

Design Considerations for Interlocking Concrete Pavements

Applicable to Standard, Textured & Heavy Duty Unit Pavers.

UNILOCK INTERLOCKING CONCRETE PAVER DESIGN GUIDE

TABLE OF CONTENTS

1. INTRODUCTION

- 1.1. Concept
- 1.2. Uses
- 1.3. Advantages

2. SCOPE OF THE MANUAL

- 2.1. Principal Components of Interlocking Concrete Paver Systems
 - 2.1.1. Concrete Pavers
 - 2.1.2. Bedding Sand
 - 2.1.3. Jointing Sand
 - 2.1.4. Geotextile Fabric
 - 2.1.5. Base/Subbase
 - 2.1.6. Subgrade
 - 2.1.7. Edge Restraint
 - 2.1.8. Surface Sealers

3. PAVER SAFETY AND RELIABILITY

- 3.1. Resistance to Fuels, Oils and Chemicals
- 3.2. Skid Resistance
- 3.3. Smoothness
- 3.4. Durability

4. INSTALLATION

- 4.1. Before You Dig....
- 4.2. Subgrade Condition, Compaction and Proof rolling
- 4.3. Geotextile Application
- 4.4. Base Construction
 - 4.4.1. Stabilized Bases
 - 4.4.2. Soil/Aggregate Bases
- 4.5. Manual Installation of Pavers
- 4.6. Mechanical Installation of Pavers
- 4.7. Cutting Pavers for Infill
- 4.8. Patterns for Trafficked Areas
- 4.9. Applying Jointing Sand
- 4.10. Inspection

5. GENERAL MAINTENANCE AND REINSTATEMENT

- 5.1. Pavement Condition Evaluation
- 5.2. Paver Removal

- 5.3. Paver Cleaning
- 5.4. Subgrade Repair
- 5.5. Base Repair
- 5.6. Drainage Improvement
- 5.7. Unshrinkable Fill
- 5.8. Sealer Application

6. WINTER MAINTENANCE

- 6.1. Snow and Ice Removal
- 6.2. De-icing Chemicals

7. DRAINAGE

- 7.1. Subsurface Drainage
- 7.2. Surface Drainage

8. STRUCTURAL DESIGN

- 8.1. Basis for Structural Design
- 8.2. Design Factors
 - 8.2.1. Pavers and Bedding/Joint Sand
 - 8.2.2. Subbase Types and Factors
 - 8.2.3. Assessment of Existing Pavements for Overlay Design
- 8.3. Design Methods
 - 8.3.1. Catalog
 - 8.3.2. LOCKPAVE PRO™

9. PAVEMENT REHABILITATION DESIGN

- 9.1. Asphalt Pavement Overlays
- 9.2. Concrete Pavement Overlays
- 9.3. Non-Structural Overlays

10. LIFE-CYCLE COST ANALYSIS

- 10.1. Present Worth Analysis
- 10.2. Analysis Period
- 10.3. Service Life of Pavement Types
- 10.4. Components Of Pavement Life-cycle Cost Analysis
 - 10.4.1. Initial Costs
 - 10.4.2. Maintenance Costs
 - 10.4.3. Rehabilitation Costs
 - 10.4.4. Residual and Salvage Values
 - 10.4.5. User Delay Costs
 - 10.4.6. Value Engineering

Appendix

ASTM C 936 - Standard Specification for Solid Interlocking Concrete Paving Units

1. INTRODUCTION

1.1. Concept

UNILOCK[®] interlocking concrete pavements are generally composed of a surface consisting of precast modular concrete units of varying shapes, colors and texture. The surface is placed over a graded sand base and interlocked with bedding and joint sand, which can be constructed over a variety of subbases. The concept dates back to the roads of the Roman Empire, and was refined after World War 2 in Europe. The modern concept of high quality, precision manufactured concrete pavers has resulted in the construction of millions of square meters of interlocking concrete pavements constructed each year in Europe, and an expanding market in North America.

Due to the segmental nature of the pavement, concrete interlocking pavements can articulate under applied loads, much like flexible pavements. Unlike flexible pavements, the interlocking nature of the pavements increases significantly under traffic. Conventional flexible pavement design and construction methods have been easily adapted to the concept of concrete interlocking pavements.

1.2. Uses

In North America, the present predominant use of interlocking pavements is in the residential and architectural segments. The acceptance of pavers in these markets has contributed to the growing use of pavers as an alternative to asphalt and cast in place concrete in other applications. Although aesthetic appeal has a great influence on their use, they are recognized load-carrying pavements with a ride quality and favorable safety characteristics. There are significant examples of pavers used for;

- Streets.
- Industrial parking areas.
- Container and multimodal facilities.
- Airport taxiways and aprons.

1.3. Advantages

The architectural advantages of interlocking concrete pavements are readily apparent. With their small size, color and shape variety, they offer a warmth and human scale that is difficult to achieve with conventional concrete and asphalt. They are a perfect complement to almost any architectural style. Unilock concrete pavers can be installed in a variety of patterns including curves, straight lines, intricate designs, and add vitality to almost any environment.

Being manufactured from high strength, low absorption concrete, the pavers are very resistant to freeze-thaw cycles and de-icing chemicals. High temperatures, moisture, petrochemicals or point loads do not damage them. They offer high frictional resistance. They arrive on the job as a finished product, and require no curing, allowing traffic immediately after installation. Year round, construction is possible using pavers. If pavers must be removed in order to correct pavement distress, or to allow utility repair, the units are completely reusable and recyclable.

Pavers have a proven record of long-term performance under heavy loads in industrial and port applications. They provide high resistance to abrasion and point loads that are

common to these applications. Often industrial and port pavements are built on sites that have poor soil conditions. These soils often settle and consolidate unevenly under load resulting in serious damage to pavements. This deformation is more easily handled by interlocking pavers as they can withstand greater deformation than conventional pavements while remaining in service. Where areas have settled, or require access to utilities, the pavers are easily removed, the necessary repairs made, and the pavers reinstalled.

The methodology used in the design of interlocking paver pavements is the same as that used for the design of flexible (asphalt) pavements. The designer has the ability to assess all the factors that impact the pavement structure. These include the subgrade soils, the available roadbed construction materials and the imposed loads which all are assessed in a fashion similar to the methods used to design asphalt streets, parking lots and industrial pavements.

There is sufficient data to allow the designer to assess the life-cycle costs of interlocking paver pavements and compare them to alternative pavement structures. Pavers can easily provide long-life, low-maintenance pavements for all applications. More owners and designers are evaluating the life-cycle costs of pavement design alternatives in order to obtain the most benefits for the pavement investment.

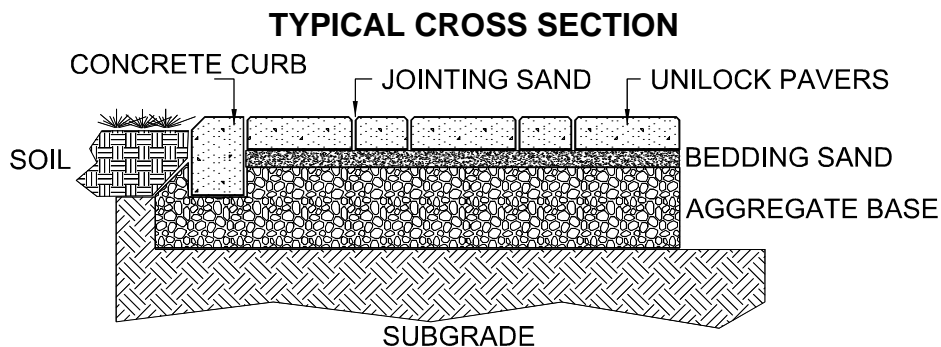
2. SCOPE OF THE MANUAL

This manual presents standards and guidelines for the structural design and construction of interlocking concrete paver pavements for many applications. Paving stone systems can be used for light, medium and heavy-duty pavements in residential, commercial, industrial and municipal applications. This manual will deal with most recommended applications for exterior use.

2.1. Principal Components of Interlocking Concrete Paver Systems

The principal components of interlocking concrete paver pavements are shown in related cross sections. They include base materials, pavers, bedding sand, jointing sand, sealer, geotechnical fabric and edge restraints. UNILOCK[®] pavers come in many sizes, shapes, and colors to enhance the architectural flavor of the pavement. Contact UNILOCK (1-800-UNILOCK – www.unilock.com) for the full range of pavers and other paving elements available.

The pavers are generally bedded on 25 to 40 mm (1 to 1.5 in.) of high quality bedding sand, with a high quality sand used for infilling of the joints between the pavers. The jointing sand allows the pavers to interlock and structurally function as one durable layer.



2.1.1. Concrete Pavers

The manufacturing of high quality concrete pavers involves combining Portland cement, coarse and fine aggregate and sufficient water to produce zero-slump concrete. This concrete is molded in, specialized manufacturing equipment under vibration and extreme pressure. Admixtures may be used to increase various engineering properties (strength, density) and reduce the likelihood of efflorescence and decrease water absorption. Normally, the paver units are constructed with spacer bars to ensure uniform, properly spaced joints and with chamfered edges to prevent chipping.

Pavers are manufactured to specifications outlined in ASTM C 936, Standard Specification for Interlocking Concrete Paving Units. This standard requires average paver strengths of 55 MPa (8000 psi), minimum unit paver strengths of 50 MPa (7200 psi), average absorption of 5 % and maximum unit absorption of 7 %, and resistance to 50 freeze-thaw cycles, with no breakage greater than 1.0% loss in dry weight of any individual unit.

2.1.2. Bedding Sand

Bedding sand is placed to resist the compressive forces associated with loads and tire pressures. A clean (i.e. less than 1 percent passing the 75 μ m sieve size), hard, natural or manufactured sand is normally required. Gradation analysis and degradation testing are performed for approval purposes. In many locations, locally available clean concrete sands conforming to ASTM C 33 will meet the necessary requirements for bedding sand. Some older specifications allow the use of crusher screenings, but this practice is discouraged, especially under trafficked pavements. Some crusher screenings may, however, be used, provided that the gradation of the screenings is similar to the specified gradation. Caution should be exercised with screenings, as they may contain an excess of particles passing the 75- μ m sieve size, and too many flat and elongated particles. This is not recommended for typical paver installations.

2.1.3. Jointing Sand

Finer graded (100 percent passing the 1.18 mm sieve size), high quality sand is required to fill joints (typically 5 to 6 mm (1/4 in.)) between the pavers. Typically sands conforming to the gradation requirements of ASTM C 144 will meet the necessary requirements. The jointing sand among the individual paver units provides interlocking thus transmitting loads to surrounding blocks by shear forces. This enables the pavers and bedding sand to structurally function as a distinct layer allowing distribution of loads in a manner similar to a hot mix asphalt concrete layer.

An alternative for regular sand is the Polymeric Jointing Sand. It is a mix of graded sand and binder, especially formulated for the filling of narrow or wide joints between pavers. Unlike regular sand, Polymeric Sand resists insect infestation, weed growth and erosion caused by rain, frost, wind, suction, etc. It is ideal for stabilizing horizontal or sloped installations. It allows for some movement of the pavers without loss of the jointing sand. This type of sand is applied dry and hardens after moistening.

2.1.4. Edge Restraints

Edge restraints are an important part of the paving stone pavement system. They hold pavers tightly together, enabling consistent interlock of the units throughout the entire pavement. They prevent the pavers from spreading apart under horizontal traffic forces

and from minor settlement. They can take the form of existing structures such as buildings, curbs or external material.

Where there is a possibility of loss of the bedding sand along a restraint, a geotextile shall be placed to prevent this migration. A 12 in. (300 mm) wide strip can be applied along the base and up the sides of the restraint.

Restraints can take the form of precast concrete, plastic, cut stone and aluminum. Restraints can also be constructed on-site using poured concrete.

2.1.5. Sealer

Although not normally required to enhance the surface durability of the paver units, a sealer may be necessary on some pavements such as airport pavements to prevent loss of the joint sand from the effects of repeated jet blast and propeller wash. The sealer will also prevent the ingress of water, oils, and fuel through the joint sand into the bedding sand. Several commercially available sealers have been used for airport projects, including elastomeric monomer urethane and siliconate resins.

2.1.6. Geotextile Fabric

Geotextile fabrics are normally not required with an aggregate or hot mix asphalt base. However, for a cement treated base, a woven geotextile fabric is recommended to prevent migration of bedding sand through shrinkage cracks which normally develop as the cement treated base cures. With inlays or overlays over existing asphalt or concrete surfaces, a geotextile is also recommended. The fabric shall be turned up against edge restraints or structures to prevent sand from migrating into the joint between the pavement and the edge restraint.

2.1.7. Installation

After construction, inspection and acceptance of the pavement base, the bedding sand is spread and screeded to the proper thickness (typically 25 to 40 mm (1 to 1.5 in.)). The moisture content of the sand should remain as consistent as possible to ensure uniform compaction during installation.

The paver units can be placed either by hand or mechanically. A 90-degree herringbone pattern is the most common pattern used to minimize movement and maximize interlock between the paver units in trafficked pavements. In general it is important to avoid patterns with long continuous lines; these may be subject to failure under vehicular traffic. A single or double soldier course (one or two rows) of pavers is usually placed beside the edge restraint. The soldier course is not only an architectural feature, but assists in holding in small cut pieces. The herringbone pattern abuts this soldier course resulting in a more stable surface at the edge and transition area to other pavements. Other patterns may be used in lightly trafficked and architectural pavements.

70 mm (2 3/4 in.) and 80 mm (3 1/8 in.) thick paver units for heavily trafficked pavements are compacted with a minimum 22 kN (5000 lb) force plate compactor. Lighter use pavements use typically 60 mm (2 3/8 in.) pavers, which are compacted in place with a 13 kN (3000 lb) force plate compactor. Jointing sand is swept into the paver joints and the pavers are re-compacted. This procedure is repeated until the joints are filled with sand. The surface of heavily trafficked pavements is final rolled with 70 - 90 kN (16000 to 21000 lb) pneumatic rollers.

3. PAVER SAFETY AND RELIABILITY

The pavement designer requires a working knowledge of different pavement materials to select an appropriate pavement system. The selection should be based upon the following parameters:

- Safety and reliability (i.e. Operational requirements)
- Environmental and climatic considerations.
- Constructability and operational disruption during the construction process.
- Structural requirements (i.e., loading)
- Construction budget.
- Maintenance requirements.
- Cost-effectiveness.

3.1. Resistance to Fuels, Oils and Deicing Chemicals

Pavements constructed with asphalt concrete surfaces are subject to deterioration by spilled fuels and oils. Consequently, Portland cement concrete (PCC) has been the material of choice around fuel islands in service stations, etc. where these chemicals are in abundance. However, while PCC does resist deterioration by fuels and oils, these fluids have been found to have deleterious effects on some joint sealant materials.

The interlocking effect of the joint and bedding sand between the pavers has been shown to resist the passage of these chemicals through the system to collect in the granular layers beneath the pavers. Tests conducted at London Luton Airport under the supervision of the County Petroleum Officer indicated that no explosive vapors are present when sample pavers were removed from an area heavily contaminated with aviation fuel [11].

The most disruptive environmental factor in the consideration of cast in place concrete pavements is freezing and thawing while the concrete is wet, particularly in the presence of deicing chemicals. Deterioration is caused by the freezing of the water in the paste (cement, fine aggregate and water fraction of the concrete), the aggregates or both. Normal concrete provides relief from this disruptive expansion with air entrainment (the microscopic bubbles act as tiny pressure relief valves). Zero-slump pavers combat this action by being designed and manufactured as extremely dense, high strength units. This allows little or no water into the concrete, and is assured by low absorption rate. The most common deicing chemical used is salt, either in the form of sodium chloride or calcium chloride. In the absence of freezing, salts have little or no effect on concrete. The use of deicers containing ammonium nitrate and ammonium sulfate shall be strictly avoided as they rapidly attack and disintegrate concrete.

ASTM C 672 Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals is recommended for the assessment of concrete pavers exposed to freeze-thaw cycles or deicing agents. This standard assesses the weight loss of pavers after the paver has been subjected to 50 freeze-thaw cycles while submerged in a 3 percent salt (sodium chloride) solution. As this test method may be more severe and expose concrete pavers to higher stresses and damage than that of deicers, an added measure of safety and durability from deteriorating concrete is provided.

3.2. Skid Resistance

Skid resistance is measured in terms of the coefficient of friction developed between a braking tire and the pavement surface. Friction testing of pavements is commonly carried out at airports. Pavers at Dallas/Ft. Worth International Airport were tested with skid resistance testing equipment and the results of the skid testing indicated that the skid resistance was more than acceptable. Low and high-speed (up to 70 mph (110 kph)) tests were also conducted in 1992 by NASA at the Langley Research Center in Hampton, Virginia. Results have shown superior skid resistance over portland cement concrete pavement. Further, skid resistance studies on street pavements have shown pavers to have resistance equal to or better than asphalt surfaces.

3.3. Smoothness

Smoothness is most easily defined as the subjective measurement of the comfort (or discomfort) experienced while traveling over a paved surface. Smoothness can be measured mechanically as well, with profiling equipment such as the California Profilograph or the Face Rolling Dipstick for high-speed pavements (in excess of 30 mph (50 kph)). Commonly, pavements tend to be rehabilitated when user complaints about roughness begin to rise.

The smoothness of interlocking paver pavements can be measured easily, depending on the ultimate use of the pavement. Low speed or architectural pavements can be easily spot checked using straightedges of varying lengths. Commonly, a variation of not more than 3/8 in. under a 10 ft straightedge (10 mm under a 3-m straightedge) is required. As speed increases, the tolerance is usually less (1/4 in. under a 10 ft straightedge (6 mm under a 3 m straightedge) for 30 mph (50 kph) plus pavements is suggested).

Roughness may be built in, as a result of construction defects, or added, as a result of an inadequate design (traffic loads heavier than anticipated) or poorly executed repairs to utilities. With careful attention to details, interlocking paver pavements can be constructed to provide a comfortable ride for many years.

3.4. Pavement Markings

Concrete pavers can be integrally colored and used for pavement markings for lanes, parking areas, crosswalks, etc. Entire areas can be colored to compliment the architecture of the surrounding landscape. The units can also be painted with lines and numbers common to normal pavement construction.

3.5. Traffic Calming

Contemporary residential developments include curving streets with variable widths to restrict vehicle speed, maximize land use and to add visual appeal. Interlocking paver pavements are particularly conclusive to this use. The construction process allows them to fit varying geometry. In traffic management schemes to control flow in established areas, pavers offer a visual contrast to assist in defining the character of the streets and pavement usage. Permanent road markings and colors can be incorporated into the pavement at the time of construction.

4. INSTALLATION

4.1. Before You Dig....

Check with the local utility companies to ensure that digging does not interfere with or damage underground piping or wires. Many utilities have one telephone number to call (One Call Centers) at least two weeks before excavation to have utilities located and checked. If heavy equipment or boom trucks are to be used, check overhead clearances so that equipment does not interfere with wires. Ensure that the site is accessible to vehicles and equipment in order to prevent delays.

Any areas which require removal of material should be staked out, with stakes placed such that they will not be removed during grading. Grade lines can be marked on the stakes and string lines pulled to provide the required grade. Check grade stakes periodically to ensure that they have not been disturbed.

4.2. Subgrade Condition, Compaction and Proofrolling

As with most pavement installations, the key to adequate performance is uniformity of the subgrade. Normally, some material will require excavation for placement of base material. The subgrade soil will, in most cases, have been analyzed by a soils engineer. While this is not required, it is strongly recommended in the case of vehicular pavements.

When conditions are favorable for frost action (soil having excessive quantities of fine (silt-sized) particles, the presence of water and freezing temperatures), care must be taken with the construction of the pavement system. In some cases where the depth of frost is less than the thickness of the pavement structure, no action is required. Where the depth of frost is greater than the pavement structure, it may not be economical to remove all the frost-susceptible subgrade material. If possible, elimination of the water in the subgrade with adequate drainage is usually the most effective measure against frost heave. Often the best defense is to provide uniformity in the subgrade soils through grading, blending and compaction.

In the case of very poor subgrades, these soils can be modified or stabilized in order to provide a working platform for the construction of the remainder of the pavement system. Soil modification usually takes the form of the addition of small amounts of lime or Portland cement (proprietary materials also may be used) to the soil in order to change the liquid limit and plastic limit of the soil. Soil stabilization usually consists of the addition of greater quantities of lime, Portland cement or fly ash, kiln dust or combinations of these materials in order to make the soil substantially stronger.

Following excavation and stabilization if necessary, the subgrade must be graded, and recompacted as necessary to provide a uniform foundation for the pavement. Where utilities have been constructed, the material removed should be reused in the backfilling operation whenever possible, and replaced at the same moisture/density relationship.

Compaction of the subgrade must be carried out using the appropriate equipment. Granular materials such as sands and gravel respond better to smooth drum rollers or vibratory plate compactors. Fine-grained soils such as silts and clays are more easily compacted using sheepsfoot rollers. In either case, the compaction shall be in layers not exceeding the capacity of the equipment, and parallel to the surface of the pavement (not on extreme slopes).

Where pavements are to be trafficked, it is recommended that the subgrade be proofrolled. Depending on the ultimate use of the pavement, a loaded vehicle such as a gravel truck can be run over the subgrade, and any soft or excessively yielding areas identified, removed and replaced.

4.3. Geotextile Application

Geotextiles are primarily used to separate fine-grained subgrades from granular bases. This action prevents contamination of the base material with the existing soil. The use of a geotextile does not reduce the quantity of granular base required. Geotextiles are not required on every project, and the use of a geotextile shall be determined by a qualified civil engineer.

Prevention of bedding sand migration along structures is one of the most important functions of a geotextile. The loss of sand along edge restraints results in settlement of the pavers. The sand can be lost through cracks and joints in the restraints, or into the base and subgrade. This is easily alleviated by placing a 12 in. (300 mm) wide strip of filter fabric along the base and up the side of the restraint.

The type of geotextile, if any, to be used is dependent on the application. It is recommended that the manufacturer be consulted for information on the type of geotextile that may be required. In general, the finer the subgrade soil, the more likely that a geotextile will be required. The installation of a geotextile shall follow the recommendations of the manufacturer.

4.4. Base Construction

Proper consideration during the design of the base course is often the most effective way to ensure good paver performance.

4.4.1. Soil/Aggregate Bases

Granular bases provide most of the support to the loads imposed on the pavement system. Either the base or subbase material used can be natural gravel or any material specified for use in typical flexible pavement design. Typical materials fall into the gradation envelopes provided for conventional granular or class A or B materials. These materials are typically well graded with sufficient coarse, angular material to provide load support, and are easily compacted and graded.

The layer(s) of granular material over the subgrade are typically composed of lower quality (and less expensive) granular subbase, with the upper 6 in. (150 mm) minimum thickness of granular material usually specified to be a higher quality base material. The thickness of base and subbase are dependent on the ultimate use of the paver system.

Granular layers shall be placed in uniform layers not exceeding the capacity of the compaction equipment to ensure uniform and adequate compaction. In general, these layers shall never exceed 150 mm (6 in.) in thickness. Water shall be added as necessary to ensure that compaction is easily achieved. The final grade shall allow water to run off, and the surface should be as smooth as necessary to allow the placement of a uniform bedding sand layer. Any corrections in the base layers shall be made prior to the placement of the bedding sand.

After setting the final grades, and inspection of the base, bedding sand may be placed. The sand shall be spread loosely, and screeded to a uniform depth between 25 to 40 mm (1 to 1.5 in.) thick. To check the required thickness, place a paver on top of approximately 30 mm (1.25 in.) of bedding sand, and tap the paver solidly with a rubber mallet. After the paver has been compacted into the sand, determine the difference in height from initial placement to compaction.

If possible, the starting point should be in a corner at the end of one of the longest sides of the pavement, and proceeding in the direction of travel of any vehicles. The grades are set with the use of string lines and grade stakes. String lines should be set to the top of the finished grade, ensuring that a minimum 2 percent slope is maintained. Grades shall be set with the use of a line level or survey transit.

Screed rails shall be set on the base material just below the string line, with the rail parallel to the string. The top of the screed rail represents the finished grade of the bedding layer. With a paver resting on the screed rail, adjust the rail height to compensate for compaction. Set the screed rails on the well-compacted base such that they are supported along their entire length. Set screed rails parallel to each other and approximately 3 m (10 feet) apart, using a level to ensure that the rails are set at the same grade.

Place the bedding sand uniformly between the rails. Starting at one end of the rails, screed using a stiff piece of lumber (2x4) or aluminum screed across the rails and pull the material along the length of the rails. The resulting layer shall be uniformly smooth and level. Fill any voids and remove any irregularities at this time and rescreed if necessary. Remove excess bedding material along edges, buildings and edge restraints. Ensure that the bedding sand is not disturbed by traffic, including pedestrians.

4.4.2. Stabilized Bases

In order to support high loads without constructing very thick granular bases (remembering that the pavers generally act as a wearing surface, and shall not be considered to compensate for poor or non-uniform bases or subgrades), it is sometimes economically viable to stabilize the base or subbase material. This is commonly accomplished by adding a small amount of Portland cement (in the range of 4 to 6 percent) to a well-graded granular base material, and compacting the material at its optimum moisture content.

4.5. Manual Installation of Pavers

After completion of the inspection and acceptance of the base, paver placement can begin. Efficient placement of the pavers requires planning of the direction of paving, setting of string lines and location of materials.

Manual installation is labor intensive; therefore, the handling of units should be kept to a minimum. Hand carts or paver carts can speed up the hand placement of pavers. These carts can deliver substantial numbers of pavers to the installation area, and reduce handling. Avoid trafficking the prepared base if possible. Cubes of pavers shall be located around the jobsite to not interfere with paver placement or other construction activities.

The laying pattern and shape of the paver is critical in the performance of the pavement, especially if traffic is a consideration. The most effective shape and pattern is the dentate paver, such as Anchorlock, Ecoloc or Optiloc, placed in a herringbone pattern. If pedestrian traffic is the loading requirement, any shape paver is suitable.

Paving should always start at adjoining hard surfaces or buildings, and continue out and away from these surfaces, in one direction. Do not depend on the straightness of adjacent surfaces, and use a string line to determine the straightness of the edge. Keep small trim pieces to a minimum.

Be sure to check string lines and paver installation frequently. This will allow the detection and early correction of any drift and the avoidance of major corrections. Start with a single row of pavers under the string line. This ensures that the first row is straight and will provide a straight edge from which to work. When placing the pavers, ensure that 1/8 in. (3 mm) space is maintained between them. Most pavers manufactured today have built-in spacers to provide for this. Pavers without spacers shall be laid hand tight and not kicked into position. Pavers placed too close together may chip and break under loading.

4.6. Mechanical Installation of Pavers

In order to reduce the labour intensity of hand placing pavers, and to increase the production rate, mechanical laying machines have been developed. They are generally equipped with a clamping system that can lift an entire layer of pavers from a pallet or cube and place them accurately on the bedding sand. This results in over a square yard of pavers being placed at one time.

The use of mechanical installation equipment requires certain considerations. The manufacturer must have molds that produce the desired shape and pattern; the blended product must be manufactured uniformly; and the pavers must be of the highest quality.

A properly planned mechanical placement with a crew of four men can result in the placement of up 600 to 900 square meters (6000 to 10000 square feet) of pavers in a working day. The use of mechanical equipment should be considered on any project which is appropriate.

4.7. Cutting Pavers for Infill

Begin cutting infill pavers as soon as the installation is far enough ahead to allow room for cutting, thereby reducing the potential for lateral creep. Small pieces (less than 1/3 of a paver) shall be avoided as much as possible.

There are two types of cutting tools, the guillotine type cutter and the diamond blade power saw. The diamond saw allows completion of sharper, more accurate cuts. Pavers shall be cut to a size that will allow ample spacing for joint sand, and not to fit tight.

4.8. Applying Jointing Sand

The jointing sand is broadcast uniformly over the entire paving stone surface. This sand is then swept into the paver joints. The joints shall be filled with the sand. After filling the joints, the pavers are compacted using a plate compactor of sufficient size. This action will force the jointing sand into the joints and interlock the pavers. After compaction, the

entire area shall be swept again to ensure that the joints are filled with sand. In all cases, a second pass with the compactor is required to assist in the penetration of joint sand well into the joints.

4.9. Compaction of Pavers

70 mm (2 3/4 in.) and 80 mm (3 1/8 in.) thick paver units for heavy vehicular pavements are compacted with a minimum 22 kN (5000 lb) force plate compactor to compact pavers into the bedding sand. Lighter use pavements use typically 60 mm (2 3/8 in.) pavers, which are compacted in place with a 13 kN (3000 lb) force plate compactor. Jointing sand is swept into the paver joints and the pavers are re-compacted. This procedure is repeated until the joints are filled with sand. Twice is usually sufficient. The surface of heavily trafficked pavements is final rolled with 70 - 90 kN (16000 to 21000 lb) pneumatic rollers.

4.10. Sealing

Some amount of maintenance and protection is usually required for any pavement to maintain their appearance. Interlocking concrete pavers can be stained by many substances, most of which can be easily removed with household cleaners, while others may require industrial chemicals. It is recommended that a qualified contractor is consulted prior to using these chemicals. Please consult with your UNILOCK® dealer before using any chemicals on the pavers.

A transparent coating can be applied to pavers to preserve and protect their original beauty. The coating may act as a sealer, preventing contaminants from penetrating the surface of the units. Some sealers enhance the color of the pavers by giving them a wet or glossy appearance without making them slippery.

Applying a sealer will not necessarily strengthen or extend the life of a paver, as the pavers are manufactured to withstand environmental conditions without this application. The coatings will wear over time, and reapplication is usually necessary after two or three years. The life-cycle cost of a paver pavement is not enhanced by the use of a sealer in most applications, as the use is generally an aesthetic issue.

4.11. Final Inspection

The overall appearance of the installation is critical. Prior to the final inspection, the entire area shall be swept clear of the jointing sand, and any debris removed. Ensure that the paver joints are completely filled with the jointing sand; that the pavers are true to levels and grades as shown on the drawings; that positive drainage to the curbs and outlets is provided; and that all damaged pavers have been marked and replaced.

5. GENERAL MAINTENANCE AND REINSTATEMENT

Properly installed paver pavements will provide years of relatively low maintenance service. However, all pavements should be surveyed regularly in order to ensure that defects are corrected early in the pavement service life. It is a well-known fact that pavements last longer and are more economically maintained if maintenance is carried out when defects are relatively minor.

In order to determine what maintenance is required and what will be most effective, a visual distress survey of the pavement is required. The following is a description of

paver distresses, and methods of rating them for inclusion in a pavement maintenance program.

5.1. Pavement Distress Survey and Maintenance Procedures

Surface distress types shall be identified within unique randomly selected sample areas. Each sample shall be $500 \text{ m}^2 + 100 \text{ m}^2$ ($5000 \pm 1000 \text{ ft}^2$). The total selected sample area shall be at least 50 percent of the total area (it may be 100 percent of the total area if time permits).

5.1.1. Type of Distress: Loss of Sand in Joints

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

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

Severity levels:

Low: 0 mm to 6 mm (0 to 1/4 in.) loss.

Moderate: 6 mm to 19 mm (1/4 to 3/4 in.) loss.

Severe: over 19 mm (3/4 in.) loss.

Remedy: Reapply sand to joints if units have consistent joint widths.

5.1.2. Name of Distress: Inconsistent Joint Widths

Description: Joint widths are usually no more than 3 to 4 mm (1/8 in.), or specified in the original construction document. Actual joint widths shall be as close to those nominally specified.

Measurement: Visually inspect the area for irregular joint widths. Identify an area that exhibits this distress. Insert calipers into the joint below the chamfer at the middle of the length of the unit and read measurement. Measure the number exceeding tolerances in a 3 meter (10 foot) line within the area under inspection. Joint widths that are too narrow or too wide can be precursors to edge chipping or interlock damage.

Severity levels:

Low: Only a few joints out of dimensional tolerances, movement of only scattered units.

Moderate: Joint widths are out of tolerance, concentrated in one (1) sample unit.

Severe: Joint widths are out of tolerance in several sample units.

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

5.1.3. Name of Distress: Corner or Edge Chipping

Description: A corner or edge chip intersects the joint at an angle. It does not extend vertically through the paving unit. It can be caused by loss of sand, loads and/or settlement which cause the top edges of adjacent units to creep together and break.

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

Severity levels:

Low: Chip has little or no loose particles. Width of chipping is less than 3 mm (1/8 in.) wide.

Moderate: Moderately chipped with some loose, in-place particles. Chipping is 3 mm to 25 mm (1/8 to 1 in.) wide.

Severe: Chip is greater than 25 mm (1 in.) wide with loose, in-place, or missing particles. Tire damage (or FOD for airports) is a risk.

Remedy: For Moderate and Severe severity levels, remove damage blocks and replace.

5.1.4. Name of Distress: Cracked Pavers

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

Measurement: Identify cracked pavers at each severity level.

Severity Level:

Low Units have cracks that are not chipped.

Moderate Units have cracks that are lightly chipped with loose particles.

Severe Units have cracks that are severely chipped with loose or missing particles. (FOD is a high risk for airports).

Remedy: For Moderate and Severe severity, remove cracked pavers, replace, and recompact.

5.1.5. Name of Distress: Disintegration

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

water, the action of freeze-thaw, and/or unsuitable aggregates. Note that individual pavers within a bundle may be defective while the rest are within specification. This may be a normal part of the manufacturing process, and not cause for rejection of the entire bundle.

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

Severity levels:

Low: Small cracks in surface of unit. No loose material.

Moderate: Cracked surface and slight amount of loose material forming on top of units.

Severe: Most or entire surface of units are loose or missing. Rough surface is exposed.

Remedy: Moderate and Severe severity, replace paver and recompact.

5.1.6. Name of Distress: Depressions/distortions

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

Measurement: Depressions are measured in surface area. The maximum depth determines the level of severity. Place a straightedge across the depressed area and measure the maximum depth. Depressions must be measured by either visual estimation or by direct measurement when filled with water.

Severity levels:

Low: Depression can be observed only by stained areas or brief ponding after a rainstorm. Depression ranges from 13 mm to 25 mm (1/2 to 1 in.).

Moderate: Depression is visible without ponding. Depression ranges from 25 mm to 50 mm (1 to 2 in.).

Severe: Depression can be readily observed and severely effects riding quality. Depression is greater than 50 mm (2 in.).

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

5.1.7. Name of Distress: Settlement Or Faulting

Description: This is defined as a clear difference in elevation between areas of pavers caused by movement of underlying layers or differential consolidation of the sand or base.

Measurement: The surface area of the affected pavement is recorded in square meters and differentiated by severity level.

Severity levels:

Low: Roads and Streets: less than 6 mm (1/4 in.); Parking Areas: 3 mm to 13 mm (1/8 to 1/2 in.) difference in elevation.

Moderate: Roads and Streets: 6 mm to 13 mm (1/4 to 1/2 in.); Parking Areas: 13 mm to 25 mm (1/2 to 1 in.).

Severe: Roads and Streets: greater than 13 mm (1/2 in.); Parking Areas: greater than 25 mm (1 in.).

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

5.1.8. Name of Distress: Polished Aggregates

Description: Some aggregates polish under traffic or polish naturally from weather.

Measurement: Friction testing.

Severity level: Use skid resistance standards.

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

5.1.9. Name of Distress: Pumping and Water Bleeding

Description: Pumping is the ejection of material by water through joints caused by deflection of the units under passing loads. Sand slurry is ejected through the joint resulting in surface staining. Material on the pavement close to joints is evidence of pumping. Pumping indicates poor drainage usually accompanied by base or soil deformation.

Measurement: Identify area that is pumping.

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

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

5.1.10. Name of Distress: Rutting

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

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

Severity level:

Low: 6 mm to 13 mm (1/4 to 1/2 in.).

Moderate: 13 mm to 25 mm (1/2 to 1 in.).

Severe: greater than 25 mm (1 in.).

Remedy: For Moderate and Severe severity, remove units and sand, repair base, install pavement materials to desired elevation. Reinststate sand, pavers and recompact with sand. Full depth repair of base and subbase layers may also be required to provide adequate structural support.

5.1.11. Name of Distress: Horizontal Creeping

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

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

Severity levels:

Low: 6 mm (1/4 in.) or less deviation from reference line.

Moderate: 6 mm to 13 mm (1/4 to 1/2 in.) deviation from reference line.

Severe: greater than 13 mm (1/2 in.) deviation from reference line.

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

5.1.12. Name of Distress: Swell

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

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

Severity levels:

Severe: less than 19 mm (3/4 in.) height differential. Swell is barely visible.

Remedy: Remove pavers, correct base and reinstall units.

5.2. Paver Removal

When a utility cut or opening for base repair must be made in an interlocking paver pavement, the system must be reinstalled to the same level of quality as was originally designed. This is true of all pavements, of course. However, cuts in paver pavements can be seamless and unnoticeable.

Almost all of the pavers to be removed can be totally recycled. The first paver or two may have to be broken out, especially if the interlock is competent. After the interlock has been broken in a local area, the pavers will come out fairly easily, especially if they are pried from underneath.

The pavers shall be removed to a point at least 1 meter (3 feet) from the edge of the excavation, in order that the base and subbase can be easily compacted, and the bedding sand can be reinstalled.

The pavers should be stacked near the opening of the cut after being cleaned, for reinstallation.

5.3. Paver Cleaning

Pavers can be easily cleaned after removal with the use of portable power washers. Stains can be removed with commercial detergents. Harsh chemicals shall be avoided, as they may damage the pavers. New pavers used in reinstatement may be somewhat brighter than the surrounding pavers, which can be brightened with a sealer, or the new pavers can be allowed to fade with use. Contact UNILOCK (1-800-UNILOCK – www.unilock.com) for a list of safe cleaning agents for pavers.

5.4. Subgrade Repair

After careful removal of the pavement, subgrade repair can begin. It is important to remember that the uniformity of the subgrade is one of the most important characteristics of a pavement, and a key to the success of the pavement.

If a cut has been made, the best material to place back into the cut is the original soil. The soil shall be replaced at the same moisture/density relationship as the surrounding soil. If the soil is contaminated with water or fines, or is frost susceptible, it must be replaced. The replacement subgrade soil must be as close as possible physically to the original surrounding subgrade. Never replace fine-grained soil with granular material, especially in areas that are subject to frost heaving. If this is not possible, the new material must be gradually tapered into the original subgrade, in a transition section. Depending on the depth of the excavation, the transition section can be long, and sufficient base and pavers must be removed to provide adequate space for reinstatement.

Compaction of the subgrade shall be at the optimum moisture density relationship, and parallel to the surface. Layers thicknesses shall be no more than 150 mm (6 in.). Appropriate compaction equipment shall be used for the type of soil placed.

5.5. Base Repair

Aggregate base and subbase material may require repair due to loss by migration with water, or contamination of fine-grained subgrade material into the base. If water is causing migration or contamination, the drainage must be improved.

After paver removal to a point at least 1 meter (3 feet) beyond the edge of the repair area, the base shall be excavated entirely. After repairs have been made to drainage, geotextiles repaired or replaced, the base can be reinstated. The material used should be as close as possible to the physical nature of the surrounding base/subbase.

Compaction of the base/subbase shall be at the optimum moisture density relationship, and parallel to the surface. Layers thicknesses shall be no more than 150 mm (6 in.). Appropriate compaction equipment shall be used for the type of granular material placed.

5.6. Unshrinkable Fill

Unshrinkable fill, controlled low strength material, flowable fill, etc., is a mixture of aggregates, cement and water, often containing fly ash and admixtures. It is used as a backfill material especially in hard to get to areas, around utilities, etc.

The mix design usually has a maximum cementitious content, in order to limit the strength of the material to a point where it can be excavated with hand tools if necessary in the future. It also has sufficient water to make it flow, and fill odd-shaped excavations. Unshrinkable fill is mixed and delivered in ready-mix or transit-mix concrete trucks. It should not be considered concrete, although the standard concrete tests can be used to evaluate it.

After placement in the excavation, no consolidation or compaction is required. The unshrinkable fill is self-leveling. It dehydrates and consolidates rapidly, allowing traffic after one day.

When used under pavers, it must be recognized that the material is not frost-susceptible, and if the surrounding soil is frost-susceptible, there may be differential movement in the soil, causing differential heaving or settling of the paver surface.

The unshrinkable fill shall be placed up to the level of the base/subbase layers, and these layers replaced as described above. After compaction, the bedding sand and pavers can be reinstalled.

6. WINTER MAINTENANCE

Winter is no barrier to the use of interlocking concrete paving stones. The same snow and ice removal techniques are used for pavers as they are for poured concrete and asphalt.

6.1. Snow and Ice Removal

Scrapers and blades used on interlocking concrete pavers should be equipped with either shoes or high-density plastic blades in order to reduce the chance of damaging joints in the pavement. Scarification of the surface in order to remove ice may affect the aesthetics of the pavers, but will not cause any structural damage.

6.2. De-icing Chemicals

The most common deicing chemical used is salt, either in the form of sodium chloride or calcium chloride. In the absence of freezing, salts have little or no effect on concrete. The use of deicers containing ammonium nitrate and ammonium sulfate shall be strictly avoided as they rapidly attack and disintegrate concrete.

De-icing salts should not be applied sparingly out of fear of damaging the concrete. If only a small amount of salt is applied, this will tend to initiate a number of freeze-thaw cycles, rather than just the one if an adequate amount is used.

7. DRAINAGE

As with all other pavements, the most important factor to consider in the design and construction of interlocking paver pavements is the drainage of the system. Water can infiltrate the base/subbase and substantially weaken these layers, resulting in pavement damage.

7.1. Subsurface Drainage

Water can enter a pavement from two basic directions. It can percolate up from the subgrade into the granular layers, or it can infiltrate through the surface through unfilled joints and along edge restraint. Subsurface water is best dealt with through the placement of subdrains at regular intervals, and along the edges of the pavement. The subdrains shall be designed and constructed to be at low points in the pavement structure, and the subgrade shall be sloped sufficiently to allow the water that does infiltrate the pavement to flow to the subdrains. Subdrains shall be connected to each other and to catch basins or into ditches.

7.2. Surface Drainage

The surface of the pavement shall be designed with sufficient cross slope (approximately 2 percent or more) in order for surface water to drain to the edges of the pavement, and on to catch basins or ditches. Depressions which are allowed to fill with water may result in joint sand being washed from the joints under traffic. Once this occurs, the surface water can easily drain down into the base and weaken the pavement.

8. STRUCTURAL DESIGN

Interlocking concrete paver pavements are generally considered to be flexible pavements, in that they are somewhat dependent on an aggregate base and uniform subgrade to support most of the imposed loads. Like flexible pavements, they can accommodate minor settlements and occasional overloads. Like concrete pavements, the concrete pavers are resistant to the effects of de-icing salts, freezing and thawing, and have high abrasion and skid resistance, and are unharmed by petroleum products. Unlike both asphalt and poured in place concrete, paver pavements are ready for use immediately after construction. If necessary, pavers can be almost completely reused, not just recycled.

8.1. Basis for Structural Design

A paver pavement generally consists of the pavers and jointing and bedding sand, considered the riding surface; an aggregate base, usually composed of granular base material; and may have granular, cement-treated granular, asphalt or concrete base. Residential and architectural pavements may not require subbases, depending on the soils and the imposed loads.

The paver and sand surface layer depends on interlock to transfer the loads to the granular layer(s). There are three types of interlock to be considered. Horizontal interlock is achieved by the use of laying patterns that disperse or transfer the forces of braking, turning and accelerating vehicles. Herringbone patterns are the most effective pattern for providing horizontal interlock. Vertical interlock is provided by the shear transfer of loads to surrounding pavers through the joint sand in the joints. Rotational interlock is maintained by providing pavers of an adequate thickness for the application, by maintaining a proper joint width, and by providing edge restraint.

The loads transferred through the pavers to the granular layers are further dispersed by these layers, until the loads that reach the subgrade are so diminished that the subgrade does not yield under the loads. This requires an adequate thickness and quality of granular material. Granular base materials are recommended for the upper layers in contact with the bedding sand. The gradation of these materials provides good load carrying capacity, while containing sufficient smaller particle sizes to ensure that adequate compaction is achieved, and that the bedding sand is not lost into the granular matrix. Clear stone shall not be used directly under a paver surface, nor shall crusher screenings.

In cases where the loads are substantial, the provision of an adequate thickness of granular material may require deep excavations. It may be more economical to use treated subbases under the granular base in order to increase the strength of the subbase, and reduce the thickness. Cement treated granular subbases and concrete and asphalt subbases can be used. Pavers can be used to overlay or inlay asphalt pavements, and to overlay concrete pavements.

8.2. Design Factors

Four factors should be considered in the design of a paver pavement. The environment, traffic, strength of the existing subgrade soil and the quality of the base and subbase materials all will affect the final pavement design thickness. As the complexity of a project increases, the more detailed the information on each factor should be.

8.2.1. Environment

As with other pavement types, paver pavements are affected by temperature and moisture. Water in the granular base/subbase reduces the load carrying capacity. Moisture in the subgrade can cause swell or heave, especially in freezing temperatures. Temperature can reduce the strength of asphalt stabilized layers.

Frost heaves can be dealt with in a number of ways. If little or no water is available, no frost heave can occur. Edge drains, subdrains and ditches can all combine to reduce heave. Frost susceptible materials can be modified with lime or Portland cement to reduce frost heave potential. Frost susceptible materials can be replaced with granular

material. The economics of each solution should be investigated fully before proceeding.

In the design procedure, the soils and pavement materials are characterized according to their support and drainage quality. The subgrade soil strength is reduced according to its degree of frost susceptibility.

8.2.2. Traffic

The loads imposed by the traffic expected on a pavement are one of the most important and hardest to quantify factors in pavement design. The damage caused to a pavement by traffic depends on the mass of the vehicles and the number of expected load repetitions over the traffic analysis period. This period is usually 20, but more often lately, 30 years. In order to quantify this damage, the number of equivalent single axle loads (18 kip (80 kN) ESAL) must be calculated. Each of the distinct loads, from cars, light trucks, buses and tractor-semi-trailers can be converted to an ESAL loading through the use of load equivalency factors developed for pavement design use. In order to complete this calculation, detailed knowledge of the actual traffic and projected usage rate is needed. In the absence of this data, typical loadings for different classes of road can be used to determine the design ESAL.

8.2.3. Assessment of Existing Pavements for Overlay Design

Keeping in mind that uniformity in the supporting layers of a pavement is fundamental to the success of the pavement, the assessment of existing pavements for overlay design should be done carefully. Manuals and methods for this evaluation are available, with the manual produced by the Strategic Highway Research Program being recommended. This manual describes a method of visual assessment of poured concrete and asphalt pavements.

If there is some question of the support qualities of a pavement, some testing may be required. A fast method of determining pavement support quality and uniformity is the deflection test. Equipment such as the Falling Weight Deflectometer (FWD) can rapidly load test the pavement and calculate several load/deflection related statistics.

Assessment of existing pavements is a subjective activity, and it is recommended that this be completed by qualified pavement engineers.

8.3. Design Methods

8.3.1. Catalog

"Catalogs" for design of interlocking paver pavements are simply tables that allow the designer to choose a pavement structure to suit a particular application. While these catalogs simplify the design process, they are not a substitute for good design. They may be used for light duty applications without further analysis, but heavy-duty applications should follow a more rigorous design method. However, these catalogs or tables allow the designer to quickly determine a design for estimating purposes, and a starting point for optimization. The following table was developed in order to provide such estimations and starting points.

**TABLE 1
TYPICAL PAVEMENT STRUCTURE BY SUBGRADE SOIL TYPE**

Loading Conditions	Material	Subgrade Soil Type									
		Granular Suitable as Borrow		Silty Sand (Silt and Fine Sand less than 40%)		Silty Sand (Silt and Fine Sand 40 - 60%)		Silt (Silt and Fine Sand greater than 60%)		Clay	
		in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Pedestrian Use	Pavers	2 3/8 - 2 3/4	60 - 70	2 3/8 - 2 3/4	60 - 70	2 3/8 - 2 3/4	60 - 70	2 3/8 - 2 3/4	60 - 70	2 3/8 - 2 3/4	60 - 70
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6	150	6	150	6	150	6	150	6	150
	Subbase										
Light Duty (Driveways, Car Parking Areas)	Pavers	2 3/8 - 3 1/8	60 - 80	2 3/8 - 3 1/8	60 - 80	2 3/8 - 3 1/8	60 - 80	2 3/8 - 3 1/8	60 - 80	2 3/8 - 3 1/8	60 - 80
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6*	150	8	200	6	150	6	150	6	150
	Subbase					12	300	20	500	20	500
Minor Residential Roads	Pavers	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6*	150	9	215	6	150	6	150	6	150
	Subbase					15	375	24	600	24	600
Residential and Collector Streets (25 to 500 ESAL/day)	Pavers	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6*	150	6	150	6	150	6	150	6	150
	Subbase			11	275	17	425	26	660	26	660
Medium to Heavy Industrial Areas (500 to 1000 ESAL/day)	Pavers	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6*	150	6	150	6	150	6	150	6	150
	Subbase			12	300	18	450	29	720	29	720
Heavy Industrial Areas (1000 to 1500 ESAL/day)	Pavers	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80	3 1/8	80
	Bedding Sand	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30	1 1/4	30
	Base	6*	150	6	150	6	150	6	150	6	150
	Subbase			14	340	20	490	30	740	30	740

* Minimum recommended base course thickness.

NOTE: The pavement structure requirements for streets and heavy duty pavements should be reviewed by a qualified pavement engineer for specific loadings and equipment involved.

8.3.2. LOCKPAVE PRO™

LOCKPAVE PRO™ is a software paver pavement design aid published in the United States and Canada by F. von Langsdorff Licensing Limited, and available from UNILOCK. The program allows the designer the choice of either using the AASHTO based design methodology or a full mechanistic analysis. It was designed for use by engineers, architects and planners in analyzing alternative pavement designs using interlocking concrete pavers.

LOCKPAVE allows the designer to consider the subgrade soil, the pavement materials and their characteristics, traffic and environmental effects. The program will allow the design of overlay pavements of asphalt and concrete pavements. Multiple pavement surface, base and subbase material cases and what if scenarios can be run without

exiting the program. Several different material classification models such as Elastic Modulus, Marshall Stability, CBR, etc., can be specified.

The program also contains a paver and an installation specification for customizing or for immediate use by the designer. In brief, the program is simple to use, yet allows the designer to input experienced-based values, and compare alternatives easily.

9. PAVEMENT REHABILITATION DESIGN

Concrete pavers can be used for either structural (strengthening) or non-structural (functional) rehabilitation of existing pavements. As with new paver pavements, the pavers are modeled as a flexible (asphalt) material when performing structural overlay design calculations. Pavers are appropriate for overlaying both concrete and asphalt pavements. The sequence for design involves:

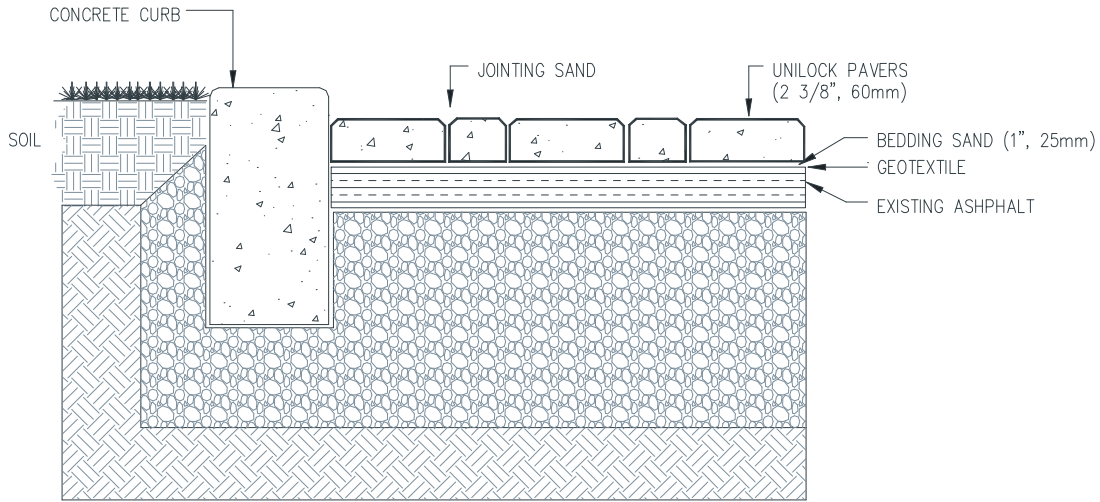
- Evaluation of the existing pavement conditions.
- Determination as to whether the overlay is to be structural or functional.
- Design of the overlay thickness for strengthening.
- Determination of the amount and type of required base pavement repairs prior to construction of the overlay.

9.1. Asphalt Pavement Overlays

If structural rehabilitation and strengthening are required, the designer should use the flexible overlay procedures described above. The inputs required are the traffic, the bearing capacity of the existing pavement and the environmental characteristics.

If the surface of the existing asphalt surface is significantly deteriorated, localized repairs such as crack sealing, patch and base repairs, etc., shall be completed. If the overlay requirement is 100 mm (4 in.) or less, and grades permit, the pavers and bedding sand may be placed directly on the asphalt surface. If the overlay thickness required is more than 100 mm (4 in.), the required strengthening can be made up with additional asphalt concrete as an overlay. The minimum practical thickness of the asphalt is 50 mm (2 in.). For pavers and sand placed in a cracked or broken asphalt, a geotextile filter fabric shall be placed over the asphalt to prevent loss of the bedding sand. If a thick overlay of 200 mm (8 in.) is required for strengthening, consideration shall be given to a sandwich overlay (a lift of granular followed by geotextile, bedding sand and pavers).

TYPICAL ASPHALT OVERLAY

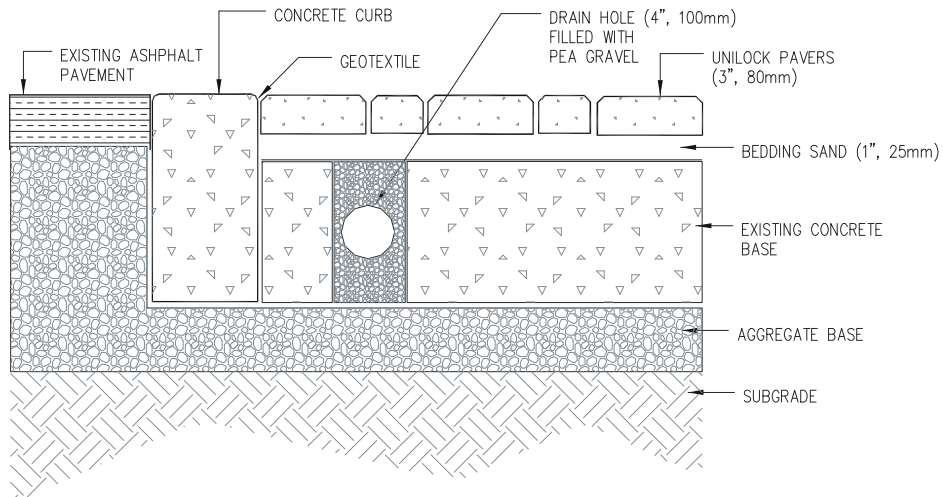


9.2. Concrete Pavement Overlays

Similar to the overlay of a flexible pavement, the required thickness for overlay can be determined using the LOCKPAVE PRO™ software or the AASHTO equations. As with flexible overlays, if the required thickness of overlay is greater than 100 mm (4 in.), the difference between the required thickness and the thickness of the paver/sand layer can be made up with an asphalt overlay.

- The design of a concrete pavement overlay using pavers may require some special treatments such as:
- Use of a geotextile filter fabric to prevent the loss of the bedding sand into the concrete cracks or joints.
- Possible jointing of the pavers over the underlying slab expansion joints (inserting a soldier course).
- Improvement of the joint load transfer of the concrete slabs before overlaying.
- Localized repairs of severely deteriorated slabs, etc.

TYPICAL CONCRETE OVERLAY



9.3. Non-Structural Overlays

In some cases a pavement may be structurally adequate for the forecast traffic, but its surface condition may have deteriorated to the point where safety or reliability may be compromised. In these instances, an overlay or inlay with pavers may be an appropriate rehabilitation option. Where grade considerations are not a factor, an overlay with pavers may be considered. However, where grade constraints make an overlay impractical, either surface reconstruction with pavers or an inlay (removal of sufficient surface thickness to allow for the paver/sand layer) may be considered depending on the thickness of the surface layer.

As with structural overlays, pavement repairs shall be completed and a geotextile filter fabric placed prior to constructing the paver/and layer.

10. Life-Cycle Cost Analysis

Selection of the most appropriate alternative for a particular pavement requires consideration of a number of factors that can significantly impact on the use, performance and costs of the pavement.

Although the use of premium materials such as concrete pavers may increase the initial capital cost of construction, the performance benefits over the life span of the pavement can result in significant savings over conventional pavement alternatives.

In addition to the increased service life which results from the use of pavers in pavement construction, the adoption of a systematic and timely maintenance and rehabilitation program will increase the performance of the pavement.

The pavement which is the least expensive for the owner is not the pavement which costs the least to construct, but the pavement which gives the best return for the amount spent on it over its service life. To evaluate essentially equivalent (from a structural viewpoint for pavements) alternatives using different materials, it is necessary to consider not only the initial cost of each alternative but also the total costs accumulated over its service life. The alternative having the lowest initial cost may not be the least expensive once factors such as maintenance, rehabilitation, inflation and interest (the value of money invested today for future use) are taken into account. The most effective method of measuring the cost-effectiveness of alternative designs is life-cycle cost analysis.

10.1. Present Worth Analysis

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

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

It is worth noting that even in times of very low and high interest rates, the inflation rate follows quite closely, with the result that the discount rate varies only slightly. Historically, the discount rate has generally averaged 3 to 4 percent over the last 30 years. The present worth method equates present and future expenditures for each alternative, and associated maintenance and rehabilitation costs over the life of the project. This concept, known as discounting, is used to permit comparison of alternatives that require expenditure over an extended period, and allows the designer to consider the dual effects of interest rates and inflation on project cost.

10.2. Analysis Period

The life-cycle analysis periods used for pavements are generally 20 to 30 years. This reflects the trend by some agencies towards longer-lasting pavements and the consideration of extended life-cycle analysis periods.

It is generally acknowledged that pavements designed for longer traffic or life-cycle analysis periods have lower life-cycle costs. The analysis period also represents the time that the design axle loads and traffic must be considered for design purposes.

10.3. Service Life of Pavement Types

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

10.4. Components Of Pavement Life-cycle Cost Analysis

Several major cost components influence the outcome of a life-cycle cost analysis. They include:

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

discomfort costs. These user costs are difficult to quantify and should be in terms of extra user costs over those usually anticipated.

The relative influence of the major cost components on life-cycle cost analysis for concrete pavers is shown in Table 2.

**TABLE 2
FACTORS AFFECTING LIFE-CYCLE COST ANALYSIS
FOR CONCRETE PAVERS**

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

10.4.1. Initial Costs

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

10.4.2. Maintenance Costs

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

10.4.3. Rehabilitation Costs

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

10.4.4. Residual and Salvage Values

In addition to the initial cost of construction, maintenance and rehabilitation costs over the life of the pavement, residual values and salvage values can be incorporated to

represent the remaining or unrealized value of the pavement structure and individual components/materials at the end of the analysis period. Salvage value is usually defined as the benefit attributed to being able to reuse a given material at the end of its service life; residual value is the unrealized value of the pavement and/or component at the end of the analysis period, and represents the service life remaining at the end of the analysis period. The residual and salvage values for concrete pavers may be more significant than traditional pavement materials, as they are almost completely reusable.

10.4.5. User Delay Costs

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

10.4.6. Value Engineering

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