Types	
Surface Irregularities	Paver Distress
Rutting Deformation Differential Settlement	Spalling Cracking Polishing
Joint Distress	
Deformed Joints Loss of Joint Sand	

Although the two lists above indicate the different opinions regarding distress parameters, they do agree on the most important types. As more CBPs are installed, standardized evaluation criteria for pavement assessment will be needed.

4.5 CBP PERFORMANCE EVALUATIONS

A review of the available literature showed generally satisfactory performance with the concrete paver system. No major structural distress with this system has been reported.

A summary of various CBP applications over the past ten years and their performance is provided in Table 4.1. Unfortunately, not all the information desired was available. The majority of applications were for heavy industrial use (airports, port areas), while only two applications (North Bay, Timmins) were on downtown streets. Two-way traffic on the North Bay, Ontario, street was approximately 8,000 vehicles per day (automobiles, buses, trucks), including 4 to 5 percent delivery trucks and buses. [24] The Timmins, Ontario, street was similar, with approximately 6,000 vehicles per day. Reported project area quantities varied from a low of 1,400 sy (1,150 m^2) to a high of 418,000 sy (350,000 m^2). Most were new installations and were laid by hand; only one was identified as machine-laid, and only two used pavers over an existing pavement. The pavers used were 3 1/8 inch (80 mm) thick, except for the port areas, which used 4-inch (100-mm) pavers. Bedding sand thicknesses varied from a low (compacted) of 1/2 inch (15 mm) to a high (compacted) of 2 inches (50 mm), and a low (loose) of 1 inch (25 mm) to a high (loose) of 2 1/2 inches (65 mm).

Where design life was provided, the majority of projects used 20 years, which is similar to the design life for flexible pavements. Interestingly, one application used a 30-year design life, but that was revised after 10 years of service. The original design used the Shell formula to calculate allowable vertical compressive strain. For the revised design life estimate, the more stringent BPF formula [17] was used, with the 62 percent increase in PAWLs experienced. This led to a design life of only 7 years. Because the pavement was already 10 years old, and no visible failure had been noted, Oldfield concluded that either the BPF formula does not model the real performance of the CBP or other parameters used for design were not set properly. [15] Consequently, the subgrade stiffness was increased 20 percent, the stiffness of the underlying pavement layers (crushed rock, 3 percent CTB) was increased 10 percent, and the composite paver system modulus was increased 750 percent from 145 ksi (1,000 MPa) to 1,088 ksi (7,500 MPa). The BPF formula with the modified parameters resulted in a revised design life of 14 years. Because of excellent in-service performance and high construction standards, the 30-year design life originally predicted is probably sound, but the increased PAWLs may reduce the life by half.

A more detailed summary of the specific performance characteristics for the CBP applications listed in Table 4.1 is provided in Table 4.2. Table 4.2 indicates that up to 5 years after construction, the majority of the reviewed projects were performing well. Most of these projects were older than 5 years; the oldest project was 10 years. The 10-year-old project was a port in Melbourne, Australia, which has required virtually no maintenance and none is foreseen. Despite the significant loadings, and at times abuse by dropped containers, this pavement was exposed to, its performance is an example of the effectiveness of pavers in this application. The port in Jakartra, Indonesia is another example of the advantages of pavers. Although after only two years the entire pavement had settled 12 inches (300 mm), the surface remained serviceable and relatively even. The two roadways in Ontario were the closest in age (8 and 7 years), environment, and traffic loadings, and their performances were similar to each other, with little distress (mostly localized) and small rut depths.

Although overall CBP performance is satisfactory, problems do exist. Despite the advantages of an invisible excavation patch, easy paver removal, and reinstatement with the same pavers, settlement over excavated areas were noted at Lyttelton, New Zealand, North Bay, Ontario, and Fayetteville, North Carolina. No further information is available regarding these areas, but most likely either improper compaction or use of the wrong material in the layers below the pavers caused the problems. At any rate, the utility cut and resulting settlement does not affect the load carrying capability of the pavement. This is unlike conventional, monolithic pavements, in which utility cuts destroy the continuity of materials on which the pavement relies for strength. Aside from the loss of jointing sand, which is unique to CBP and is avoidable with proper precautions, other minor problems (rutting, spalling, cracking) and their magnitudes appear to be the same as those of conventional pavements.

4.6 ADDITIONAL FACTORS AFFECTING PERFORMANCE

In addition to the structural performance characteristics described above, several other factors also contribute to CBP performance. These factors include an adequate site investigation, the proper selection and/or specification of materials, maintenance, and careful construction techniques.

An adequate site investigation includes an assessment of the in-situ soil strength or stiffness, and a determination of the soil's permeability or water drainage capability. The main reason for CBP failure is usually improper evaluation of the subgrade strength during the design stage. [2,4] As for water drainage, a CBP is not waterproof, especially early in its life. Water will permeate into the pavement layers beneath the pavers and is a significant concern when moisture susceptible materials are used. Therefore, a CBP should include proper surface and subsurface drainage as required by the local site conditions.

Of all the materials used in constructing a CBP, the bedding/jointing sand has the greatest impact on pavement performance. The bedding/jointing sand and its different gradations allows interlock to develop, giving the CBP its load carrying capability. This difference in material gradation must be maintained, and any substitution of one for the other will lead to reduced pavement performance. [15,23] In addition to the different gradations, it is also important that the sand not degrade and that it conforms with the specified abrasion tests. A bedding sand that did not meet the proper gradation caused Seattle's Pine Street to fail within a short period of time (actually a "few" days). [21]

Normally, CBPs require little maintenance under most operating conditions. However, in heavy industrial applications, delayed replacement of severely damaged pavers may lead to premature pavement failure. The paver loses its interlocking potential, and the subsequent loss of bearing capacity leads to local settlement and rutting. [8]

Not following established construction techniques leads to faulty work and can be directly attributed to poor supervision. The most common faults observed in Australia during construction included, laying the pavers too close to one another (which led to paver spalling and rotation); failure to progressively compact the pavers/bedding sand and to fill the joints (which led to surface deformations); failure to maintain proper subgrade, base, and bedding sand thicknesses (which led to rutting and surface deformations); and failure to establish a good end-of-day stopping point (which led to unevenness along this line). [23] The influence of construction supervision was illustrated by an investigation by Pearson et al [23] of residential area cul-de-sacs with similar soil conditions and traffic loadings in two Australian cities. One was successful and one was not. The successful project had an experienced supervisor who ensured that all stages of construction and materials used were thoroughly inspected by competent and experienced road inspectors. In the unsuccessful project, supervision was intermittent and construction proceeded without inspection of previous work. The successful project has performed well with little distress for more than 15 years, whereas the unsuccessful project exhibited severe surface deformations within a few months of construction, requiring complete removal and replacement.

Table 4.1. Concrete Block Pavement Applications and Performance

Location	Application	Qty (sy)	Year Installed	Installation	Paver Size (in.)	Bedding Sand (in.)	Design Life (yrs)	Performance	Ref
Melbourne, Australia	Port Area Container Terminal	84,000 24,000	1981 1985	New, by hand	3 1/8	1.2 (comp.)	30/7/14*	Satisfactory	[15]
Newport News, VA	Coal Terminal	67,800	Oct 1982 - Feb 1983	New, by hand	3 1/8	1 (?)	-	Excellent	case study
Luton, U.K.	Aircraft Aprons and Turning Areas	3,200 6,000 6,000	Jan/Feb 1983 Nov 1983 Nov/Dec 1984	Overlay on PCC	3 1/8	2 1/2 (loose)	-	Successful	[13]
North Bay, Ontario	Roadway	16,700	Jul/Nov 1983	New	3 1/8	1.2 (loose)	20	Excellent	[24]
Timmins, Ontario	Roadways	13,300	1984	New	3 1/8	1.2 (loose)	-	Excellent	[24]
Fayetteville, NC	Transit Mall	4,600	May 1985	New	3 1/8	1 1/2 (loose)	-	Excellent	[24]
Lyttelton, N.Z.	Port Area Container Yard	3,500	Apr/May 1986	Overlay on AC, by hand	4	1.6 (loose)	20	Satisfactory	[26]
Lyttelton, N.Z.	Port Area Container Yard	6,500	Oct/Nov 1986	New, Machine	4	1.6 (loose)	20	Satisfactory	[26]
Jakartra, Indonesia	Port Area Container Yard	155,500	1988	New and Overlay on AC, by hand	4	2 (comp.)	-	Satisfactory	[20]
Surabaya, Indonesia	Port Area Container Yard	418,600	1989	New, by hand	4	2 (comp.)	-	Satisfactory	[20]
Aberdeen Proving Ground, MD	Tank Road Intersection (M-88, M-578)	1,400	May 1989	New, by hand	3 1/8	1 (loose)	20	Excellent	[39]
Cairns, Australia	Aircraft Apron	16,700	Aug/Sep 1990	New, by hand	3 1/8	1/2 (comp.)	15	Excellent	[28]
Dallas/Fort Worth, TX	Aircraft Taxiways	28,700	Sep/Nov 1990	New, by hand	3 1/8	1 1/2 (loose)	20	Satisfactory	[16]

* 30 yrs. original design life, revised to 7 yrs as a result of increased loadings and more stringent BPF formula, revised again to 14 yrs by increasing original stiffness of each pavement layer.

Table 4.2. Concrete Block Pavement Performance Summary

Location	Application	Performance	Ref
Melbourne, Australia	Port Area Container Terminal	Excellent after 10 yrs. Virtually no maint. required and none foreseen in immediate future. Pavers in equipment yard not affected by large hydraulic/lubricating oil spills. No evidence of rutting. No apparent penetration of water through paver surface. Minor settlement at pavement/wharf interface and at deep drainage pits - caused by settlement of subgrade and underlying fill. Corners of containers dropped onto pavers created significant impact loads causing cracking and loss of .4 - .6 in. of paver thickness. Cracking not considered a problem since interlock compressive forces keep joints tight.	[15]
Newport News, VA	Coal Terminal	Excellent after 7.5 yrs.	
Luton, U.K.	Aircraft Aprons	Successful after 3 yrs. 9 mos. Continual problems with erosion of jointing sand, especially at aircraft turning areas. After several different attempts, joint sand erosion corrected in 1986 by application of a polymer sealer. After 5 years, no more loss of joint sand evident.	[13,14, 29]
North Bay, Ontario	Roadway	Excellent after 8 yrs. 6400 sy area surveyed. 4.2% of area exhibited depressions (not rutting), but was confined to one area where excavation of paver surface was necessary to access utilities. 3.6% of area exhibited paver corner/edge spalling mostly caused by inferior quality pavers and snow plow operations. Left wheel rut depths varied from .047 - .927 in. Right wheel rut depths varied from .010 - .662 in.	[24]
Timmins, Ontario	Roadways	Excellent after 7 yrs. 4800 sy surveyed. 18.8% of area exhibited scratch marks from snow plows. 2.8% exhibited paver spalling, mostly caused by inferior quality pavers and snow plow operations. Left wheel rut depths varied from .000 - .449 in. Right wheel rut depths varied from .014 - .706 in.	[24]
Fayetteville, NC	Transit Mall	Excellent after 6 yrs. 3000 sy surveyed. 3% of area exhibited staining, mostly from bus oil leaks. Swell/heave and depressions (not rutting) were noted in 2.95% and 1.25% of area, respectively. Swell/heave confined to one area where broken water main required removal and replacement of pavers. Left wheel rut depths varied from .014 - .253 in. Right wheel rut depths varied from .008 - .313 in.	[24]

Table 4.2. Concrete Block Pavement Performance Summary (continued)

Location	Application	Performance	Ref
Lyttelton, N.Z.	Port Area Container Yard	Satisfactory after 6 yrs. Additional joint sand required initially and recurring settlement problems over cable trench excavation requiring lifting and relaying of pavers. No water runoff problems experienced.	[26]
Lyttelton, N.Z.	Port Area Container Yard	Satisfactory after 5 yrs. Additional joint sand required initially but no other problems with pavers or water runoff noted.	[26]
Jakartra, Indonesia	Port Area Container Yard	Satisfactory after 2 yrs. Although entire pavement area settled 12 in., pavement remained serviceable and relatively even. Less than 2% of area had .75 - 1 in. rutting. In area where existing AC was overlaid, rutting of 4 in. in wheel paths of large rolling crane noted. Rutting can also be attributed to use of asphalt grade 80-100 and 60-70, but not the 40-50 more suitable to climate. Less than 1% of area exhibited cracking/spalling. Less than 1% of area exhibited joint deformation. Most of pavement had jointing sand loss to depth of 3/8 in. requiring additional placement.	[20]
Surabaya, Indonesia	Port Area Container Yard	After 1 yr, no indication of settlement, rutting, or loss of jointing sand. Placement of surcharge prior to CBP installation resulted in settlement of 4.9 to 6.5 ft after 2 yrs.	[20]
Aberdeen Proving Ground, MD	Tank Road Intersection	Excellent after 2 yrs. No maint. during this time period. Some rutting of less than .4 in. found near intersection areas where traffic is channelized. Virtually no maint. expected throughout design life.	[39]
Cairns, Australia	Aircraft Apron	Excellent after 16 mos. No visible rutting. No surface defects such as spalling or abrasion. Major fuel spill of 1980 gal (7500 L) did not affect CBP, but did affect a nearby AC surfaced parking bay requiring closure of that bay for repairs.	[28]
Dallas/Fort Worth, TX	Aircraft Taxiways	Performed as expected after 14 mos. Minor drainage problems and settlement along edge.	[16]

CHAPTER 5

CONCRETE BLOCK PAVEMENT COSTS

5.1 CHAPTER SUMMARY

On a first cost basis, a CBP is more expensive than AC or PCC for most applications. What makes a CBP attractive is that it combines the strength of PCC with the flexibility of AC. A separate, thorough, detailed, and fair comparative cost analysis must be conducted for the specific application considered. Even though a life cycle costs (LCC) analysis of options is preferred, the determination of LCC is clouded by lack of sufficient information regarding actual maintenance costs and a lack of long-term CBP performance data in the U.S.

5.2 INTRODUCTION

Acquiring accurate cost estimates from suppliers and contractors about CBP is not easily accomplished. The reasons the task is difficult vary and include the lack of specific job size information, unknown pavement geometry (how many individual pavers must be cut to fit), whether prevailing wages must be paid, the type of installation (hand laid or mechanically laid), and competition. However, some cost information from completed installations can be gleaned from the literature. Normally in the U.S., CBPs are more expensive on a first cost basis than AC or PCC. However, lower maintenance costs may make pavers the more economical choice. The best way to determine the most economical pavement choice is to perform a LCC analysis. An LCC analysis includes all the costs associated with construction, maintenance, rehabilitation, and, preferably, user impacts of a pavement over the analysis period. In light of the difficulty surrounding the assignment of costs associated with maintenance and user impacts, this type of comparison was not conducted. Instead, some CBP square foot costs and reasons for this choice are reviewed below. Local CBP estimated costs and WSDOT unit prices for AC and PCC are also compared below.

5.3 CBP COSTS

Unfortunately, very little information on the installed square foot cost of pavers is available. A review of recent literature provided some cost data, and this information is summarized in Table 5.1. Although no actual costs were available, the port areas in Melbourne, Australia, and Jakartra and Surabaya, Indonesia, used pavers as a result of comparative cost analyses that showed that AC was more expensive over the design life of the pavements. In Lyttelton, New Zealand, bid prices for pavers were less than those for AC.

In Cairns, Australia, a cost comparison based on the required pavement thicknesses above the subgrade and select fill layers for an aircraft apron for the B747-200/400 aircraft concluded that 3 1/8-inch (80-mm) pavers on top of 0.50 inches (15 mm) of compacted bedding sand would be more expensive than 22 to 26 inches (550-650 mm) of AC, but less expensive than 16 inches (400 mm) of PCC. It is not clear whether the 10 inches (250 mm) of 2 percent portland cement modified fine crushed rock (CMFCR) and the 0.2-inch (5-mm) primer seal on top of the CMFCR were considered in the square foot cost of the pavers for this analysis.

The cost analysis for the tank road intersection project at the Aberdeen Proving Ground, Maryland, predicted that the installed price for pavers would equal that of AC. In this application AC was considered unsuitable for the abrasive turning loads of the expected tracked vehicle traffic. The use of PCC was considered an acceptable pavement option, but the small area (1,400 sy) increased the unit price 10 to 30 percent over that of the CBP.

The city of Dayton, Ohio, installed a CBP roadway as an experimental capital improvement project. In this application, despite the small area (1,385 sy), both a 3 1/8-inch (80-mm) AC overlay and 6 inches (150 mm) of non-reinforced PCC were less expensive than machine installed pavers. However, pavers were chosen so that their use as an alternative pavement option could be evaluated, and the higher price was not an issue.

For the Dallas/Fort Worth airport taxiways, the decision to use pavers instead of AC or PCC was based on the user costs attributed to runway closure time. Any reduction in runway closure time decreased these costs. Installing pavers reduced the runway closure time from

14 hours to 12 hours each night during the 114-night construction period. The airlines considered this to be crucial to their operations, and it also satisfied the contractor's concerns about completing a PCC pavement section in the time allotted. [16] When user costs are the primary factor in choosing CBP, comparing its cost to the unit cost of conventional pavements becomes more difficult.

The unit prices for CBPs vary depending on factors such as local labor costs, paver size, bedding sand thickness, distances pavers must be shipped, and the amount of pavement to be constructed.

5.4 CBP COMPARISONS

As previously stated, a CBP usually costs more than conventional pavements on a first cost basis. However, in some cases pavers can be competitive with AC or PCC. WSDOT's "Summary of Costs and Resources Used" for the period of June 1, 1992, through May 31, 1993, lists current installed unit costs for conventional pavement materials. These costs are from actual project bids. The specific pavement materials reviewed include those listed below.

Standard Item Number	Description
5764	Asphalt concrete pavement, Class A, (ton)
5765	Asphalt concrete pavement, Class B, (ton)
5775	Asphalt concrete pavement, Class D, (ton)
5602	Cement concrete pavement, 14 day, 0.75 ft section, (sy)
5614	Cement concrete pavement, 14 day, 0.83 ft section, (sy)

A summary of the lowest and highest unit costs, the quantity, and the item's percentage of the project cost are shown in Tables 5.2 and 5.3.

Discussions with local manufacturers and a local contractor revealed that the cost for supply and installation of 3 1/8-inch (80-mm) pavers and 1 inch (25 mm) of bedding sand in the Puget Sound area varies between $3.25 and $5.00 per square foot for hand installation. This cost is greatly influenced by the size of the job and site access. Some economy of scale is realized with projects in excess of 50,000 square feet.

Discussions with local manufacturers indicated that for jobs larger than 15,000 square feet (1,400 m^2), machine installation can reduce the unit cost as much as 15 percent. Table 5.1 shows that machine installation at the airport in Luton, United Kingdom, cost 12 percent less than hand installation in 1984. In 1985, the Dayton, Ohio, street was installed mechanically for 42 percent less than if it had been done manually. The actual cost savings realized with mechanical installation depends on site access, the geometry of the pavement, and the total pavement area.

5.4.1 CBP versus AC

Table 5.2 appears to show that for most projects that use any of the three AC classes, projects in which the pavement represents a small percentage of the overall work have a higher unit cost. Alternatively, projects in which the pavement represents a high percentage of the overall work have lower unit costs. The information does not indicate how the small pavement area, which varies from 526 to 10,631 square feet, affects these higher unit costs. (The increased price of AC is probably caused by the need to spread mobilization costs over a small area and/or an unbalanced bid.) However, the information does reveal that CBP may be cost competitive, on a first cost basis, in places where a small area of AC pavement must be placed.

5.4.2 CBP versus PCC

Table 5.3 shows that the situation for PCC is similar to that described above for AC. Although the total number of projects reviewed was quite small (3 PCC projects vs. 130 AC projects), it is not unreasonable that the unit prices will be high for projects in which the quantities of PCC pavement are small. Again, in places where a small area of PCC pavement must be placed, a CBP may be cost competitive.

Table 5.1. Concrete Block Pavement Costs

Location	Application	Qty (sf)	Year	Installation	Paver Size (in.)	Bedding Sand (in.)	Cost* ($/sf)	Ref
Melbourne, Australia	Port Area Container Terminal	756,000 216,000	1981 1985	Hand	3 1/8	1.2	Less than AC after cost analysis	[15]
Newport News, VA	Coal Terminal	610,200	1982	Hand	3 1/8	1	?	case study
Luton, U.K.	Aircraft Aprons and Turning Areas	82,800 54,000	1983 1984	-	3 1/8	2 1/2 (loose)	1.80 (hand) 1.58 (machine)	[13]
North Bay, Ontario	Roadways	150,000	1984	-	3 1/8	1.2 (loose)	3.00	[41]
Dayton, OH	Street	11,000	1985	Machine	3 1/8	1	4.35 (hand) 2.52 (machine) 1.02 (3 1/8 in. AC) 2.04 (6 in. PCC)	[34]
Lyttelton, N.Z.	Port Area Container Yards	90,000	1986	Hand Machine	4	1.6 (loose)	Bid price less than for AC	[26]
Alberta,	Intermodal Yard	163,654	1986	-	-	-	2.60	[41]
Jakartra and Surabaya, Indonesia	Port Area Container Yards	5,166,900	1988 1989	Hand	3 1/8	2 (comp)	Less than AC or PCC after cost analysis	[20]
Lansing, MI	Steets	67,582	1988 1989	-	3 1/8	1	3.38	[41]
Aberdeen Proving Ground, MD	Tank Road Intersection	12,600	1989	Hand	3 1/8	1 (loose)	4.29 Equal to AC, PCC costs 10-30% more	[39]
Cairns, Australia	Aircraft Apron	150,300	1990	Hand	3 1/8	1/2 (comp)	6.50-8.83 4.65-6.50 (AC) 11.15-13.94 (PCC)	[28]
Dallas/Fort Worth, TX	Aircraft Taxiways	258,300	1990	Hand	3 1/8	1 1/2 (loose)	3.91	[16,40]
New Orleans, LA	Port Area	450,000	1992	Machine	-	-	2.05	[41]
St. Augustine FL	Airport	50,000	-	-	-	-	2.35	[41]
Herndon, VA	Parking Lot	15,000	-	-	-	-	3.00	[41]

* Includes supply and installation of pavers and bedding sand. No currency conversions required or noted.

Table 5.2. Typical WSDOT AC Costs

WSDOT Standard Item Number	District	Comments	Qty (ton)	Unit Cost ($/ton)	Qty* (sf)	Unit Cost ($/sf)	Percent of Project Cost
5764 (AC, Class A)	1	Lowest Contract	14,750	25.50	590,000	0.64	7.1
		Highest Contract	40	148.75	1,600	3.72	2.6
	2	Lowest Contract	50,503	17.00	2,020,120	0.43	30.7
		Highest Contract	3.060	44.00	122,400	1.10	7.4
	3	Lowest Contract	35,730	21.50	1,429,200	0.54	44.3
		Highest Contract	45	100.00	1,800	2.50	1.4
	4	Lowest Contract	13,780	24.35	551,200	0.61	24.0
		Highest Contract	130	185.00	5,200	4.63	3.7
	5	Lowest Contract	24,480	22.00	979,200	0.55	20.7
		Highest Contract	315	67.95	12,600	1.70	6.2
	6	Lowest Contract	31,100	17.50	1,244,000	0.44	10.1
		Highest Contract	16,871	21.00	674,840	0.53	19.3
5765 (AC, Class B)	1	Lowest Contract	9,740	21.05	389,600	0.53	30.3
		Highest Contract	12	250.00	480	6.25	1.5
	2	Lowest Contract	31,000	20.00	1,240,000	0.50	44.8
		Highest Contract	12	180.00	480	4.50	3.0
	3	Lowest Contract	10,220	24.00	408,800	0.60	12.2
		Highest Contract	75	100.00	3000	2.50	3.8
	5	Lowest Contract	10,420	19.00	416,800	0.48	4.9
		Highest Contract	44	60.00	1,760	1.50	0.4
	6	Lowest Contract	3,670	19.75	146,800	0.49	6.0
		Highest Contract	202	110.00	8,080	2.75	2.7
5775 (AC, Class D)	3	One Contract	10	405.00	400	10.13	1.3
	5	Lowest Contract	4,470	28.00	178,800	0.70	5.3
		Highest Contract	29	170.00	1,160	4.25	1.3

* Asphalt density of 145 lb/cf and thickness of 4.125 in. (1 in. sand/3.125 in. paver) used to develop conversion factor of 0.025 tons/sf.

Table 5.3. Typical WSDOT PCC Costs

WSDOT Standard Item Number	District	Comments	Qty (sy)	Unit Cost ($/sy)	Qty (sf)	Unit Cost ($/sf)	Percent of Project Cost
5602 (PCC, 14 day, 9" thick slab)	1	Lowest Contract	4,698	25.00	42,282	2.78	0.5
		Highest Contract	166	37.75	1,494	4.19	0.3
		(total of two)					
5614 (PCC, 14 day, 10" thick slab)	5	One Contract	118,460	12.50	1,066,140	1.39	36.8

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APPENDIX A

PRODUCT STANDARDS
ASTM C-936
CSA CAN 3-A231.2-M85

Designation: C 936 – 82 (Reapproved 1988)

Standard Specification for Solid Concrete Interlocking Paving Units[1]

This standard is issued under the fixed designation C 936; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers the requirements for interlocking concrete pavers manufactured for the construction of paved surfaces. Units shall not be greater than 6½ in. (160 mm) in width, 9½ in. (240 mm) in length, or 5½ in. (140 mm) in thickness.

1.2 Concrete units covered by this specification may be made from lightweight or normal weight aggregates or mixed lightweight and normal weight aggregates.

1.3 When particular features are desired, such as weight classification, higher compressive strength, surface textures, finish, color, or other special features, such properties should be specified separately by the purchaser. However, local sellers should be consulted as to the availability of units having the desired features.

1.4 The values stated in inch-pound units are to be regarded as the standard.

2. Referenced Documents

2.1 *ASTM Standards:*

C 33 Specification for Concrete Aggregates[2]

C 67 Method for Sampling and Testing Brick and Structural Clay Tile[3]

C 140 Method for Sampling and Testing Concrete Masonry Units[3]

C 150 Specification for Portland Cement[4]

C 207 Specification for Hydrated Lime for Masonry Purposes[4]

C 331 Specification for Lightweight Aggregates for Concrete Masonry Units[2]

C 418 Test Method for Abrasion Resistance of Concrete by Sandblasting[2]

C 595 Specification for Blended Hydraulic Cements[4]

C 618 Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete[2]

3. Materials

3.1 *Cementitious Materials*—Materials shall conform to the following applicable ASTM specifications:

3.1.1 *Portland Cements*—Specification C 150.

3.1.2 *Blended Cements*—Specification C 595, Types IS or IP.

3.1.3 *Hydrated Lime, Type S*—Specification C 207.

3.1.4 *Pozzolans*—Specification C 618.

3.2 Aggregates shall conform to the following ASTM specifications, except that grading requirements shall not necessarily apply:

3.2.1 *Normal Weight*—Specification C 33.

3.2.2 *Lightweight*—Specification C 331.

3.3 *Other Constituents*—Air-entraining admixtures, coloring pigments, integral water repellents, and finely ground silica shall be previously established as suitable for use in concrete and either shall conform to ASTM standards where applicable, or shall be shown by test or experience not to be detrimental to the concrete.

4. Physical Requirements

4.1 *Compressive Strength*—At the time of delivery to the work site, the average compressive strength of the test samples shall be not less than 8000 psi, (55 MPa) with no individual unit less than 7200 psi (50 MPa) as required in 7.2.

NOTE—It is the consensus of the Task Group that compressive strength does not truly express a significant property of a paving unit. Rather, a flexural property evaluated by means of a tensile splitting test will be more meaningful. Accordingly, test data are to be developed by NCMA and C 27 will do an evaluation of existing data to arrive at a specification value, using the test method of ISO DIS 4180. Upon completion of these tests, compressive strength values will be replaced by a tensile splitting requirement.

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4.2 *Absorption*—The average absorption of the test samples shall not be greater than 5 % with no individual unit greater than 7 % as required in 7.2.

4.3 *Resistance to Freezing and Thawing*—The manufacturer shall satisfy the purchaser either by proven field performance or a laboratory freezing-and-thawing test that the paving units have adequate resistance to freezing and thawing. If a laboratory test is used, when tested in accordance with Section 8 of Method C 67, specimens shall have no breakage and not greater than 1.0 % loss in dry weight of any individual unit when subjected to 50 cycles of freezing and thawing. This test shall be conducted not more than 12 months prior to delivery of units.

4.4 *Abrasion Resistance*—When tested in accordance with Test Method C 418, specimens shall not have a greater volume loss than 0.915 in.^{3} per 7.75 in.^{2}, (15 cm^3 per 50 cm^2). The average thickness loss shall not exceed 0.118 in. (3 mm).

5. Permissible Variations in Dimensions

5.1 Length or width of units shall not differ by more than ±1/16 in. (±1.6 mm) from approved samples. Heights of units shall not differ by more than ±⅛ in. (±3.2 mm) from the specified standard dimension. All tests shall be performed as required in 7.2.

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[1] This specification is under the jurisdiction of ASTM Committee C-27 on Precast Concrete Products and is the direct responsibility of Subcommittee C27.20 on Architectural and Structural Products.

Current edition approved Feb. 23, 1982. Published March 1982.

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 04.05.

[4] *Annual Book of ASTM Standards*, Vol 04.01.

6. Visual Inspection

6.1 All units shall be sound and free of defects that would interfere with the proper placing of the unit or impair the strength or permanence of the construction. Minor cracks incidental to the usual methods of manufacture, or minor chipping resulting from customary methods of handling in shipment and delivery, shall not be deemed grounds for rejection.

7. Sampling and Testing

7.1 The purchaser or his authorized representative shall be accorded proper facilities to inspect and sample the unitsat the place of manufacture from the lots ready for delivery.

7.2 Sample and test units in accordance with Method C 140, except as required in 4.3.

8. Rejection

8.1 In case the shipment fails to conform to the specified requirements, the manufacturer may sort it, and new specimens shall be selected by the purchaser from the retained lot and tested at the expense of the manufacturer. In case the second set of specimens fail to conform to the test requirements, the entire lot shall be rejected.

CAN3-A231.2-M85
Precast Concrete Pavers

1. Scope

1.1

This Standard specifies requirements for concrete pavers manufactured from hydraulic cement concrete and intended to be utilized in the construction of pedestrian and vehicular traffic areas.

Note: *Appendix A contains information on efflorescence and recommends methods for its removal. Appendix B provides a bibliography of information on the installation of concrete pavers.*

2. Definitions

2.1

The following definitions apply in this Standard:

Lot means the lesser of an order delivered to a site where the total quantity is less than 20 000 m^2, a 20 000 m^2 portion of an order, or an order, or portion of an order, comprising 2 months production to the manufacturer.

Paver means a precast concrete unit having no dimension greater than 250 mm.

3. Reference Publications

3.1

This Standard refers to the following Publications and where such reference is made it shall be to the edition listed below, including all revisions published thereto:

CSA Standards

CAN3-A5-M83,
Portland Cements;

CAN3-A23.1 and CAN3-A23.2-M77,
Concrete Materials and Methods of Concrete Construction,
Methods of Test for Concrete;

CAN3-A23.5-M82,
Supplementary Cementing Materials and Their Use in Concrete Construction;

CAN3-A266.1-M78,
Air-Entraining Admixtures for Concrete;

CAN3-A266.2-M78,
Chemical Admixtures for Concrete;

CAN3-A362-M83,
Blended Hydraulic Cements;

ACI* Standard

212-1R-81,
Admixtures for Concrete.

**American Concrete Institute.*

4. Materials

4.1 Portland Cement

Portland cement shall conform to the requirements of CSA Standard CAN3-A5. Blended cements shall conform to the requirements of CSA Standard CAN3-A362.

4.2 Supplementary Cementing Materials

Supplementary cementing materials shall conform to the requirements of CSA Standard CAN3-A23.5.

4.3 Aggregates

Aggregates shall conform to the requirements of CSA Standard CAN3-A23.1, except for gradation requirements.

Note: *It may be necessary for a manufacturer to require properties above the minimum specified in CSA Standard CAN3-A23.1 in order to meet the durability requirements of this Standard.*

4.4 Admixtures

Admixtures shall conform to CSA Standards CAN3-A266.1 and CAN3-A266.2.

4.5 Water

Water for use in concrete for pavers shall conform to the requirements of CSA Standard CAN3-A23.1.

4.6 Colouring Material

Pigment used integrally in the manufacture of pavers shall be natural or synthetic mineral oxides with a history of colour fastness.

Note: *ACI Report No. 212-1R provides guidance on the use of pigments.*

4.7 Other Constituents

Other constituents, such as integral water repellents, that are not covered by CSA or ASTM Standards, shall have a proven record of performance. Test reports may be required by the purchaser.

5. Sampling and Testing

5.1 General

Sampling and testing shall be carried out by a concrete testing laboratory, certified in accordance with CSA Standard A283, by a certification organization accredited by the Standards Council of Canada in the subject area of Building Products and Structures.

5.2 Sampling

Ten full-sized concrete pavers between 1 and 3 days old shall be randomly selected from the manufacturer's production at the time of packaging or bundling. All 10 pavers shall be checked for dimensional variation. Three pavers representative of the sample shall be subjected to a deicing salt freeze-thaw durability test, and five shall be tested for compressive strength, all after the prescribed period of curing. Sampling shall be carried out at the intervals specified in Clause 5.3.

5.3 Frequency and Number of Tests

The quality of production shall be monitored for compressive strength, dimensional tolerances, and durability on a continuing basis. Tests shall be performed at least once for every 20 000 m^2 of production, or every 2 months when in production (whichever is first), or at any time when a change in manufacturing process, mix design, cement aggregate, admixture, or other material occurs. The manufacturer shall maintain a record of test results and make this available to the purchaser upon request. Compressive strength and durability tests shall be conducted when the pavers are 28 days old.

5.4 Identification

Sample pavers shall be marked with the manufacturer's code name, batch number, and date of manufacture. The manufacturer shall maintain a production record showing batch numbers and the date of manufacture, and the product shall be marked with a batch number on the strapping or packaging for identification by the purchaser.

6. Required Characteristics and Conformance

6.1 Compressive Strength

6.1.1

When tested in conformance with Clause 7.2, the average compressive strength of concrete pavers shall be not less than 50 MPa after 28 days based upon the average of five cube specimens cut from five full size pavers, after curing in accordance with Clause 7.1. No individual test shall be below 45 MPa.

6.1.2

Testing of whole pavers is permissible provided that

(a) the testing laboratory establishes the strength ratio for that particular shape compared to cubes;

(b) the resulting strength is clearly stated as being established upon the testing of full pavers; and

(c) the equivalent cube strength is stated.

6.2 Durability

When tested in accordance with Clause 7.3, the average weight loss of three full size pavers, after having been subjected to 50 freeze-thaw cycles while totally immersed in a 3% sodium chloride solution, shall not exceed 1.00% of the initial constant dry weight of the specimens.

Note: *Because a period of 12 weeks is normally required to perform the freeze-thaw test, pavers may, at the option of the purchaser, be delivered and installed before the durability test results are available. Regardless, the acceptability of supplied pavers depends upon their meeting the requirements of this Standard.*

6.3 Permissible Variation in Dimensions

Dimensions of pavers shall not differ from those agreed upon by the purchaser and the manufacturer by more than the following amounts:

(a) length—±1.6 mm;

(b) width—±1.6 mm; and

(c) height—±3.2 mm.

6.4 Conformance

Where pavers tested fail to conform to the specified requirements, the manufacturer may sort them, and new specimens shall be sampled by the purchaser and tested. Should the second set of specimens fail to conform to the test requirements, the entire lot shall be deemed not to have met the requirements of the Standard.

7. Test Methods

7.1 Curing

After sampling, test specimens shall be cured in a moist chamber, as specified in Clause 7.3.2.3, for 14 days. Moist curing shall be followed by storage in air at 23 ± 3°C until the start of the test procedures.

7.2 Compressive Strength Test

7.2.1 Scope and Equipment

Capping and compressive strength testing shall be carried out in accordance with the requirements of Test Method 9C of CSA Standard CAN3-A23.2, except that cubes or full pavers shall be substituted for cylinders. Compressive strength tests shall be conducted so that the testing axis is perpendicular to the manufacturing surface.

7.2.2 Test Specimens

Test specimens shall consist of five cubes prepared from five pavers where the dimensions of each cube shall be equal to the thickness of the concrete paver, or five full pavers.

7.2.3 Calculation of Compressive Cube Strength

The average of the cross sectional areas of the top and bottom cube faces shall be used for calculation of the compressive strength.

7.2.4 Report

7.2.4.1

The report shall include the following:
(a) identification of specimens;
(b) the date manufactured;
(c) the type of paver;
(d) the colour;
(e) the date tested;
(f) the compressive strength of each specimen;
(g) the average strength of the five specimens tested; and
(h) the type of specimen (cube or full paver).

7.2.4.2

In cases where the specimen cube strength is less than 45 MPa, the following additional information shall be reported:
(a) the type of fracture;
(b) the appearance of the internal concrete structure; and
(c) defects in the specimen or the caps.

7.3 Deicing Salt Freeze-Thaw Durability Test

7.3.1 Scope

This method covers the determination of the resistance of concrete pavers to repeated cycles of freezing and thawing when fully submerged in a 3% sodium chloride solution.

7.3.2 Apparatus

7.3.2.1

The freezing apparatus shall consist of a suitable cabinet or cold room with controls to reach and maintain an air temperature of −15 ± 2°C within 1 hour of the introduction of specimens.

7.3.2.2
The thawing chamber (cabinet or room) shall be suitable to maintain a controlled air temperature of 23 ± 3° C.

7.3.2.3
The moist chamber (cabinet or room) shall be suitable to maintain a controlled air temperature of 23 ± 2° C and a relative humidity of at least 90%. If storage in water is desirable, a saturated lime solution shall be used, and the temperature shall be maintained at 23 ± 2° C.

7.3.2.4
For measuring fine spalled material, a balance having a capacity of not less than 500 g sensitive to 0.1 g shall be used. For measuring the dry weight of pavers, a balance having a capacity of not less than 5000 g sensitive to 1 g shall be used.

7.3.2.5
The drying oven shall be capable of being maintained at 110 ± 5° C, and the rate of evaporation shall average at least 25 g per hour. This rate shall be determined by the loss of water from 1 L Griffin low-form beakers, each containing 500 g of water at a temperature of 23 ± 2° C, placed at each corner and at the centre of each shelf of the oven, and heated for at least 4 hours, during which period the doors of the oven shall be kept closed.

7.3.2.6
The containers shall be made of noncorroding material and have such dimensions as to permit complete submersion of the specimens in the saline solution.

7.3.3 Test Specimens
Test specimens shall consist of three full size pavers, 28 days old, cured in accordance with Clause 7.1.

7.3.4 Oven Drying
Specimens shall be oven dried for not less than 24 hours and until two successive weighings at intervals of 2 hours show an increment of loss of not greater than 0.2% of the last previously determined weight of the specimen.

7.3.5 Freezing and Thawing Cycle
One freeze-thaw cycle shall be completed every 24 hours. The cycle shall consist of 16 ± 1 hour of freezing followed by 8 ± 1 hour of thawing. If, for any reason, a thaw period cannot commence at the specified time, the specimens shall remain in a frozen condition until conditions are suitable for resumption of the test.

7.3.6 Test Procedure

7.3.6.1
Following completion of the oven drying and cooling to room temperature, the specimens shall be placed in individual containers with the bottom surface of the specimens resting on glass, stainless steel, ceramic, or plastic spacers (approximately 3 mm high) to ensure exposure of at least 95% of the bottom surfaces to the saline solution.

7.3.6.2
The containers shall be filled with a 3% NaCl solution at a temperature of 23 ± 3° C, suitably closed to minimize evaporation, and left at a room temperature of 23 ± 3° C for 24 hours. The level of the solution shall be at least 2 mm above the surface of the specimens, but excess solution volume shall be avoided in order to ensure rapid freezing of the specimens.

7.3.6.3
Following the 24 hour saturation period, the specimens shall be subjected to continuous freeze-thaw cycles as outlined in Clause 7.3.5.

7.3.6.4
After 10, 25, and 50 cycles the specimens shall be washed with a 3% NaCl solution to remove all loose particles. These particles and spalled material collected at the bottom of the containers shall be washed, strained through a filter, and dried to constant weight. This residue shall be defined as weight loss, and expressed as a percentage of the initial dry weight of the specimens. The residue shall be cumulatively weighed after 10, 25, and 50 cycles.

7.3.6.5
A new solution of 3% NaCl shall be used following each weight loss determination. The 24 hour presoaking period shall be waived at 10 and 25 cycles providing that the specimens are maintained in a saturated condition during weight determinations.

7.3.6.6
The weight loss shall be calculated to the nearest 0.01%.

7.3.6.7
The test shall continue until 50 freeze-thaw cycles have been completed unless the test specimens have disintegrated or lost more than 1.0% of their original dry weight. If, because of high spalling losses or disintegration, testing of the specimen has to be terminated prematurely, the weight loss shall be determined (see Clause 7.3.6.4) and added to the previously lost weight.

7.3.7 Report
The report shall include the following:
(a) identification of specimens;
(b) dimensions;
(c) weight losses of the specimens and the average results after 10, 25, and 50 cycles or at the time of termination of the test;
(d) the number of cycles at termination time;
(e) the visual rating of the specimens after 10, 25, and 50 cycles in accordance with the following scale:
  (i) 0—no scaling;
  (ii) 1—very slight scaling (3 mm depth maximum, no coarse aggregate visible);
  (iii) 2—slight to moderate scaling;
  (iv) 3—moderate scaling (some coarse aggregate visible on 50% of the surface);
  (v) 4—moderate to severe scaling (some coarse aggregate visible on 75% of the surface);
  (vi) 5—severe scaling (coarse aggregate visible over 100% of the surface);
(f) a description of the damages suffered by the specimens, and photographs where possible;
(g) the manufacturer;
(h) the date; and
(i) the batch.

APPENDIX B

PUGET SOUND AREA MANUFACTURERS

PUGET SOUND AREA MANUFACTURERS

TRENDSET CUSTOM PAVERS
6820 176TH NE
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(206) 869-1632

WESTCON CONSTRUCTION PRODUCTS
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APPENDIX C

EXAMPLE CBP DESIGN USING THE MODIFIED AASHTO FLEXIBLE PAVEMENT DESIGN METHODOLOGY

CBP DESIGN EXAMPLE

This example is patterned after Rada et al [2,5] with additional refinements to enhance clarity. The CBP design is based on the AASHTO flexible pavement design method wherein layered elastic analysis was used to model the paver/sand composite layer (from which layer coefficients were developed). Essentially, all aspects of the design are the same as for AC with the exception of the design layer coefficient which is considered equal to that of AC only after 10,000 ESAL's.

The design assumes the use of 3 1/8 inch pavers, one inch (minimum) bedding sand layer, and a herringbone pattern for ESAL's of 2,000,000 or less. For ESAL's greater than this, 4 inch pavers are needed or 3 1/8 inch pavers can still be used but the base must be made stiffer.

The following values are used in this design:

S_0 = standard deviation = 0.45
Initial effective modulus = 50,750 psi (350 MPa)
Maximum effective modulus = 450,000 psi (3,100 MPa)
(reached only after 10,000 ESAL's)
$a_{P/S}$ = layer coefficient of the composite paver/sand layer
$E_{P/S}$ = modulus of the composite layer, psi

To determine the appropriate value of $a_{P/S}$, both the reduced-strength and full-strength periods must be covered by use of a weighted layer coefficient.

for t_s (settling period) $\leq t_d$ (design life):

$$a_{P/S} = 0.44 - 0.09(t_s/t_d). \qquad (1)$$

for $t_s > t_d$:

$$a_{P/S} = 0.26 + 0.09(t_s/t_d). \qquad (2)$$

t_s is calculated by solving for the number of years to reach 10,000 ESAL's with the following equation:

$$ESAL's = 365 * ADT * (ESAL_0/100) * (DS/100) * (LF/100) * (((1 + (i/100))^n-1)/(i/100)). \qquad (3)$$

ADT = average daily traffic in both directions
$ESAL_0$ = number of ESAL repetitions per 100 vehicles at start of design period
DS = directional split, %
LF = lane distribution factor, %

i = traffic growth rate, %
n = pavement design life, yrs.

The following steps must be followed in using the thickness design curves shown in Figure 3.4:

1. Determine moisture and drainage conditions.

2. Determine design ESAL's.

3. Characterize subgrade strength taking into account any frost considerations.

4. Determine base thickness requirement using the subgrade resilient modulus. and design ESAL's as input into either of the design curves in Figure 3.4, depending on the material in question.

5. Characterize paving materials in terms of AASHTO layer coefficients. If material properties are not known use the recommended default values. If they are, use the a_i correlations in Table C-1 below and the following regression equation:

$$a_i = K_1 + K_2 * \log_{10} \text{(material strength)} \qquad (4)$$

Table C-1. Structural Layer Coefficient Correlations
(From Rada [2,5])

Material	Strength Parameter Units	Recommended Regression Constants K1	K2	Maximum Default Allowable a_i value*	a_i value	Minimum Allowable Thickness (in.)
Asphalt Treated Base/Subbase (psi)	Modulus Marshall Stability (lb)	-1.453 -0.323	0.316 0.187	0.30	0.40	3.0
Cement Treated Base/Subbase (psi)	Modulus Unconfined Compressive Strength (psi)	-2.651 -0.395	0.486 0.212	0.22	0.30	4.0
Unbound Granular Base (psi)	Modulus CBR (%) R-value	-0.976 -0.053 -0.514	0.249 0.098 0.338	0.14**	0.25	4.0 or 6.0***
Unbound Granular Subbase (psi)	Modulus CBR (%) R-value	-0.839 0.012 -0.205	0.227 0.065 0.176	0.11**	0.20	4.0 or 6.0***

* for use in the absence of material strength information
** must be corrected for moisture and drainage conditions, unless reflected in design strength value used
*** use 4.0 in. if ESAL's < 500,000; 6.0 in. if ESAL's > 500,000

6. Correct the base thickness requirement for a_i values other than the default value recommended in the above table:

$$t' = t * (a_{actual}/a_{default})$$

t' = corrected base thickness

t = base thickness from Figure 3.4

a_{actual} = layer coefficient derived from known material property

$a_{default}$ = default layer coefficient of 0.14, 0.30, and 0.20 for unbound granular, asphalt treated, and cement treated materials respectively

The final layer thicknesses should not be less than the allowable value indicated in the above table.

Numerical Example

A two-lane urban commercial street is to be designed using pavers. The pavement will be exposed to moisture levels approaching saturation more than 25% of the time, drainage quality is fair, and frost is a design consideration. Design traffic is 840,000 ESAL's. Subgrade modulus is 7,500 psi and is in frost susceptible group F4. The unbound granular layer modulus is 44,000 psi. The asphalt-treated base layer modulus is 350,000 psi. The unbound granular subbase modulus is 14,000 psi.

Using this information, develop CBP designs for both granular and asphalt-treated base materials.

Step 1

Determine moisture and drainage conditions. The information provided indicated moisture levels approaching saturation more than 25% of the time and fair drainage quality.

Step 2

Determine design ESAL's. The design ESAL's of 840,000 was given.

Step 3

Characterize the subgrade soil stiffness. The subgrade modulus of 7,500 psi was given. However, since frost is a consideration (Group F4), using Table C-2, the appropriate design stiffness value is reduced to 4,500 psi.

Table C-2. Frost Susceptible Soil Categories
(after Rada et al [2,5])

Frost Susceptible Group	Description	Modulus (psi)
NFS	Non-frost susceptible soils (less than 2% passing 0.02 mm sieve); no problem	N/A
F1	Gravelly soils (3 to 20% passing 0.02 mm sieve); slight problem	12,000
F2	Sands (3 to 15% passing 0.02 mm sieve); slight to medium problem	9,000
F3	Gravelly soils (greater than 20% passing 0.02 mm sieve); sandy soils except silty sands (greater than 20% passing 0.02 mm sieve); plastic clays (PI > 12); varved clays (with uniform condition); medium to high problem	4,500
F4	Silts, including sandy silts and fine silty sands (greater than 15% passing 0.02 mm sieve); lean clays (PI < 12); varved clays (with non-uniform conditions); highest problem	4,500

Step 4

Determine the base thickness requirements. Using the design ESAL's of 840,000 and the subgrade modulus of 4,500 psi as input into the appropriate curves in Figure 3.4. This yields an unbound granular base thickness of 10.5 inches and an asphalt-treated base thickness of 5.25 inches.

Step 5

Determine the AASHTO layer coefficients.

For the composite paver/sand layer. From the traffic data and a 20 year design life, the time to reach 10,000 ESAL's, t_s, is determined to be 0.7 years. Using Equation 1, $a_{P/S}$ is determined:

$$a_{P/S} = 0.44 - 0.09 * (t_s/t_d) = 0.44 - 0.09 * (.72/20)$$
$$a_{P/S} = 0.43685 = \underline{0.44}$$

For the unbound granular layer. Using Equation 4 and the a_i correlations given in Table C-1, a_{GRAN} is determined:

$$a_{GRAN} = -0.976 + 0.249 * \log_{10}(44{,}000) = 0.180$$

This value must be corrected for moisture and drainage conditions. From Table 2.4 in the AASHTO Pavement Design Guide, fair draining soil exposed to moisture levels approaching saturation more than 25% of the time has a drainage coefficient of 0.8. Therefore:

$$a_{GRAN} = 0.180 * 0.8 = 0.144 = \underline{0.14}$$

for the asphalt-treated base layer:

$$a_{ATB} = -1.453 + 0.316 * \log_{10}(350{,}000) = 0.2989 = \underline{0.30}$$

for the unbound granular subbase layer:

$$a_{SUB} = -0.839 + 0.227 * \log_{10}(14{,}000) = 0.102$$

correcting for moisture/drainage conditions,

$$a_{SUB} = 0.102 * 0.8 = \underline{0.08}$$

<u>Step 6</u>

Calculate the corrected base thickness requirements. Since both the granular and asphalt-treated base materials under consideration have layer coefficients equal to those used to develop the design curves in Figure 3.4, no corrections are necessary. The final granular and asphalt-treated base thicknesses are 10.5 and 5.25 inches respectively.

The base thickness can also be used to develop the subbase thickness by using the following structural number (SN) equation:

$$SN = a_i * t_i. \qquad (5)$$

Using equation 5, the SN for the unbound granular base layer is:

$$SN = 0.14 * 10.5 = 1.47$$

Substituting the a_i value of 0.08 for the granular subbase, and solving for the equivalent subbase thickness required,

t_{SUB} = 1.47/0.08 = 18.375 = <u>18.5 in.</u>

Since all designs must include a base layer, only that thickness exceeding the minimum allowable value in Table C-1 (4 in. for granular bases and 3 in. for asphalt-treated bases) is converted into subbase quality material.

For the granular base: t_{GRAN} = 10.5 - 6.5 = 4 in.
SN_{GRAN} = 0.14 * 6.5 = 0.91
t_{SUB} = 0.91/0.08 = 11.375 = <u>11.5 in.</u>

For the asphalt-treated base: t_{ATB} = 5.25 - 3.0 = 2.25 in.
SN_{ATB} = 0.30 * 2.25 = 0.675
t_{SUB} = 0.675/0.08 = 8.4375 = <u>8.5 in.</u>

The final CBP cross-sections are:

For the granular base: 3 1/8 in. pavers, 1 in. bedding sand, 4 in. base, 11.5 in. granular subbase.

For the asphalt-treated base: 3 1/8 in. pavers, 1 in. bedding sand, 3 in. ATB, 8.5 in. granular subbase.