ENGINEERING BULLETIN

Subgrades and Subbases for Concrete Pavements

AMERICAN CONCRETE PAVEMENT ASSOCIATION

EB204P

Subgrades and Subbases for Concrete Pavements

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ACPA is the premier national association representing concrete pavement contractors, cement companies, equipment and materials manufacturers and suppliers. We are organized to address common needs, solve other problems, and accomplish goals related to research, promotion, and advancing best practices for design and construction of concrete pavements.

Keywords: AASHTO, ASTM, asphalt-treated, cement-treated, cement-stabilized, chemical modification, concrete pavement, cross-hauling, cut-fill transition, daylighted, drainable subbase, econocrete, edge drainage, expansive soil, faulting, free-draining, frost heave, frost-susceptible soil, granular subbase, lean concrete, pavement structure, permeable subbase, pumping, reclaimed asphalt pavement (RAP), recycled concrete, separator, sieve analysis, soil, soil classification system, spring subgrade softening, stabilized subbase, subbase, subgrade, unstabilized subbase, volume stability.

Abstract: This engineering bulletin provides the necessary background information for the proper selection and application of subbases and the appropriate consideration of subgrade variables for concrete pavements used for streets, roads and highways. It emphasizes the major objective of obtaining long-lasting uniform support for a concrete pavement. Subgrade soil material classification and problems (expansion, heaving, etc.) are discussed in detail along with many various options for stabilized and unstabilized subbases, and the materials that they are composed of. Multiple reasons for avoiding the use of permeable subbases (a.k.a. drainable or open-graded subbases) also are presented.

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Executive Summary

Analysis of the Federal Highway Administration's (FHWA's) Long-Term Pavement Performance (LTPP) data reveals that a pavement's foundation (base or subbase and subgrade) is one of the most critical design factors in achieving excellent performance for any type of pavement.* For concrete pavements, the design and construction requirements of a roadbed or foundation structure may vary considerably, depending upon subgrade soil type, environmental conditions, and the amount of anticipated heavy traffic. In any case, the primary objective for building a roadbed or foundation for concrete pavement is to obtain a condition of uniform support for the pavement that will prevail throughout its service life.

Drainage considerations are also important in the proper design and construction of a roadbed or foundation for concrete pavement. It is important not to build a supporting layer system that holds water underneath the pavement slabs. This has been a common mistake in the design of concrete pavement structures, which has led to poor field performance of some concrete pavement sections. It is equally important not to over design the permeability of a subbase layer. Overzealous engineering of a permeable subbase will most likely lead to a foundation that does not provide the requisite stability for long-term pavement performance. Where stability has been sacrificed for drainage, concrete pavements have performed poorly and have experienced unacceptable numbers of faulted joints and cracked slabs within a relatively short period. **Free-draining and daylighted subbases are the reasonable alternatives to rapidly draining permeable subbases with an edge drainage system that often lack stability for long-term performance or cause other performance problems.**

In northern or cold climates, the influence of frost and freezing of the roadbed is an important consideration. Certain subgrade soils are particularly susceptible to frost action, which raises the foundation and concrete pavement layer(s) vertically during freezing periods (commonly referred to as heaving or frost heaving). Generally, frost heave is limited to areas of freezing climates with silty soils. If the heaving is uniform along a pavement section it is not detrimental, but if heaving is localized, it upsets the uniformity of support provided to the surface pavement. Removing or treating these materials will be necessary to ensure that the pavement performs as expected.

For nearly every pavement design there are many different subbases to choose from (i.e., unstabilized recycled concrete aggregate, cement-treated, lean

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* The use highly open-graded or permeable subbases for concrete pavement is not recommended. This conclusion was reached through experiences with poorly performing pavements built on permeable subbase layers. It is supported by a national performance evaluation study that concluded that these systems do not have a significant influence on pavement performance, positively or negatively (NCHRP 2002). However, the cost of these systems can be quite significant, sometimes as much as twenty-five percent of the section cost compared to a more conventional subbase (Cole and Hall 1996). For these reasons, and others described in this publication, the following categories of subbase layers are not recommended: cement-treated permeable subbase, asphalt-treated permeable subbase and unstabilized open-graded subbases with a permeability coefficient more than about 350 ft/day (107 m/day) in laboratory tests.

concrete, etc.), as well as the decision of a natural or a treated subgrade. In some cases, as for most clays and some silty soils, it may be most economical and advantageous to treat the subgrade soil and then to provide a unstabilized (granular) subbase as a construction platform. In the case of a road for a relatively low level of traffic it is likely that a natural subgrade may suffice, as long as it is evaluated to be acceptable as a roadbed. The optimal subbase and subgrade design or selection must balance both cost and performance considerations. The same combination of subbase and subgrade treatment used for heavily-trafficked highways is likely not necessary for a low-volume roadway, even in the same area and subject to the same climate.

Finally, it is likely that as this document is printed and distributed, some new and emerging technologies are advancing within the grading and paving industries. This guide captures the fundamental parameters, recommendations, and considerations for subgrades and subbases for concrete pavement. Emerging technologies, such as intelligent compaction and GPS-guided grading/placing equipment, are likely to become more commonplace in the future. These improvements to existing methods are not a replacement for the necessary consideration of the fundamentals. By the same token, we encourage agencies and contractors to advance their construction methods and improve the quality of their work using advanced technology.

Executive Overview

For quick reference, key concepts for each chapter are listed as follows and indexed to the tabs on the page edges of this publication.

Chapter 1. Introduction and Terminology – Page 1

Key Point		Page
●	Roadbed (subgrade and subbase) design is key to long-term performance and smoothness of concrete pavements.	1
●	The pavement structure of a concrete pavement typically consists of a concrete surface and subbase(s) placed upon a prepared subgrade (a “base” is part of an asphalt pavement structure, while a subbase is an optional element of a concrete pavement structure).	1

Chapter 2. Design Principles – Page 3

Key Point		Page
●	Every foundation for a concrete pavement structure should be free from abrupt changes in character of the materials (should be uniform), should resist erosion, and be engineered to control subgrade soil expansion and frost heave.	3
●	Above all other design concerns, uniformity is of utmost importance.	3
●	Because of the rigid nature of concrete pavements, loads are distributed over relatively large areas, greatly reducing stresses on the subgrade/subbase; thus, concrete pavements do not necessarily require exceptionally strong foundation support.	4
●	The pavement design engineer should consider all subbase types (stabilized or unstabilized) and available materials (recycled or virgin) for each pavement design; there is no standard recommended subbase for any concrete pavement. Subbase selection is the designer’s option, but should consider fundamentals and decision factors described in this guide.	4

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Chapter 2. Design Principles – Page 3 *(Continued)*

	Key Point	Page
●	Recommended minimum subbase thicknesses are 4 in. (100 mm) for unstabilized subbases, 4 in. (100 mm) for cement-stabilized subbases (i.e., cement-treated subbases and lean concrete subbases), and 2 in. (50 mm) for asphalt-stabilized subbases.	4
●	Concrete pavement design thickness is relatively insensitive to support stiffness (modulus of subgrade reaction), so it is improper engineering to make a subgrade/subbase stronger or thicker in an attempt to decrease concrete pavement thickness.	6
●	Free-draining subbases are preferred over permeable subbases.	9
●	Daylighted subbases are more economical and yield better long-term performance than edge drain piping.	11

Chapter 3. Subgrades – Page 13

	Key Point	Page
●	Soil classification systems such as the AASHTO and/or ASTM (Unified) Soil Classification Systems will help the pavement design engineer determine factors such as the California Bearing Ratio (CBR) or modulus of subgrade reaction (k-value), but the engineer must be mindful of the preferred soil classification method for each project because conversion between methods is not intuitive.	20
●	A minimum CBR of 6 in the top 24 in. (610 mm) of subgrade provides an adequate working platform for construction, while limiting subgrade rutting under construction traffic to ½ in. (13 mm) or less.	25
●	Typically, a specified percentage of compaction of 95 percent, according to AASHTO T99 will provide an adequate working platform for construction equipment and for excellent in-service performance of the subgrade portion of a concrete pavement structure.	25
●	Special attention should be given to expansive and frost-susceptible soils. Expansive soils can be mitigated by compacting the subgrade at the proper moisture content, selectively grading the subgrade material and/or chemically modifying the subgrade. Frost heave can be mitigated by controlling the grade and water table elevation, selectively grading and mixing the subgrade, removing silt pockets and refilling with select borrow materials. It also can be mitigated by covering the existing subgrade with a non-frost-susceptible cover and/or compacting the subgrade at the proper moisture content.	26

Chapter 4. Subbases – Page 41

Key Point	Page
● For pumping of a subbase to occur, several conditions must exist. They are: ■ the pavement must have undoweled joints or joints with poor load transfer, ■ water must be present, ■ the roadway must have fast moving, heavy loads to deflect the slabs (trucks, not automobiles), ■ and the subgrade must be a fine-grained material or the subbase must be an erodible material. Eliminating one or more of these casual factors should mitigate pumping.	41
● Pavements that are expected to carry 200 trucks or fewer per day (or less than 1,000,000 18-kip (80 kN) ESAL's over the course of the service life of the pavement) do not typically require a subbase to prevent pumping.	43
● Unstabilized subbases must have a maximum particle size of no more than ⅓ the subbase thickness, less than 15 percent passing the No. 200 (75 µm) sieve, an in-place density of 95 percent according to AASHTO T99, a Plasticity Index of 6 or less, a Liquid Limit of 25 or less, a L.A. abrasion resistance of 50% or less, and a target permeability of no more than 350 ft/day (107 m/day) in laboratory tests. Of these, limiting the percent of fines passing the No. 200 (75 µm) sieve is of utmost importance to creating a good unstabilized subbase.	45
● The higher degree of support offered by a stabilized subbase will not alter the required concrete pavement slab thickness appreciably, but it will add pumping resistance and increase the overall strength of the pavement structure, spreading loads over larger areas and reducing strains.	50
● There is typically no strength requirement for cement-treated subbases (CTB) because a CTB is best controlled using compaction and/or density requirements. However, when specified, a target compressive strength range of 300 to 800 psi (2.1 to 5.5 MPa) is typical to ensure long-term durability to repeated cycles of wetting and drying or freezing and thawing, while keeping the layer from getting too stiff.	53
● Material requirements oftentimes may be relaxed for cement-stabilized subbases (i.e., cement-treated subbases or lean concrete) when compared to unstabilized subbases. For example, granular material used in a cement-treated subbase may have up to 35 percent of particles passing the No. 200 (75 µm) sieve and a Plasticity Index of up to 10.	53

(Continued on next page)

Chapter 4. Subbases – Page 41 *(Continued)*

	Key Point	Page
●	Strength of a lean concrete subbase should be limited to 1,200 psi (8.3 MPa) or less to keep the subbase from getting too stiff, minimizing curling and warping stresses in pavement slabs. If this strength is exceeded, measures may need to be taken (i.e., scoring joints into the lean concrete subbase) to mitigate the potential problems.	56
●	Recycled concrete and other alternative subbase materials should be considered for inclusion in a subbase for their positive economic and environmental benefits, as well as resource conservation.	60
●	Permeable subbases (subbases with a permeability of 350 ft/day (107 m/day) or greater in laboratory tests) have had a problematic history in the field. The reasons include loss of support caused from aggregate breakdown, loss of support caused from infiltration of the subgrade into the subbase, early age cracking caused from penetration of concrete mortar into the subbase voids during paving, instability as a construction platform, cost effectiveness, and various other overall field performance problems. Thus, permeable subbases are no longer recommended for concrete pavement structures. Free-draining subbases (subbases with a permeability between 50 and 150 ft/day (15 and 46 m/day) in laboratory tests) and daylighted subbases are the reasonable alternative to rapidly draining permeable subbases.	63

Chapter 1.
Introduction and Terminology

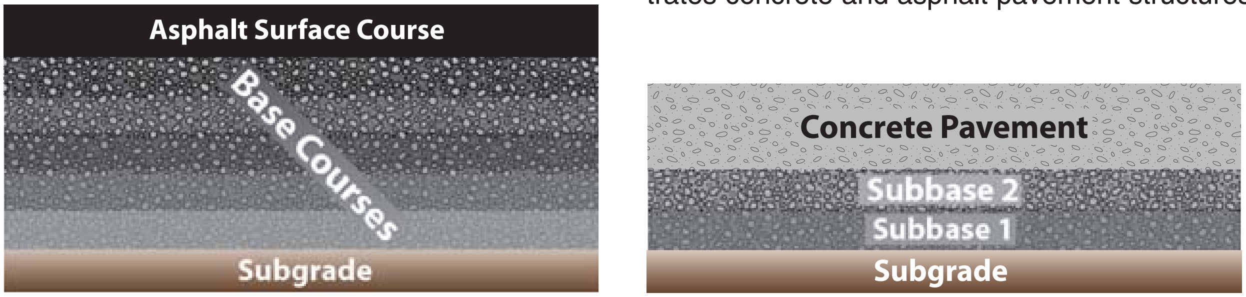
The design and construction of the roadbed for any pavement structure is key to its long-term performance and smoothness over time. A roadbed is characterized by the layer(s) that provide the foundation for the riding surface. For concrete pavement, the foundation is typically comprised of a subbase layer on top of the subgrade soil. A variety of engineered subbase materials and subgrade treatment methods exist for use with concrete pavement.

Careful attention to the design and construction of subgrades and subbases is essential to ensure the structural capacity, stability, uniformity, durability, and smoothness of any concrete pavement over the life of that pavement. Of utmost importance is the uniformity of the foundation. This bulletin publication discusses each essential factor and provides the necessary background information for the proper selection and application of subbases and the appropriate consideration of subgrade variables for concrete pavements used for streets, roads, and highways.

Because the terminology for engineered roadbeds is unique and sometimes unfamiliar to pavement design engineers, an extensive glossary of terms is included as an Appendix of this publication. (Refer to the tabs at the edge of this publication for quick reference.) Thus, this section is not intended to be a comprehensive glossary, but a means of distinguishing between foundation components for concrete and asphalt pavement structures. The key terms necessary for discerning between concrete and asphalt pavement structures are:

- *Pavement Structure* — The combination of asphalt/concrete surface course(s) and base/subbase course(s) placed on a prepared subgrade to support the traffic load.
- *Base* — A layer within an asphalt pavement structure; usually a granular or stabilized material, either previously placed and hardened or freshly placed, on which the pavement surface is placed in a later operation.
- *Base Course* — The layer(s) of hot mix asphalt immediately below the surface course, generally consisting of less asphalt and larger aggregates than the surface course. Also known as binder course (AI 2007).
- *Subbase* — The layer(s) of select or engineered material of planned thickness placed between the subgrade and a concrete pavement that serve one or more functions such as preventing pumping, distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction. Common subbase types include unstabilized (granular) subbase, cement-treated subbase, lean concrete (econocrete) subbase and apshalt-treated subbase.
- *Subgrade* — The natural ground, graded and compacted, on which a pavement structure is built.

In practice, subbase layers are commonly referred to as base courses. Strictly speaking, however, a base course is a layer of material beneath an asphalt surface; thus, base courses exist only under asphalt pavements and subbases exist only under concrete pavements. The pressures imposed on a base course underneath an asphalt pavement are dramatically different than those imposed on a subbase beneath a concrete pavement. Because of this difference, material quality requirements for a subbase may be relaxed in comparison to what is required for a base. The distinction in terminology (base versus subbase) recognizes these basic differences. This publication discusses concrete pavement subbases, and the reader is encouraged to adopt this term into their common or local terminology. Figure 1 illustrates concrete and asphalt pavement structures.



Asphalt Pavement Structure

Concrete Pavement Structure

Figure 1. Cross-sectional illustration of the relative difference in design terminology and layout between asphalt and concrete pavement structures.

Chapter 2.
Design Principles

Understanding the basic premise and principle of foundation design for concrete pavement requires a knowledge of how concrete slabs transfer loads from vehicles to the subgrade. Compared to asphalt pavements, concrete pavements spread a given load over a larger area of the roadbed or foundation which, in-turn, reduces the pressure on the support layer materials and subgrade. The importance is that the foundation strength is not as important to the performance of concrete as it is to asphalt pavement, even when considering pavements for heavy loads.

Although subbase and subgrade strength are important factors in pavement design, other foundation properties besides strength need to be considered in the design of a foundation for concrete pavement. Every foundation for use in a concrete pavement structure should provide the following characteristics:

- Uniformity; no abrupt changes in character of the materials (i.e., weak spots or stiff spots).
- Control of expansive subgrade materials to ensure uniform support through wet and dry seasons.
- Resistance to frost heave during winter and cold temperatures.
- Resistance to erosion by slabs that deflect under heavy loads.

Of these characteristics, uniform support is of utmost importance. Providing uniformity is also one of the largest challenges in the design and construction of any pavement structure. Because every foundation design starts with the in-situ natural soils, the challenge always begins with the subgrade. In practical terms, the subgrade must, at least, provide a stable working platform for constructing the subsequent layers of the pavement structure.

The potential for frost heaving and/or shrinkage and swelling of subgrade materials must be assessed by the engineer during the design phase. The methods available to address expansive subgrade materials are selective grading and/or chemical modification (commonly referred to as soil stabilization) of the in-situ soils. Both of these subgrade conditions (e.g. frost heave and shrink/swell) should be considered separately from providing pavement support, but are inherently part of the primary goal of providing a uniform foundation. In other words, even though a subgrade can be compacted and prepared to provide adequate support for construction activities and future traffic loading, it may be a poor foundation for a concrete pavement if the subgrade is prone to volume change from swelling, shrinking, or heaving. Therefore, the expansive potential of the subgrade must be evaluated and controlled.

Preparation of the subgrade includes:

- Compacting soils at moisture contents and densities that will ensure uniform and stable pavement support.
- Whenever possible, setting the profile gradeline at an elevation that will allow adequate depth in the side ditches to protect the pavement structure from the water table.

- Improving expansive or weak soils by treatment with portland cement, fly ash, cement kiln dust (CKD), lime, or alternatively, importing better soils.
- Cross-hauling and mixing of soils to achieve uniform conditions in areas where there are abrupt horizontal changes in soil types.
- Using selective grading in cut-and-fill areas to place the better soils closer to the top of the final subgrade elevation.
- Fine grading the top of the subgrade to meet specified grade tolerances in the specifications and for thickness control of the subbase and/or the concrete pavement.

Perfect subgrade materials—those that would economically meet all design criteria—are rarely encountered in nature. This is particularly true of materials that would be used in heavily trafficked pavement. For this reason, a subbase layer provides an added measure of assurance that both uniform support and a non-erodible layer are provided for the concrete pavement slabs. Subbases consist of engineered materials or materials that are produced and controlled to a specification. Most commonly used subbases fall into one of the following categories:

- Unstabilized (granular) subbases.
- Stabilized subbases, which include:
    - cement-stabilized subbases (cement-treated subbases or lean concrete subbases, both of which may include fly ash and/or slag) and
    - asphalt-treated subbases.

For light traffic pavements, such as residential streets, secondary roads, parking lots, and light-duty airports, a subbase may not be required if proper subgrade preparation techniques will minimize shrink, swell, and/or heave potential, provide an adequate construction platform and provide adequate pavement support.

When the use of a subbase is considered appropriate, the best results are obtained by:

- Selecting subbase materials and combinations of layers that adequately prevent pumping of subgrade soils for the life of the pavement.
- Specifying gradation controls that will ensure a reasonably constant subbase gradation for individual projects.
- Specifying a minimum density of 95 percent of AASHTO T99 (ASTM D698) for unstabilized subbases.
- Specifying stabilized subbase material requirements (cement-treated, lean concrete, or asphalt-treated) that consider the delicate balance between the requirement of uniform support and the risk of cracks associated with high strength subbases due to loading of unsupported edges (caused by curling and warping).
- Designing the width of the subbase to accommodate the paving equipment. The subbase should extend beyond the width of the pavement by at least 3 ft (1 m) on either side to provide a stable all weather working platform for the paving equipment or fixed side forms. This additional width of subbase is a critical feature to help ensure smoother pavements. Secondary benefits over the life of the pavement include improved load transfer at the edge of the concrete slab.
- Specifying a minimum subbase thickness of 4 in. (100 mm) for unstabilized (granular) subbases, 4 in. (100 mm) for cement-stabilized subbases and 2 in. (50 mm) for asphalt-treated subbases.

UNIFORM SUPPORT

Paving concrete typically has a 28-day flexural strength ranging from 550 to 750 psi (3.8 to 5.2 MPa), or greater, and a modulus of elasticity ranging from 4 to 6 million psi (28,000 to 41,000 MPa), helping provide a high degree of rigidity. This rigidity enables concrete pavements to distribute loads over large areas of the supporting layers, as shown in Figure 2. As a result, pressures on the underlying layer(s) are very low and deflections are relatively small. Concrete pavements, therefore, do not necessarily require exceptionally strong foundation support.

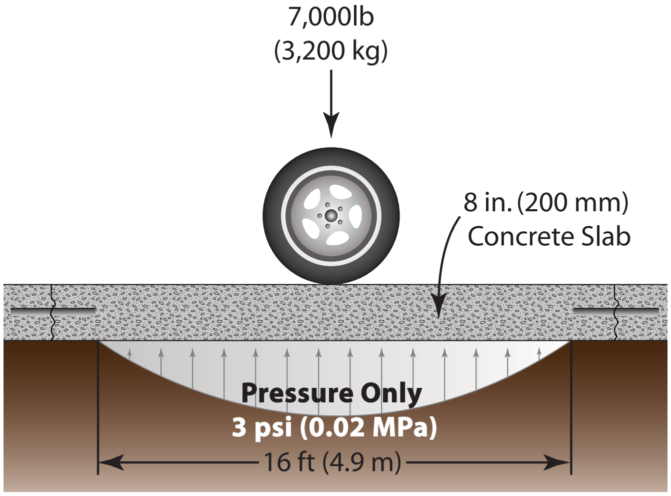
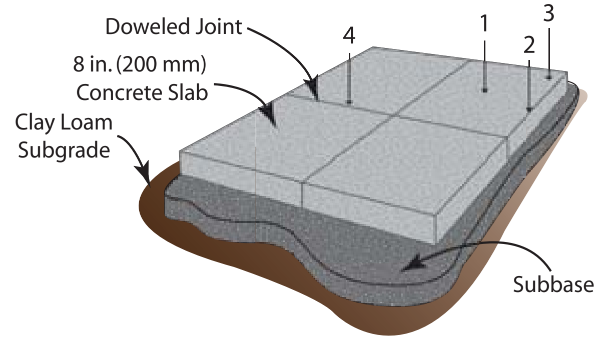


Figure 2. The rigidity of concrete helps a concrete pavement distribute wheel loads over large areas, keeping subbase/subgrade pressures low.

	Maximum Subgrade Pressure	
Loading Position	psi	MPa
1. Slab Interior	3	0.02
2. Outside Edge	6	0.04
3. Outside Corner	7	0.05
4. Transverse Joint Edge	4	0.03



A 12,000 lb (5,400 kg) load is placed on a 12 in. (380 mm) plate. This yields a pressure of 106 psi (0.73 MPa) on the pavement surface and the resultant subgrade pressures listed above.

Figure 3. Subgrade pressures for a 12,000 lb (5,400 kg) load applied at several positions on a slab.

Childs and Kapernick (1958) showed that heavier loads are distributed over large areas of the subgrade and, thus, do not cause high subgrade pressures. Figure 3 gives test conditions and subgrade pressures for a 12,000 lb (5,400 kg) load. The applied pressure of 106 psi (0.73 MPa) was reduced to subgrade pressures of only 3 to 7 psi (0.02 to 0.05 MPa) because the applied load is distributed over more than 20 ft (6 m). Other studies (Childs, Colley, Kapernick 1957; Childs and Nussbaum 1962; Childs and Kapernick 1963) confirm that the subgrade pressures below a concrete pavement structure are quite low and, in fact, considerably less than the bearing strengths of almost all subgrades.

For a concrete pavement structure, it is extremely important that the support be reasonably uniform with no abrupt changes or isolated weak or stiff spots in the character of the foundation. This is in contrast to the principle of design for asphalt pavements, where successively stronger base layers are required closer to the surface layer to distribute the much higher pressure transmitted by wheel loads through each layer and ultimately to the subgrade.

The importance of the principle of uniform subgrade support is best explained by anomalies in pavement performance from the field. Performance surveys have been conducted over many miles of old concrete pavements that were constructed without proper subgrade compaction control and without subbases. Where the subgrade was naturally uniform, many of these old pavements are still in excellent condition. Distress is limited to cut-fill transitions and other locations where there are abrupt changes in subgrade materials and moisture conditions. Surveys show that low-strength soils where construction methods provided reasonably uniform support perform better than stronger soils lacking uniformity (ACPA 1995).

INFLUENCE OF FOUNDATION STRENGTH ON CONCRETE PAVEMENT THICKNESS

Although subbases are used to increased composite support strength and protect the subgrade, it is the subgrade that must ultimately bear the load, making it the starting point for support characterization and design. As mentioned, the primary requirement of the subgrade beneath a concrete pavement structure is that it be uniform. This is the fundamental reason for specifications on subgrade compaction. While a uniform, good-quality, and properly-compacted subgrade will improve the performance of the pavement, it is not necessarily true that a stronger subgrade will do the same; most of the structural capacity of a concrete pavement structure is supplied by the concrete slab and not by the foundation (subgrade and/or subbase).

The strength of the foundation for a concrete pavement structure is often quantified as the modulus of subgrade reaction (k-value). The modulus of subgrade reaction is determined by the plate load test (AASHTO T222 or ASTM D1196). The plate load test models the subgrade as a bed of springs, with the k-value being analogous to the spring constant; in fact, k is sometimes referred to as the subgrade “spring constant.” The test involves placing a 30 in. (762 mm) diameter plate on the subgrade and loading it with a very heavy load. The plate distributes the load to the subgrade via the pressure on the face of the plate. The k-value is found by dividing the plate pressure by the plate deflection under the load. The units for k-value are psi/in. (MPa/m).

An exact k-value of the subgrade is not typically required; a measured subgrade k-value is heavily dependent on the season, moisture conditions, location, etc. Furthermore, when a subbase system is used, there can be a significant increase in the composite k-value and an exact value of the k-value of the subgrade is of even less concern. The composite k-value may be measured by a repetitive static plate load test (AASHTO T221 or ASTM D1195) for use in design or evaluation of components of the concrete pavement structure. This test, which is widely used in Europe, is a modification of the standard plate load test used on subgrades (AASHTO T222 or ASTM D1196). It includes repeated loading and bearing plate diameters down to 6 in. (150 mm), to more accurately model a vehicular load.

The magnitude of the increase in k-value from the inclusion of a subbase in the design of the pavement system depends on the subbase material and whether the subbase is treated or untreated. Normal variations from an estimated subgrade or composite k-value will not appreciably affect pavement thickness in typical k-value ranges, as shown in Figure 4.

Note that it is not economical to use an overdesigned subbase system for the sole purpose of increasing the composite k-value; increasing the slab thickness, concrete strength, edge support and many other variables often proves to be more economical. Figure 4 shows an increase in the k-value from 100 psi/in. (27 MPa/m) to 500 psi/in. (135 MPa/m), which will only decrease the required concrete slab thickness by about 20 percent.

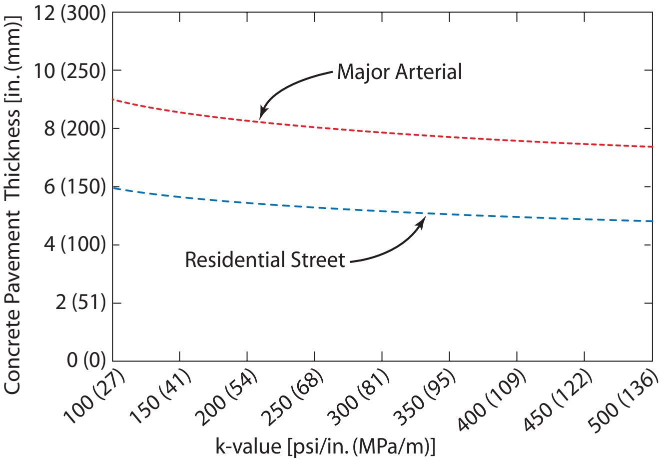


Figure 4. Sensitivity of k-value for a residential street and a major arterial. Assumptions for the residential street include: 12 ft (3.7 m) joint spacing, no dowel bars, 20 year design life, ADTT of 3, and a flexural strength of 600 psi (4.1 MPa). Assumptions for the major arterial include: 15 ft (4.6 m) joint spacing, 1.25 in. (32 mm) diameter dowel bars, 20 year design life, ADTT of 10,000, and a flexural strength of 600 psi (4.1 MPa).

INFLUENCE OF FOUNDATION STIFFNESS ON STRESSES AND STRAINS IN CONCRETE PAVEMENT SLABS

Although concrete pavement is commonly referred to as ‘rigid,’ because of its relatively high modulus of elasticity when compared to asphalt pavement (commonly referred to as ‘flexible’), the modulus of elasticity of concrete is not so high that a concrete pavement does not deflect under a heavy load. In fact, once a crack initiates in a concrete pavement (top-down at a corner or mid-slab, bottom up at the mid-slab, etc.), the zone immediately around the crack tip is more appropriately modeled as pseudo-elastic than brittle as the term rigid might suggest. The subsequent opening and propagation of the crack tip is the origin of concrete pavement fatigue, which can result in distresses such as mid-slab transverse cracks.

When a concrete pavement is placed either on the subgrade or on any number of subbase layers, the properties of these foundation layers will directly influence the stresses and strains of the concrete slabs and, in turn, have some bearing on the long-term performance of the system. The most often utilized common material property used in quantifying this interaction between the foundation and the concrete slab is the modulus of elasticity, often measured indirectly by the compressive strength in stabilized subbases. Figure 5 illustrates how the concrete pavement, composite subbase layers and composite subgrade might be modeled in a modern design analysis, showing the combining of support modulus (stiffness) in layers under the concrete pavement.

Counter to intuition, the stronger and stiffer the foundation becomes, the more problematic it may be for concrete pavement performance. If the concrete slab is in full contact with the foundation, a stiffer support system will reduce deflections and, thus, stresses under heavy loads. If a concrete pavement could be constructed on a perfectly rigid foundation (infinite modulus of elasticity) and remain perfectly planar, there would be zero deflection and zero flexural stress, the primary mode of fatigue failure in concrete pavements. Stiffer support systems, however, will increase deflections and stresses under environmental loading (thermal curling and moisture warping); if a concrete pavement is constructed on a very rigid foundation, the foundation is not capable of conforming to the shape of the slab so support from the foundation might be lost upon environmental loading. The converse is true for a concrete pavement built upon a very flexible foundation, with higher stresses resulting from applied loads due to free deformation and lower stresses under environmental loading because the foundation conforms to the slab shape. These two extremes of foundation

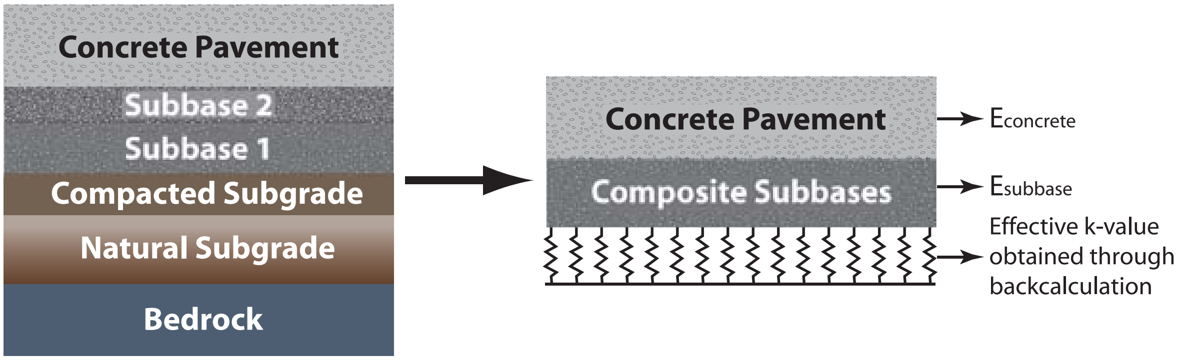


Figure 5. Structural model for concrete pavement structural response computations.

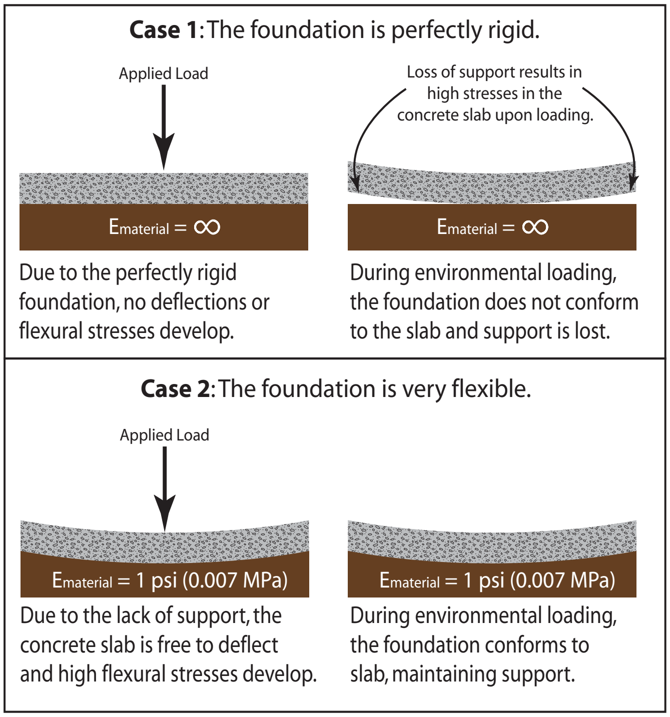


Figure 6. Illustration of the effects of foundation support on applied and environmental loads in a concrete pavement system. The best foundation support condition for a concrete pavement is somewhere between Case 1 and Case 2.

support are illustrated in Figure 6. A balance of strength and flexibility in the foundation system is necessary for excellent long-term pavement performance, placing the best foundation support conditions between Case 1 and Case 2.

Higher curling stresses have a more damaging impact when the concrete is relatively young, when the slab has not yet developed the strength and fracture toughness necessary to resist cracking. Strength is important to prevent the initiation of a crack and fracture toughness is important to prevent propagation of a crack. If the stiffness of a stabilized subbase becomes too great, not only will the curling stresses in the pavement slabs increase, but the probability of reflective cracks from a stabilized subbase will also increase (assuming drying shrinkage cracking has occurred in the subbase). Also, the thicker a subbase layer is constructed, the greater the increase in support stiffness.

The pavement design engineer must recognize that subbase thickness and stiffness (by way of compressive strength) are important on a concrete pavement foundation system. Recommended minimum subbase thicknesses are 4 in. (100 mm) for unstabilized subbases, 4 in. (100 mm) for cement-stabilized subbases and 2 in. (50 mm) for asphalt-treated subbases. Unstabilized subbases and cement-treated subbases are best controlled using compaction and/or density requirements. Cement-treated subbases should be in a strength target range of 300 to 800 psi (2.1 to 5.5 MPa) (PCA 2006), while lean concrete subbases require a maximum strength limit of 1,200 psi (8.3 MPa). Methods to mitigate problems due to excessive strength are discussed throughout this publication.

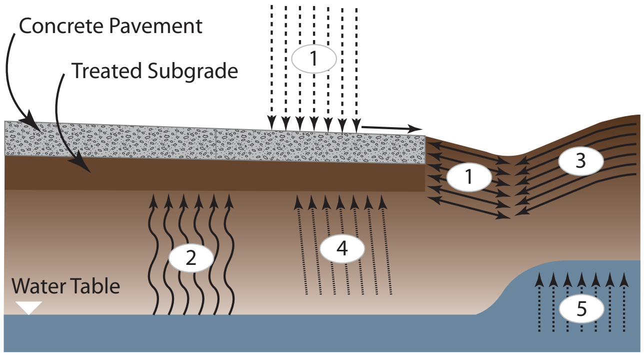
PAVEMENT SYSTEM DRAINAGE

It is important for the reader not to overlook drainage as unimportant in concrete pavement design. Quite the contrary is true. Drainage, however, must be put into the proper perspective as just one element of many needed to optimize performance of a concrete pavement structure. Uniform support is the primary driver of good performance and the most important fundamental in engineering and selecting a subgrade and subbase combination for a concrete pavement.

In many respects, drainage should be addressed in preparing a subgrade and shaping the roadway template with ditches and adequate horizontal and vertical sloping; however, consideration of drainage in subbase layers is also important.

Sources of Moisture in a Pavement Structure

The sources of moisture to a pavement structure are shown in Figure 7. The significance of the influence of moisture on the performance of pavements cannot be ignored. However, an engineer must also recognize that even though there may be some controls possible, drainage systems such as subsurface edge drains, edge ditches, and culverts are never an absolute control for preventing moisture from gaining



1. Precipitation and entry from the pavement edge
2. Capillary suction from the water table
3. Drainage from natural high ground
4. Vapor movement through the soil
5. Water table rise in elevation

Figure 7. Sources of moisture to a pavement structure.

access to the pavement. Instead, drainage systems are tools for minimizing moisture variations in the confines of a pavement structure to within reasonable limits (maintain equilibrium). Extremes in moisture variation (non-uniformity) contribute more to pavement distresses and problems than the presence of moisture alone.

Capillarity is the action by which a liquid (water) rises or wicks in a channel above the horizontal plane of the supply of free water (water table). The number and size of the channels in a soil determine its pore size distribution and thus its capillarity. This soil property is measured as the distance (ranging from zero to 30 ft (9.1 m) or more) moisture will rise above the water table by this action. Moisture in clay soils may be raised by capillarity for vertical distances as great as 30 ft (9.1 m), considered by highway engineers to be a “high capillarity” material. However, a long period of time is often required for water to rise the maximum possible distance in clay soils because the channels are very small and frequently interrupted. Silts also have high capillarity, but maximum capillary rise occurs in even a longer period of time than for clayey soils because the pores in a silty soil are sufficiently large to greatly reduce the capillary action. The capillary rise in gravels and coarse sands varies from zero to a maximum of a few inches because the pores are large enough to eliminate almost all capillary action.

The water table beneath a pavement will rise and fall due to seasonal and annual differences in precipitation (i.e., number 5 in Figure 7 is dependent on number 1). A higher water table will result in a greater driving force for capillary suction and vapor movement near the subgrade (i.e., numbers 2 and 4 are dependent on number 5). Thus, the design of the pavement structure must assume the highest water table expected during the life of the pavement, because that is when the subgrade and subbase will contain the moist moisture and be the weakest. The highest water table during the life of a pavement should be expected around the most major precipitation event, making runoff from areas of higher elevation most detrimental to a local water table (so number 3 is dependent on number 1).

In an effort to minimize moisture levels in the pavement structure, roadway engineers often concentrate on the easiest sources of moisture to isolate, which are numbers 1, 3, and 5. Often, highways are elevated with respect to their surroundings, a configuration that forces water to run downhill to ditches (mitigating numbers 1 and 3) while, at the same time, increasing the distance between the pavement structure and the water table (mitigating number 5 and, in turn, minimizing numbers 2 and 4). Since an elevated roadway is typically not possible for street or road applications, edge drains and sewers are used to collect any surface runoff (mitigating numbers 1, 3, and 5).

Free-Draining Subbases

Free-draining subbases are preferred over permeable subbases because of their more durable, more stable nature (Figure 8). The recommended target permeability (k) for free-draining subbase materials is between 50 and 150 ft/day (15 and 46 m/day) in laboratory tests. Materials providing as much as 350 ft/day (107 m/day) in laboratory tests may also provide adequate long-term stability for a pavement foundation.

Figure 8. Free-draining, unstabilized subbase with enough fines to be stable during construction but still provide permeability of about 200 ft/day (60 m/day) in laboratory tests. Note that the truck tires are not causing excessive rutting or displacement of the subbase material.

Older recommendations for unstabilized permeable subbases suggest a target permeability in the range of 500 to 3,000 ft/day (150 to 315 m/day) in laboratory tests (FHWA 1992). However, material with this high degree of permeability (above approximately 350 ft/day (107 m/day)) also has a high degree of void space, which decreases stability. Field reports from contractors indicate difficulty in constructing pavements on these open-graded materials. Trucks, paving machines, and other heavy equipment displace unstabilized materials that are open in their gradation (consists of mostly one aggregate size). Contractors have used the description “it’s like paving on marbles” to describe paving on a permeable subbase.

Though free-draining subbases drain slower than permeable subbases (because of the increased fines content) they still drain more quickly than conventional, dense-graded subbases. Stability is enhanced by the use of aggregate that is angular and does not degrade under repeated loading. Recycled concrete aggregate (either from an existing concrete pavement or another source) produces good results in free-draining subbases; however, it should be noted that recycled aggregate subbase has a lower permeability, strength, and resistance to particle degradation than limestone or gravel subbases.

Edge Drainage Systems

An edge drainage system can consist of a collector pipe and outlet system with redundant outlets, or a daylighted subbase system where the subbase extends and carries water to the side ditches. The common application for edge drainage systems is for high volume roadway or highway applications, such as major state roads and interstates. Even then, their use is not always required or suggested.

The use of edge drainage systems for low volume applications such as rural roads, county roads, etc., is not suggested. These types of pavements will provide excellent service with fundamental roadbed considerations, such as appropriate ditch and elevation design. Additionally, the loading on these pavements is likely to be such that pumping is not a concern. In these situations, a dense-graded unstabilized (granular) subbase or construction on appropriately prepared subgrade will suffice.

Edge Drain Piping

Where edge drains are used, the hydraulic capacity of longitudinal edge drains and outlet laterals must be high enough to drain the free water within the pavement structure within 2 hours of rain cessation (FHWA 1990). The drainage pipes typically consist of a 4 to 6 in. (100 to 150 mm) diameter flexible, corrugated polyethylene tubing (perforated) meeting AASHTO M252. Rigid PVC pipe (slotted) meeting AASHTO M278 – PC50 has also been used, but it is considerably more expensive. Trenches are backfilled with highly permeable material to easily draw moisture from the subbase. A filter fabric (geotextile) lines the trench to prevent the fine particles from intruding into the trench area; the filter fabric is extended across the pavement section to prevent fine particles in the subgrade from intruding into the free-draining subbase. The recommended detail for the filter fabric liner is found in Figure 9.

Lateral outlet pipes are made from rigid PVC or metal. Rigid pipe provides more protection against crushing due to construction or maintenance operations. Although the spacing between outlets has been as much as 300 to 500 ft (90 to 150 m) in

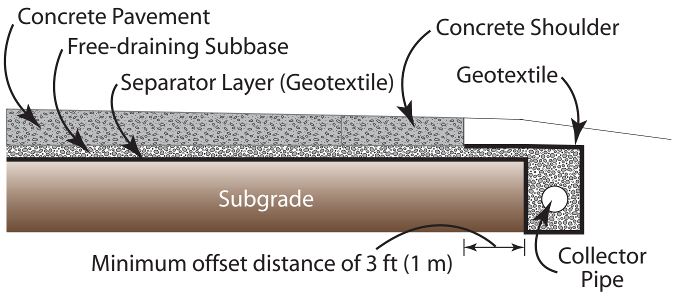


Figure 9. Detail for edge drain piping. Note that the filter fabric (geotextile) does not completely surround the trench, which prevents the fabric from being clogged by leachates or other fine particles carried by water flowing through the subbase, and the drain is offset at least 3 ft (1 m) from the edge of paving whenever possible, which protects it from construction traffic.

practice, a maximum of 250 ft (75 m) is preferred to ensure proper drainage. Outlets should also be placed at the bottom of all vertical curves. The pipes should be placed on a 3 percent grade with the outlet at least 6 in. (150 mm) above the 10 year design flow in the ditch. Concrete headwalls are important to protect pipe outlets. Outlets should be equipped with rodent screens.

For crowned pavements, edge drains are installed along both the inner and outer pavement edge. This shortens the drainage path and reduces the time for the subbase to drain. However, for pavement lanes built as an uncrowned section, only one edge drain is installed, at the low side, which is considerably less expensive.

It is important to place the longitudinal edge drain outside of the paver trackline or any location that is expected to receive loads by heavy construction equipment. A minimum offset distance of 3 ft (1 m) is recommended whenever possible.

Daylighting the Subbase

Though often disregarded in the past due to the mindset that overgrowth along the ditch line would clog the system, daylighting a subbase directly into the side ditches may yield better long-term performance than edge drains, because it does not rely on the periodic maintenance that is required for a pipe drain system. Furthermore, studies found that flexible pavements sections with daylighted bases (without edge drains) performed as well as (or better than) any other flexible pavement section (NCHRP 2002). Similar performance should be expected with concrete pavements. The recommended details for a daylighted subbase are shown in Figure 10.

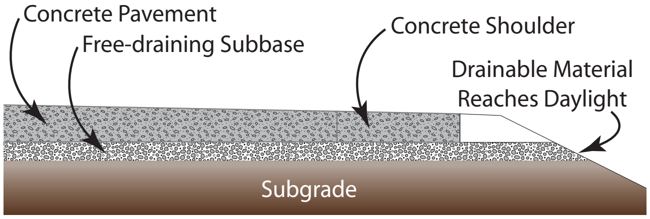


Figure 10. Detail for a daylighted subbase. Note that there is no filter fabric (geotextile) or filter layer as there is for an edge drain system. Instead, it is accepted that some local clogging of the permeable layer will take place, but overall drainage will not be lost since the entire depth of the layer is exposed for the entire length of the pavement.

Separators

Separators are geotextile fabrics or filter layers that prevent the migration of fines from the subgrade into the free-draining subbase. Geotextile fabrics are commonly used (and strongly suggested) directly below a free-draining subbase layer to prevent fines from infiltrating and plugging the subbase.

Some agencies also place a filter layer (4 to 6 in. (100 to 150 mm) thick layer of dense-grade unstabilized granular material) below a drainable subbase. This is not considered a necessity when a free-draining subbase material is employed in the design. Where used, the filter layer serves as a construction platform and as a barrier to prevent water from entering the subgrade as it flows through the subbase to the ditch or edge drain piping.

The following criteria for filter layers are recommended. It will be necessary to evaluate both the filter layer/subgrade and the subbase/filter layer interfaces (FHWA 1990, US ACoE 1941):

1. The 15 percent size (D_{15}) of subbase should not be more than 5 times larger than the 85 percent size (D_{85}) of the filter.
2. The 50 percent size (D_{50}) of subbase should not be more than 25 times larger than the 50 percent size (D_{50}) of the filter.
3. The 15 percent size (D_{15}) of the filter should not be more than 5 times larger than the 85 percent size (D_{85}) of the subgrade soil.
4. The 50 percent size (D_{50}) of the filter should not be more than 25 times larger than the 50 percent size (D_{50}) of the subgrade soil.

Note: The D_x size means that x percent of the particles are smaller than this size.

Filter material should not be placed in a manner to obstruct drainage through the subbase or edge piping. The 85 percent size of the subbase should be at least 1½ to 2 times the size of the slotted pipe openings.

Various filter design criteria for both aggregate and fabric are available elsewhere (FHWA 1990, US ACoE 1991).

Chapter 3. Subgrades

SOIL BASICS FOR PAVEMENT CONSTRUCTION

Note: This section, *Soil Basics for Pavement Construction,* is taken predominately from the Portland Cement Association's EB007 "PCA Soil Primer."

Soil forms when rock, marine shell, coral, etc. breaks into smaller and smaller size particles through the processes of abrasion and/or fracturing (physical weathering). Events that contribute to or accelerate this break-down process include wind weathering, erosion, freezing, rock impact, root growth, wetting and drying, heating and cooling, glacial action, and human factors.

Of far greater significance for fine-grained soils, although less intuitive than the physical breakdown process, are modifications by chemical processes (chemical weathering), plant and animal additions, and man's impact as the soils are transported by flowing water or are subject to moist-to-wet conditions in place.

Recognition of these soil forming processes (break-down and modification) is valuable to both the preliminary site surveys and the extension of limited subgrade sampling information across a project. Near mountain or upland sources, soils will be coarser and more closely related to the source rocks; downstream or at lower elevations, soils will be fine grained, greatly modified and subject to sorting processes (i.e., wind and water transport). Also, the break-down process will apply more directly in arctic areas, whereas chemical modification of soils will be greatest in tropical areas.

Regardless of the method of formation or the source of the soil, long-term subgrade performance depends heavily on three interdependent factors:

- Moisture content and density.
- Load bearing capacity.
- Volume stability.

The following sections provide an overview of test methods used to quantify the previously mentioned performance factors. Knowledge of these properties and their interdependence is necessary to understand the classification systems presented at the end of this section.

Moisture Content and Density

As mentioned, uniformity of support is of utmost concern to a pavement engineer. Also of interest is soil strength. Because soil consists of solid particles, water and air, the moisture condition and, to a lesser degree, the density or unit weight are also of concern because they directly influence strength. This section describes various properties relating to moisture and density of soils.

Soil Water

A soil mass is a porous material containing solid particles interspersed with pores or voids. These voids may be filled with air, with water or with both air and water. There are several terms used to define the relative amounts of soil, air, and water in a soil mass:

- *Density* — The weight of a unit volume of soil. It may be expressed either as a wet density (including both soil and water) or as a dry density (soil only).
- *Porosity* — The ratio of the volume of voids to the total volume of the mass regardless of the amount of air or water contained in the voids. Porosity is typically expressed as a percentage.
- *Void Ratio* — The ratio of the volume of voids to the volume of soil particles. The porosity and void ratio of a soil depend upon the degree of compaction or consolidation. Therefore, for a particular soil in different conditions, the porosity and void ratio will vary and can be used to judge relative stability and load carrying capacity with these factors increasing as porosity and void ratio decrease.
- *Degree of Saturation* — The ratio of the volume of water to the volume of voids, usually expressed as a percentage.

The moisture or water content of a soil is normally expressed as a percentage of the oven-dry weight of the soil. It is determined by first taking the difference in weights between a moist soil sample and the same sample dried in an oven at 230 deg F (110 deg C) until it reaches a constant weight. This difference divided by the oven-dry soil weight (expressed as a percentage) is the moisture content. AASHTO T265 or ASTM D2216 describe this test method. In common usage, the terms “moisture content” and “water content” are synonymous.

The moisture or water that makes up the measurable difference between the in-situ moisture state and the oven-dried state is of three different types:

1. *Gravitational Water* — Water free to move under the influence of gravity. This is the water that will drain from a soil. For in-situ soils it is water at and below the ground water table and is often termed “groundwater.” Groundwater is unbound or “free” water.
2. *Capillary Water* — Water held in the soil pores or “capillaries” by “capillary action.” This is the result of an attraction between fluids and solid surfaces, which, because of stronger attraction to water than to air, results in the upward curving of a meniscus at the water’s edge and to actual rising of water in a narrow tube. Water pressure is zero at the groundwater level or phreatic surface; it is under pressure below this surface and in tension above. Note that capillary water cannot exist directly in the presence of gravitational water. Effects of gravity on a mass of water result in pressure or compression from the water weight. This overrides the tension and relieves the capillary attractions. Capillary water is not generally considered to be “free” water since it is, at least weakly, bound by the surface tension action. However, because it is not strongly bound to soil particles directly, it has sometimes been described as free water in older and especially in agriculturally-oriented soil references.
3. *Hygroscopic Water* — Moisture retained by soil after gravitational and capillary moisture are removed. It is held by each soil grain in the form of a very thin film adsorbed on the surface by molecular attractions involving both physical and chemical affinity. This film is in equilibrium with the moisture content of the air and increases or decreases with changes in humidity; it can be described as the water associated with the air-dry moisture content.

■ *Moisture Equivalent*

Both capillary water and hygroscopic water are, to a degree, “bound” and represent a capacity for the soil to hold water against forces tending to remove it. Measures of this “water-holding capacity” are the “moisture equivalent” moisture contents. Low values are associated with coarse-grained soils, which are not moisture sensitive and are highly permeable. High values are associated with plastic clays, which are very moisture sensitive and are of low permeability. The tests used to quantify the moisture equivalent are:

- *Field Moisture Equivalent* — The field moisture equivalent (FME) is the minimum moisture content at which a smooth surface of soil will absorb no more water in 30 seconds when the water is added in individual drops. It shows the moisture content required to fill all the pores in sands, when the capillarity of cohesionless expansive soils is completely satisfied and when cohesive soils approach saturation. This test is no longer common and both standard procedures used to conduct it, AASHTO T93 and ASTM D426, are discontinued.
- *Centrifuge Moisture Equivalent* — The centrifuge moisture equivalent (CME) is the moisture content of a soil after a saturated sample is centrifuged for one hour under a force equal to 1,000 times the force of gravity. This test, ASTM D425, is used to assist in structural classification of soils. Low values, such as 12 or less, indicate permeable sands and silts; high values, such as 25, indicate impermeable clays. High values indicate soils of high capillarity, and low values indicate soils of low capillarity.

When both the FME and CME are more than 30 and the FME is greater than the CME, the soil probably expands upon release of load and is classified as elastic.

■ *Soil Moisture Suction (Capillary Action)*

FME and CME have origins in agricultural soil technology, but they found early applications in relation to highway subgrade assessment and right-of-way soil surveys. They continue in some use, but the technology concerned with subgrade moisture-strength in place is now more focused on “soil moisture suction.” This is the moisture tension associated with capillarity, and thus, it is often called “capillarity” or “capillary action.”

Water in soil above the water table has a pressure less than atmospheric. It rises above the water table because of the surface tension (capillary forces) and adsorption forces by which the water is bound or held in the soil.

For a soil with measurable soil moisture suction, capillarity ranges from zero at saturation to quite large values when the soil is relatively dry. Thus, soil moisture suction is dependent not only of the overall driving force of the soil but also the current moisture state.

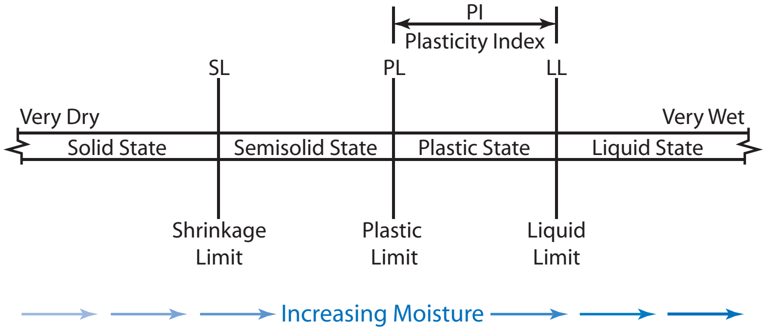
The suction can be expressed in units of (negative) pressure. Relation between the suction and moisture content is very dependent on the soil type. A test standard for measurement of soil suction is presented as AASHTO T273 and ASTM D3152.

■ *Plastic Soils*

Most soils include a fine fraction of silt or clay, or a combination of the two. The consistency of these soils can range from a dry, solid state to a wet, liquid state with the addition of water. Introducing water into a matrix of soil particles, air and water allows empty pore space (space currently occupied by air) to fill with water. Eventually, all of the empty pores will be occupied by water and the addition of any more water will cause the system to expand. If the addition of water occurs in small enough steps, the consistency of silts and clays can be seen passing from solid to semisolid to plastic and to liquid, as illustrated in Figure 11.

The shrinkage limit (SL) separates solid from semisolid, the plastic limit (PL) separates semisolid from plastic state and the liquid limit (LL) separates plastic from liquid state. The plasticity index (PI) is the width of the plastic state (LL minus PL), expressed in terms of moisture content. The PI is an important indicator of the plastic behavior a soil will exhibit; a low PI is indicative of a very moisture-sensitive soil.

Standard procedures have been developed so that consistent determinations to establish the dividing limits can be made by anyone employing these procedures. Since it is the more plastic or finer soils that reflect this pattern of response to moisture variation, the standard tests are performed on the portion of a soil that will pass a No. 40 (425 µm) mesh sieve.



Shrinkage Limit (SL)	This limit separates the solid state from the semisolid state. It is represented by the point in a drying process at which no further shrinkage takes place while drying continues. Standard test procedures can be found in ASTM D427. While this limit is an element of the soil-water consistency pattern, it has less significance or application than the other limits in relation to soil engineering.
Plastic Limit (PL)	This limit separates the semisolid state from the plastic state. It is represented by the moisture content at which the soil, when rolled into a ⅛ in. (3.2 mm) cylindrical ribbon, will begin to break into short sections. Standard test procedures are described in AASHTO T90 and ASTM D4318.
Liquid Limit (LL)	This limit separates the plastic state from the liquid state. It is represented by the moisture content at which the soil, when separated by a standard groove [0.04 in. (1 mm)] in a standard cup, will flow back together [0.4 in. (1 cm) length] under 25 standard taps or blows [0.4 in. (1 cm) fall impacts]. Standard test procedures are described in AASHTO T89 and ASTM D4318. The liquid limit is considered to relate directly to soil compressibility; the higher the LL, the greater the compressibility.
Plasticity Index (PI)	The PI is the numerical difference between the LL and the PL, each expressed as moisture content in percent. AASHTO T90 and ASTM D4318 are standards for PI determination. This index is a significant indicator of soil behavior. The higher the index number, the more plastic the soil will be. Low PI soils are very sensitive to moisture change since only a few percent (equal to the PI) moisture can change the soil from a plastic to a liquid state.

Figure 11. Soil states and consistency limits (Atterberg limits) with descriptions.

■ *Nonplastic Soils*

The soils considered in the previous section had compositions including a fine fraction of silt and clay, which provided them with a plastic consistency. Soils composed almost entirely of sand sizes, gravel or coarse silt, or any combinations of these, have a nonplastic consistency.

Coarse sands and fine gravels, which include little or no particle sizes that pass the No. 40 (425 µm) sieve, are clearly nonplastic (NP). These show no significant consistency variation with moisture variation. Dry sands have no cohesive element to join grains together. The individual particles respond with only mass, shape and gravity. When excavated or placed in piles, they will show characteristic maximum slopes at their “angle of repose.” Moist sands are bound by capillary moisture films at contact points between grains. Thus, bonding is zero when dry, increases through a maximum as moisture is increased, and returns to zero on complete saturation. This moisture variation does not cause swelling or shrinkage in undisturbed sands, but when moist sands are moved or disturbed by construction operations, the capillary fringes will compete with gravity forces. The result is increased voids and reduced density. This phenomenon is termed “bulking,” and it can lead to settlement problems, especially in light construction when not properly considered and treated.

Load Bearing Capacity

Historically, the complexity of pavement design prevented the direct use of shear strength of a soil for design. Design methods were devised based on tests that provided an index number related to soil strength that was most commonly, but not always, considered to represent shear strength. Several of these tests and methods which are still employed in modern design include:

- *California Bearing Ratio (CBR) Test* — This is a test that measures the force required to penetrate a soil surface by a round piston with a 3 in.^{2} (19 cm^2) end round piston area. The index (CBR) value is the percent of an established reference value for 0.1 in. (2.5 mm) and 0.2 in. (5.0 mm) penetration. The reference value of 100 was originally considered to represent the resistance of a well-graded crushed stone. Typical CBR values may range from 2 to 8 for clays and 70 to 90 for crushed stones.

  The U.S. Army Corps of Engineers and some highway departments use the CBR principle in conducting tests to evaluate the bearing value of materials. Methods of preparing specimens and conducting the test are given in AASHTO T193 and ASTM D1883. Several agencies have their own modifications of the CBR test.
- *Resistance Value (R-value)* — This is essentially a measure of the stiffness of the material by way of resistance to plastic flow. This test was developed as an improved CBR test and must be conducted in a laboratory. Samples are prepared so they will represent the worst case scenario during testing and are confined on all sides in the testing apparatus, resulting in a triaxial stress state. The R-value is the ratio of the vertical load applied to the resultant lateral pressures. Typical R-values for heavy clays are 0 to 5, for high plasticity silts are 15 to 30 and for well-graded crushed stone are 80 or more. Standard R-value test methods are given in AASHTO T190 and ASTM D2844.
- *Resilient Modulus of Subgrade Soil (M_{RSG} or M_R or E_{SG})* — This test measures stiffness as an estimate of the modulus of elasticity (E) of a material; modulus of elasticity is the stress divided by strain for a slowly applied load and resilient modulus is the stress divided by strain for a rapidly applied load. There are several methods of estimating the resilient modulus, both in the laboratory and in the field, and thus, they are excluded here for brevity. The standard resilient modulus test is given in AASHTO T307.
- *Modulus of Subgrade Reaction (k-value)* — This is a bearing test, conducted in the field, which provides an index to rate the support provided by a soil or subbase layer directly beneath a concrete slab. Practically all concrete pavement design is based on the modulus of subgrade reaction, k, as used in the Westergaard formulas. The k-value is defined as the reaction of the subgrade per unit of area of deformation and is typically given in psi/in. (MPa/m).

  The determination of k for concrete pavement design is made in the field on the subgrade in place, or on the subbase, if used, under conditions that will approximate reasonable mean service conditions. A 30 in. (760 mm) diameter plate is recommended standard, although variations of the test with smaller plates have been introduced to ease testing. The plate size influences bearing-test results because the forces resisting deformation consist of shear around the plate perimeter as well as consolidation under the area of the plate. With plates of 30 in. (760 mm) diameter and greater, the shear-resisting forces around the perimeter are negligible. Figure 12 shows a plate bearing test.

  Details for plate-bearing field tests are given in AASHTO T221 and T222 or in ASTM D1195 and D1196. The elastic k-value (k_e) as determined from the repetitive plate-bearing test (ASTM D1195) is a higher value since most of the inelastic deformation is eliminated in the nonrepetitive test (ASTM D1196).

  When performing plate-bearing tests on stabilized subbases, the loading equipment may not be able to produce a deflection of 0.05 in. (1.3 mm). Even if it could, the resulting pressure on the subbase would likely far exceed the pressures exerted

Figure 12. Plate load testing with a standard 30 in. (760 mm) diameter plate.

under the concrete slab by traffic loads, not accurately representing service conditions. As a result, a maximum pressure of 10 psi (0.7 MPa) is recommended for all plate loading tests and, for realistic test results, neither of these limits (0.05 in. (1.3 mm) deformation or 10 psi (0.7 MPa) pressure) should be exceeded.

- *Cone Penetrometers* — Cone Penetrometers, such as the WES Cone Penetrometer and the Dynamic Cone Penetrometer (DCP), are devices used to measure the strength of in place soil. Test results can be used to estimate the soil shear strength, CBR and k-value. Since the tests are rapid and essentially nondestructive, they are ideally suited for on-site construction evaluation and testing and can be used over large areas to evaluate uniformity. The penetrometers consist of a small cone with an apex angle between 30 degrees and 60 degrees, mounted to a steel rod (Figure 13). The projected area of the base of the cones is approximately 0.5 in.^{2} (320 mm^2). The penetrometers are driven into the ground at either a constant rate (WES) or by dropping a specific hammer weight over a given distance (DCP). Measured values are the load needed to drive the penetrometer or blow counts per unit of depth. These values are then correlated to CBR, shear strength or soil modulus value. Also, by plotting load or blow counts against depth, one can obtain profiles of changing soil strengths across the project area. This can be used for such things as checking the depth of stabilization and finding soft or stiff layers.

Figure 13. Cone penetrometer testing (Minnesota Department of Transportation).

Correlation equations exist that attempt to estimate any one of the aforementioned load bearing capacity measurements from another (i.e., k-value from CBR, CBR from R-value, etc.). Because there is no general consensus on which equations are best, none are included here, but suggested correlation equations should be readily available in any design procedure or design software documentation.

It should be noted that although stiffness is often inferred through strength measurements, stiffness and strength are not synonymous and, therefore, should not be treated as such in soil mechanics. Delineation of the two material properties can help one understand how a stronger foundation might slightly decrease the required pavement thickness, but if the foundation becomes too stiff, it might increase the stresses in the concrete pavement slabs. This concept is discussed in more detail in the *Design Principles* chapter of this publication.

Volume Stability

It is necessary to quantify the expansion and shrinkage of soils, because this overall volume change (or a differential volume change from point-to-point along the pavement) can cause serious damage to a pavement structure, particularly in regions where soils remain relatively dry until wetted by an infrequent rainy period. Tests used to quantify potential volume stability problems by way of shrinking and swelling include:

- *Index Tests for Expansion and Shrinkage of Soils* — Several simple tests that indicate the volume change potential of soils are given in ASTM D427. ASTM D4829 gives an expansive index of soils and, based on the test results, evaluates soils from very low to very high expansion potential.
- *California Bearing Ratio (CBR) and Resistance (R-Value) Tests* — Expansion tests are usually conducted in conjunction with the CBR (AASHTO T193 or ASTM D1883) and R-Value (AASHTO T190 or ASTM D2844) tests. In both instances, the test specimen is compacted to a predetermined density at a proper moisture content in a mold and a supply of water is made available. Surcharges, equal to the weight of the cover material that will overlay the soil in the ultimate pavement structure, are applied to the top of the specimen. The expansion that occurs during some given soaking period is measured as the actual change in length of the specimen, or the pressure exerted by the expanding soil can be measured by means of a calibrated restraining gage. The same specimen is then used for the CBR or R-value determination.
- *Sand Equivalent Test* — A rapid field method, known as the sand equivalent test, has been developed to detect the presence of undesirable claylike materials in soils and aggregate materials. This method tends to magnify the volume of clay present in a sample somewhat in proportion to its detrimental effects.

  The sand equivalent test is a sedimentation-type test in which a sample of the test material, in a prepared solution, is thoroughly agitated in a 100-ml glass cylinder. After setting for 20 minutes, the sand and clay fractions settle into layers. The heights of these layers are measured by taking readings with a specially calibrated rod. The sand equivalent (SE) is calculated as follows:

  SE = sand reading/clay reading x 100

  Concrete sands and crushed stone have SE values of about 80; very expansive clays have SE values of zero to 5. Details of the test procedure are given in AASHTO T176 and ASTM D2419.

Classification Systems

Soil particle sizes range from cobbles/boulders, to gravel, to sand, to silt, to clay and, ultimately, to colloids. It has become the practice to define these various particle size ranges for purposes of describing moisture characteristics and for identification and classification of the material as a whole. The Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) systems are two widely used engineering classifications. Other classifications systems exist, such as the group index system presented in ASTM D3282, but they are not as widely accepted. The AASHTO method (AASHTO M145) grew from needs and developments in the highway engineering field and the USCS method (ASTM D2487) was formulated in support of developing soil engineering technology (geotechnology). The USCS began, however, with a system devised for use in classification of materials for military airfields. It has since been subject to minor adjustments and has been adopted by many other organizations around the world.

A clear understanding of the relationship between soil identification and soil classification is necessary to prevent confusion about many factors involved in soil work. For example, a gradation test might be used to identify a specific soil sample in a lab, but the classification of that sample will depend on which classification system (AASHTO, USCS, soil texture method, etc.) is employed. Once a soil sample is classified in one classification system, it is likely difficult to classify that soil in a different system without knowledge of the soil properties. There are 11 classifications in the AASHTO system and 15 in the USCS system, so if a soil is classified in the USCS system in a group that does not have an obvious correlation to a group in the AASHTO system, the properties of the material would be needed to classify it in the AASHTO system. Thus, a pavement design engineer must be mindful of the preferred classification method for each project.

Although soil classification using the AASHTO or USCS method might aid a pavement design engineer in determining factors such as the California Bearing Ratio (CBR) value or modulus of subgrade reaction (k-value), some soils will certainly exist in the field which are not easily classifiable inside the bounds of these methods. For such soils, or for soils where such design variables are not necessary, the soil can be classified using the soil texture method.

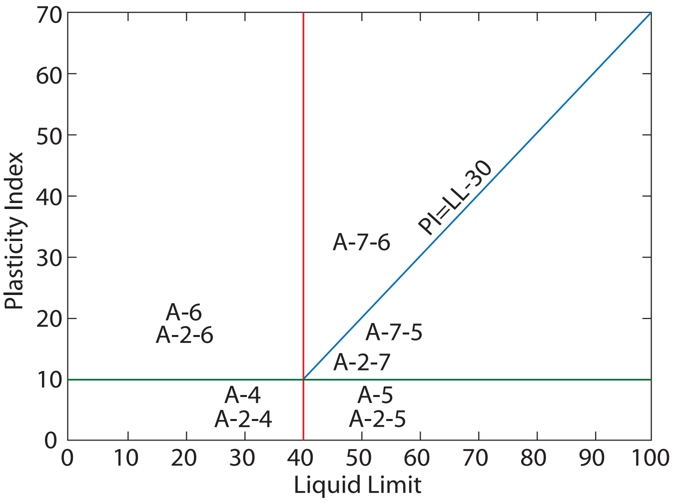
AASHTO Soil Classification System

The AASHTO system of classifying soils is an engineering property classification system based on field performance of highways. This system groups soils of comparable load carrying capacity and resultant service level in seven basic groups, designated A-1 through A-7. The best soils for road subgrades are classified as A-1, the next best A-2, and so on, with the poorest soils classified as A-7.

Soils in each classification group have similar broad characteristics. However, there is a wide range in the load-carrying capacity inside each group, as well as an overlap of load-carrying capacity between the groups. For example, a borderline A-2 soil may contain materials with a greater load-carrying capacity than an A-1 soil and, under unusual conditions, may be inferior to the best materials classified in the A-6 or A-7 soil groups. Hence, if the AASHTO soil group is the only fact known about a soil, only the broad limits of load-carrying capacity can be stated. As a result, the seven basic soil groups were divided into subgroups, with a group index devised to approximate within-group evaluations.

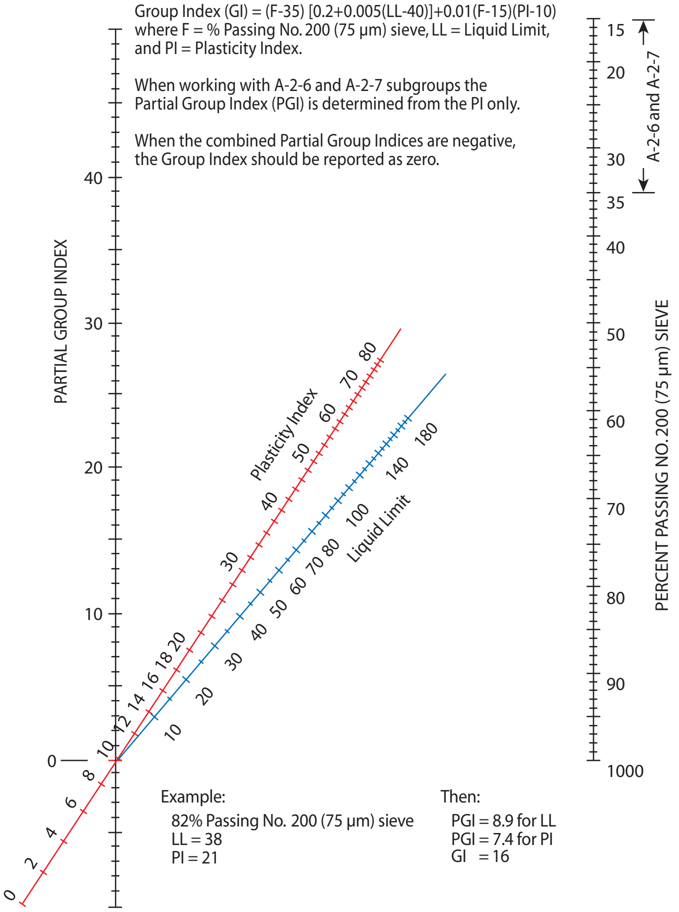
The charts and table used to classify soils in the AASHTO soil classification system (AASHTO M145) are shown in Figures 14 and 15 and Table 1.

Classification of materials in the various AASHTO M145 groups applies only to the fraction passing the 3 in. (75 mm) sieve. Therefore, any specification regarding the use of A-1, A-2 and A-3 materials in construction should state whether boulders, retained on a 3 in. (75 mm) sieve, are permitted.



Note: A-2 soils contain less than 35% finer than 200 (75 µm) sieve.

Figure 14. Liquid limit and plasticity index ranges for AASHTO soil classes. See the section titled, Plastic Soils, *earlier in this chapter for more on the liquid limit and plasticity index.*


Group Index (GI) = (F-35) [0.2+0.005(LL-40)]+0.01(F-15)(PI-10)
where F = % Passing No. 200 (75 µm) sieve, LL = Liquid Limit, and PI = Plasticity Index.

When working with A-2-6 and A-2-7 subgroups the Partial Group Index (PGI) is determined from the PI only.

When the combined Partial Group Indices are negative, the Group Index should be reported as zero.

Example:
82% Passing No. 200 (75 µm) sieve
LL = 38
PI = 21

Then:
PGI = 8.9 for LL
PGI = 7.4 for PI
GI = 16

Figure 15. Group index chart.

Table 1. AASHTO Classification of Highway Subgrade Materials

AASHTO Soil Classification System (from AASHTO M145)											
General Classification	**Granular Materials 35% or less passing the No. 200 (75 µm) sieve**							**Silt-Clay Materials >35% passing the No. 200 (75 µm) sieve**			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis, % passing											
No. 10 (2.00 mm)	50 max	—	—	—	—	—	—	—	—	—	—
No. 40 (0.425 mm)	30 max	50 max	51 max	—	—	—	—	—	—	—	—
No. 200 (75 µm)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40 (0.425 mm)											
Liquid Limit	—		—	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min*
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as a subgrade	Excellent to Good							Fair to Poor			

* Plasticity Index of the A-7-5 subgroup is equal to or less than LL minus 30. Plasticity Index of the A-7-6 subgroup is greater than LL minus 30.

ASTM (Unified) Soil Classification System

The U.S. Army Corps of Engineers developed a classification system that uses texture as the descriptive terms (see Table 2), such as “GW: gravel, well-graded”; “GC: gravel, clayey fines”; and “GP: gravel, poorly-graded.” Since its inception, this classification system was expanded in cooperation with the United States Bureau of Reclamation (USBR) and the Tennessee Valley Authority (TVA). It is now referred to as the Unified Soil Classification System (ASTM D2487).

The ASTM Soil Classification System identifies soils according to their textural and plasticity qualities and their grouping with respect to their performances as engineering construction materials. The following properties form the basis of soil identification:

1. Percentages of gravel, sand, and fines (fraction passing the No. 200 (75 µm) sieve).
2. Shape of the grain-size distribution curve.
3. Plasticity characteristics.

Each soil is classified into the group that most appropriately identifies its principal characteristics.

The ASTM system groups are easily identified by the descriptive names and letter symbols, as shown in Table 3.

Table 2. ASTM D2487 Descriptors.

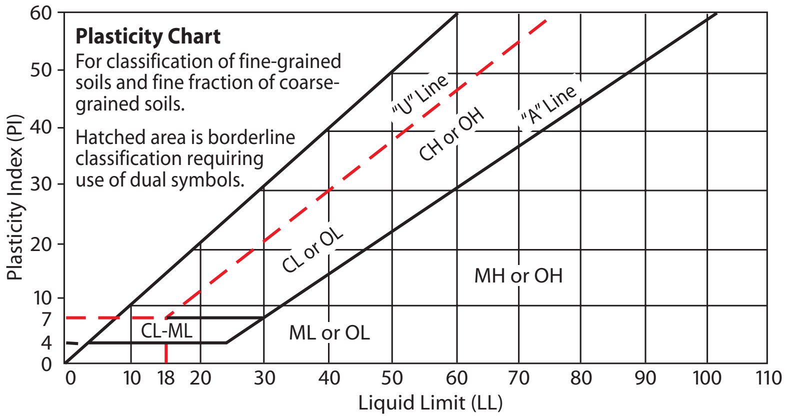
1st Letter	
Symbol	**Description**
G	Gravel
S	Sand
M	Silt
C	Clay
O	Organic
PT	Peat
2nd Letter	
Symbol	**Description**
W	Well-graded
P	Poorly-graded
M	Silty fines
C	Clayey fines
H	High plasticity
L	Low plasticity

Table 3. ASTM (Unified) Soil Classification System

Major Divisions			Group Symbols	Typical Descriptions
Coarse-Grained Soils **More than 50% retained on No. 200 (75 µm) sieve***	Gravels 50% or more of coarse fraction retained on No. 4 (4.75 mm) sieve	Clean Gravels	GW	Well-graded gravels and gravel-sand mixtures, little or no fines
			GP	Poorly-graded gravels and gravel-sand mixtures, little or no fines
		Gravels with Fines	GM	Silty gravels, gravel-sand-silt mixtures
			GC	Clayey gravels, gravel-sand-clay mixtures
	Sands 50% or more of coarse fraction passes on No. 4 (4.75 mm) sieve	Clean Sands	SW	Well-graded sands, and gravelly sands, little or no fines
			SP	Poorly-graded sands and gravelly sands, little or no fines
		Sands with Fines	SM	Silty sands, sand-silt mixtures
			SC	Clayey sands, sand-clay mixtures
Fine-Grained Soils **50% or more passes No. 200 (75 µm) sieve***	Silts and Clays Liquid Limit less than 50		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and Clays Liquid Limit 50 or more		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts
			CH	Inorganic clays of high plasticity, fat clays
			OH	Organic clays of medium to high plasticity
Highly Organic Soils			PT	Peat, muck, and other highly organic soils

* Based on the material passing the 3 in. (75 mm) sieve.

	Classification Criteria	
Classification on basis of percentage of fines Less than 5% pass No. 200 (75 µm) sieve — GW, GP, SW, SP More than 12% pass No. 200 (75µm) sieve — GM, GC, SM, SC 5% to 12% pass No. 200 (75 µm) sieve — Borderline classification requiring use of dual symbols	$C_U = D_{60} / D_{10}$ Greater than 4 $C_Z = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
	Not meeting both criteria for GW	
	Fines classify as ML or MH	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
	Fines classify as CL or CH	
	$C_U = D_{60} / D_{10}$ Greater than 4 $C_Z = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
	Not meeting both criteria for SW	
	Fines classify as ML or MH	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols
	Fines classify as CL or CH	



Visual-Manual Identification, see ASTM D2488

Soil Texture Method

While the AASHTO and USCS methods are used to designate soil particle size ranges, soils found in the field are much too varied to be limited to these specific particle size ranges. A sand soil, for instance, can include limited quantities of silt, clay, or gravel sizes, or combinations of these, and still be classified merely as sand. The same is true for silt, clay or gravel. Size ranges are standardized so other particle sizes may be present, but the soil class (sand, silt, clay, or gravel) can be designated. When greater quantities of other sizes are present, that basic soil type has a combined designation, such as clayey sand, sandy gravel, clay-silt, etc. The determination and designation of such mixtures in soil classification is referred to as "soil texture."

The texture-related terms used for various combinations of soil separates are defined by several agencies. The amount of each soil separate in the soil, which will determine the texture or feel of the soil, is determined by laboratory tests. These test results are then compared with the definitions of texture in use to determine the textural name.

The texture of a soil is given to tell as much as possible about that soil in just a few words. With texture determined, approximations and estimates of soil properties can be made, such as bearing value, water-holding capacity, susceptibility to frost heave, and adaptability to soil-cement construction.

To permit approximate textural classification, many practical shortcuts can be devised to determine the amount of silt and clay in a soil. However, since the range in clay content for the textural groups is not large, accurate weighing of samples is necessary, which requires some laboratory facilities. ASTM D2488 describes a procedure for the identification and description of soils for engineering purposes based on visual examination and simple manual tests. The types of soil texture are listed in Table 4.

Table 4. Soil Texture Method Classifications

Soil Texture	Description
Sand	Includes only small amounts of fines or no fines. These are found on beaches, in dunes or in stream bar deposits. Individual grains can be seen and felt readily. Squeezed in the hand when dry, this soil will fall apart when the pressure is released. Squeezed when moist, it will form a cast that will hold its shape when the pressure is released but will crumble when touched.
Silty-sand	Consists largely of sand, but has enough silt and clay present to give it a small amount of stability. Individual sand grains can be seen and felt readily. Squeezed in the hand when dry, this soil will fall apart when the pressure is released. Squeezed when moist, it forms a cast that will not only hold its shape when the pressure is released but will also withstand careful handing without breaking. The stability of the moist cast differentiates this soil from sand.
Silt	Consists of a large quantity of silt particles with none to small amounts of sand and clay. Lumps in a dry, undisturbed state appear quite cloddy, but they can be pulverized readily; the soil then feels soft and floury. When wet, silt loam runs together and puddles. Either dry or moist casts can be handled freely without breaking. When a ball of moist soil is pressed between thumb and finger, its surface moisture will disappear, and it will not press out into a smooth, unbroken ribbon but will have a broken appearance.
Silty-clay	Consists of plastic (cohesive) fines mixed with a significant quantity of silt. It is a fine-textured soil that breaks into hard clods or lumps when dry. When a ball of moist soil is pressed between the thumb and finger, it will form a thin ribbon that will break readily, barely sustaining its own weight. The moist soil is plastic and will form a cast that will withstand considerable handling.
Clay	A fine-textured soil that breaks into very hard clods or lumps when dry and is plastic and unusually sticky when wet. When a ball of moist soil is pressed between the thumb and finger, it will form a long ribbon.
Fat or Heavy Clay	Highly plastic clay; strongly exhibits the characteristics indicated for clay.
Lean or Lighter Clay	Moderately plastic clay; shows the characteristics indicated for clay, but to a lesser degree.

The feel and appearance of the textural groups illustrate factors used in determining the texture of soil in the field and also assist in field classification work. Note: forming two casts of soil, dry and moist, in the hand and pressing or rolling a moist ball of soil between the thumb and finger constitute two significant field tests to judge soil texture.

SUBGRADE STRENGTH AND WORKING PLATFORM

Due to the ability of a concrete pavement to spread loads over large areas, the highest subgrade stresses will normally occur during the construction phase of a concrete pavement or subbase layer. Once in place, the subbase and concrete pavement protect the subgrade from high-stress contact by loads. Thus, the required strength of a subgrade is typically dictated by providing a stable working platform to construct successive layers. Research conducted by the Wisconsin Department of Transportation has concluded that a minimum California Bearing Ratio (CBR) of 6 in the top 24 in. (610 mm) of subgrade provides an adequate working platform, while limiting subgrade rutting under construction traffic to ½ in. (13 mm) or less (Crovetti and Schabelski 2001).

Compacting the subgrade to a density that provides an adequate working platform for construction equipment will provide adequate subgrade strength for the in-service concrete pavement. The AASHTO T99 (standard proctor) field test is recommended to characterize a subgrade for acceptance. The target percentage of compaction will vary by soil type and local conditions. State departments of transportation recommend values ranging from 84 to 100 percent of the standard proctor, but a value of 95 percent is by far the most specified and, thus, is the recommended value for most applications (ACPA 2005).

Specifiers are cautioned against arbitrarily specifying high degrees of compaction because this may contribute to increasing construction durations due to the extra compaction efforts required and unnecessary project costs, all without any real associated benefit. It should be noted that subgrade strength is a function of both density and moisture content. Soils that are compacted to a given density at dryer than optimum moisture contents will lose strength if the soils become saturated over time. Under normal conditions, this loss of strength is not an issue for support of the pavement, but may be an issue for providing a stable working platform. When subgrades are compacted and accepted weeks or months in advance of the construction of the subbase or pavement, the once stable working platform may be inadequate to support construction equipment due to saturation.

Depending upon the soils that occur on a project and the density requirement in the specifications, strict conformity to a specified density can be inefficient. For example, if a stable working platform can be achieved at 90 percent density, further compaction efforts to meet an arbitrarily specified density of 95 percent is wasteful; this additional density is not necessary for uniform support of the pavement.

OBTAINING UNIFORM SUPPORT

To obtain a subgrade that provides uniform support, the four major causes of non-uniformity must be addressed:

- Expansive soils.
- Frost-susceptible soils (frost heave).
- Pumping (from erodible layers underneath the pavement slabs).
- Wet soils.

Effective control of expansive soils and frost heave is most economically achieved through appropriate subgrade preparation techniques; the inclusion of thick subbase layers in an attempt to control expansive soils and frost heave is expensive and not as effective as proper subgrade preparation. In cases where the potential for pumping exists, a subbase layer is always required.

Where subgrade conditions are not reasonably uniform, correction is most economically and effectively achieved by proper subgrade preparation techniques, such as selective grading, cross-hauling, mixing at soil-type and cut/fill transitions, and moisture-density control of subgrade compaction. No matter which techniques are applied, particular attention is necessary to control expansive soils and excessive differential frost heave.

A subbase layer also helps provide uniform support, but its primary purpose is to prevent pumping or erosion of the subgrade. Whether or not a subbase is used in a concrete pavement structure, proper subgrade preparation is the best means of obtaining uniform support.

Selection of an appropriate means to mitigate expansive soils, frost-susceptible soils and pumping is heavily dependent on the in-situ subgrade soil conditions, extent of improvement necessary, environmental concerns and construction requirements [MNDOT 2003]. Of particular concern, due to its difficulty to estimate prior to construction, is in-situ moisture content of the soil. If wet soils are encountered during construction, mitigation methods might not be as effective as planned.

The following sections provide detailed explanations of the design and construction issues regarding expansive soils, frost-susceptible soils and wet soils; pumping is addressed in Chapter 4.

Expansive Soils

Expansive soils change volume with changes in moisture content. Expansive soils that may swell enough to cause pavement problems are generally clays falling into the AASHTO A-6 or A-7 groups, or classified as CH, MH, or OH by the Unified Classification System, and with a Plasticity Index greater than about 25 by ASTM D4318. Knowledge of the volume-change potential of soils and the resulting effects on pavement performance has been gained through experience and research. Simple tests provide indices that serve as useful guides to identify approximate volume-change potential of soils (Snethen 1984; Wisemen, Komornik, Greenstein 1985). For example, Table 5 shows the approximate relationships.

It should be noted that the percent expansion data listed in Table 5 represent the change from a dry to a saturated condition. In reality, much less expansion would occur because these extreme moisture variation would not take place and the subgrade will have been compacted to the appropriate density.

Experience shows that the volume changes of clays with a medium or low degree of expansion (Plasticity Index below 25) are not a significant concern for concrete pavements, especially if selective grading operations such as cross-hauling and blending of soil types minimize or eliminate abrupt changes in soil character along the alignment.

However, experience also shows that uncontrolled shrinking and swelling of expansive soils can lead to increased stresses in a concrete pavement due

Table 5. Relation of Soil Index Properties and Probable Volume Changes for Highly Plastic Soils (after Earth Manual 1985)

Data from Index Tests[1]			Estimation of probable expansion,[2] percent total volume change (dry to saturated condition)	Degree of expansion
Colloid content (percent minus 0.00004 in. (0.001 mm)) (ASTM D422)	Plasticity Index (ASTM D4318)	Shrinkage limit percent (ASTM D427)		
> 28	> 35	< 11	> 30	Very high
20 – 31	24 – 41	7 – 12	20 – 30	High
13 – 23	15 – 28	10 – 16	10 – 20	Medium
< 15	< 08	> 15	< 10	Low

[1] All three index tests should be considered in estimating expansive properties.

[2] Based on a vertical loading of 1.0 psi (0.007 MPa). For higher loadings the amount of expansion is reduced, depending on the load and on the clay characteristics.

to non-uniform support, which accelerates pavement degradation and negatively impacts pavement smoothness. Although changes in soil moisture content are inevitable over the life of a pavement, expansive soils can be effectively addressed through selective grading operations or chemical modification (stabilization).

Construction factors that can further aggravate performance issues related to expansive soils include:

- Compacting expansive soils while too dry, resulting in the likelihood that the soil will absorb moisture and expand after preparing the subgrade.
- Placing a pavement on a subgrade with widely varying moisture contents, allowing differential volume change of the soil to take place along the road's alignment.
- Creating non-uniform support by ignoring abrupt changes between soil types with different capacities for volume change along the road's alignment.

Certain expansion test procedures such as ASTM D4546, ASTM D4829, Caltrans Test Method No. 3548 (CALTRANS 1978) and soil suction tests (AASHTO T273 or ASTM D3152) are especially suitable for evaluating the volume change of subgrade soils. Some of the important factors determined by these tests, which are not indicated by simple index tests, are:

- The effects of compaction, moisture and density on soil swell characteristics.
- The effect of surcharge loads.
- The expansion for the total sample gradation rather than only for a finer gradation fraction of the soil.

The volume change that may occur with a potentially expansive soil depends upon several factors:

- *Climate* — the degree of moisture variation that will take place in the subgrade throughout the year or from year to year. It is generally true that a pavement will protect the grade to some degree and reduce the degree of moisture variation in an underlying subgrade as long as the soil is not capable of drawing moisture from below through capillary action.
- *Surcharge* — the effect of the weight of the soil, subbase, and pavement above the expansive soil; tests indicate that soil swell can be reduced by surcharge loads (Holtz and Gibbs 1956).
- Moisture and density conditions of the expansive soil at the time of paving.

Knowledge of the interrelationship of these factors leads to the selection of economical and effective control methods.

Compaction and Moisture Control of Expansive Soils

To reduce volume changes of highly expansive soils, it is critical to compact them at 1 to 3 percent above optimum moisture content (AASHTO T99). Research has shown that compacting expansive soils at moisture contents exceeding AASHTO T99 optimum will produce a subgrade that absorbs less water, provides slightly higher strength, and will not expand or swell as much as if the soils that are compacted dry of optimum moisture at the time of preparation (Dubose 1952; Felt 1953; Holtz 1959; Parcher and Lie 1965; McDowell 1959).

Figure 16 shows the strong influence of compaction moisture and density on volume change. Lower compactive efforts (lower dry densities) will result in considerably less expansion, but this is not recommended in practice. At lower compactive efforts there may be practical difficulties in achieving a reasonably uniform degree of compaction and there is a high risk of secondary compaction of the subgrade once the pavement structure is placed onto it. Consequently, a properly compacted subgrade is best achieved by increasing the moisture content and compactive efforts near that of AASHTO T99.

It is also important not to assume that higher degrees of compaction produce a better subgrade when dealing with fine, expansive soils. The U.S. Army Corps of Engineers and various other agencies use a modified moisture-density test, AASHTO T180, which was developed to represent a higher degree of com-

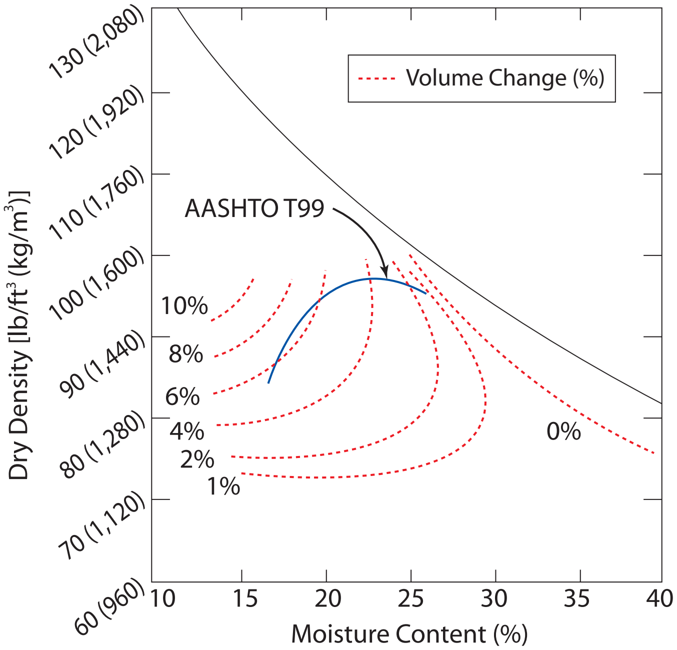


Figure 16. Volume changes for different compaction conditions.

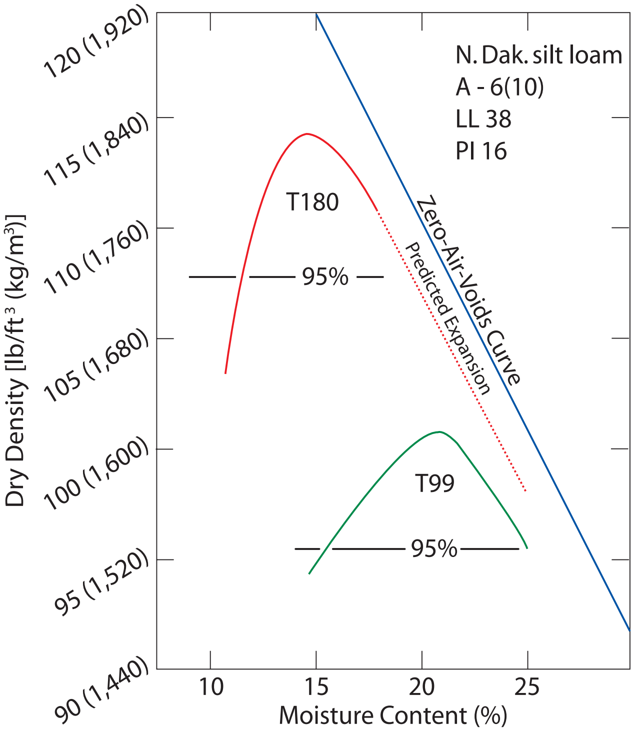


Figure 17. Moisture-density relationships (AASHTO T99 and T180) for an expansive A-6 soil.

paction than the AASHTO T99. The test was created for dense-graded unstabilized granular subbases and it results in higher densities and lower optimum moisture contents than the standard test method, AASHTO T99. It is also used for subgrade soils with low plasticity indices and, while it is acceptable for these purposes, the test's higher compactive effort results in moisture contents that are too low for expansive soils. In addition, these higher compactive efforts are not necessary for subgrades and subbases beneath concrete pavements because uniform support is more important than support strength.

To better illustrate the difference between the AASHTO T99 and T180 test methods, consider Figure 17. To obtain the maximum density of approximately 114 lb/ft³ (1,830 kg/m³) for the AASHTO T180 test, the moisture content during compaction must be slightly less than 15 percent. If the moisture content of the soil is then increased to 25 percent due to a rise in the water table, the predicted density of the soil is approximately 98 lb/ft³ (1,570 kg/m³), a decrease of over 14 percent. For the AASHTO T99 test, however, the change from the maximum density of 101 lb/ft³ (1,620 kg/m³) at a moisture content of 21 percent to 95.5 lb/ft³ (1,530 kg/m³) at 25 percent is only a 5.5 percent decrease. Any decrease in density will drive towards a proportionate increase in volume; thus, the compaction of an expansive soil at the lower optimum moisture content (as required in AASHTO T180) results in excessive swell. Furthermore, proper compaction at the optimum moisture content of AASHTO T180 requires more compactive effort.

To illustrate the effect of moisture content on soil swell, Figure 18 shows that, when compared to the high expansion obtained when compacted dry of AASHTO T180 with the extra compaction effort, the expansion for an A-6 soil is reduced when it is compacted slightly wet of AASHTO T99 optimum. The research results also show that, for soil compacted wet of AASHTO T99, greater strengths and lower moisture absorptions prevail after soaking.

Field experience also shows the best compaction moisture content to use with expansive soils (Felt 1953 and McDonald 1986). Objectionable distortions have not occurred in pavements placed on uniform plastic soils with moisture contents near the plastic limit (slightly greater that AASHTO T99 optimum).

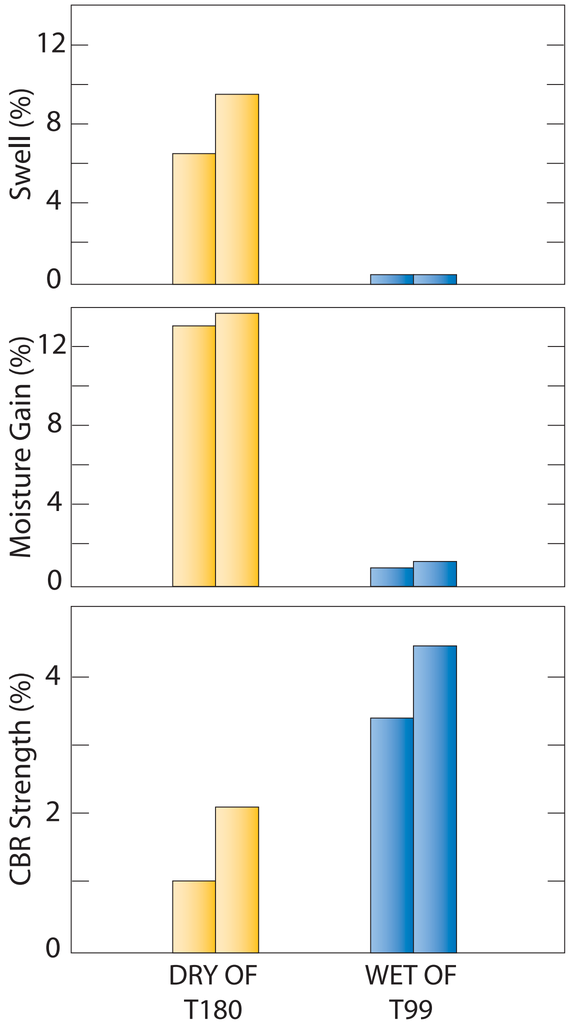


Figure 18. Strength, moisture gain and swell of soil compacted dry of AASHTO T180 and wet of AASHTO T99 optimum moistures.

On the other hand, pavement distortion has occurred for pavements placed on expansive subgrade soils of lower moisture contents. Experience also demonstrates that subgrade soils compacted slightly wet offer greater resistance to water gain by absorption or water loss by evaporation than do soils compacted under any other condition.

After pavements are placed in service, most subgrades attain a moisture content approaching their plastic limit, which is slightly above the standard optimum. When this moisture content is obtained during construction, swelling from any subsequent changes in moisture will be less, and the subgrade will retain the reasonably uniform stability necessary for excellent pavement performance.

If an expansive soil subgrade is prepared and compacted properly, but significant time passes before placing the subbase layer or pavement, the soil may dry out. Therefore, the soil should be retested just prior to subbase placement or paving and, if necessary, recompacted at the recommended moisture content (above optimum). The depth of subgrade needing reprocessing can be determined from field moisture tests.

There is an additional consideration for embankments of considerable height. Because of the overburden (mass) of the embankment, soil layers lower in the embankment do not require the same compaction as soils near the surface. The optimum compaction moisture content can be increased from slightly below optimum in the lower part of the embankment to above optimum in the top 1 to 3 ft (0.3 to 1.0 m).

Selective Grading

If expansive soils are not the predominant soil type along the roadway alignment, selective grading is typically the most cost-effective method of treatment. Selective grading operations also may be adequate for controlling the shrink and swell potential when the profile grade can be designed to keep expansive soils out of the top of the subgrade. Tests indicate that soil swell is reduced by surcharge loads (Holtz and Gibbs 1956). Field measurements show that excessive swell at depths of 1 to 2 ft (0.3 to 0.6 m) gradually decreases to a negligible amount at depths of 15 ft (5 m) or more. Thus, excessive swell can be controlled by placing more expansive soils in the lower parts of embankments. Cross-hauling or selective grading operations that effectively blend or mix soil types, resulting in less expansive soils being placed in the upper part of the subgrade, can provide reasonably uniform conditions that will minimize the volume change of expansive soils. Likewise, these operations should also be used at cut-fill transitions to eliminate abrupt changes in soil type.

In deep-cut sections of highly expansive soils, considerable expansion may occur due to the removal of the natural surcharge loads and the subsequent absorption of additional moisture. Since this expansion takes place slowly, it is essential to excavate these deep cuts well in advance of other grading work, whenever possible. When the excavation and embankment operations do not lend themselves to this early excavation, these sections should be chemically modified to control shrink and swell.

Many projects no longer lend themselves to selective grading operations due to project phasing and scheduling requirements. However, selective grading is usually more economical than chemical modification. Therefore, engineers are encouraged to evaluate the soil conditions along the project alignment carefully before choosing which method to select. Selective grading is an excellent technique for controlling the volume change of expansive soils for isolated pockets of these materials that occur on a project.

Chemical Modification

When the subgrade soils consist primarily of expansive clays and it is not economical to import non-expansive soils, chemical modification is the preferred technique. Soils can be modified with lime, portland cement, cement kiln dust (CKD), Class C fly ash or Class F fly ash in conjunction with lime. Modification provides a positive means to control the shrink-swell potential of a soil. In addition, modified subgrade soils provide an ideal working platform, and the time savings associated with subgrade modification can prove to be more economical than selective grading operations.

Each of the common stabilization materials provides a chemical and/or a physical mechanism that alters the properties of a soil. A significant contributor to the stabilizing effect of the materials is calcium. Stabilization materials react with expansive clay in two ways (Bhatty, Bhattacharja, Todres 1996; FHWA 2003):

- *Ion Exchange Stabilization (chemical mechanism)* — flocculation and agglomeration of clay particles results in granular particles with a lower PI and lower sensitivity to moisture fluctuation.
- *Pozzolanic Stabilization (physical mechanism)* — direct cementitious effects of bonding soil grains together.

Each of the materials used for subgrade modification that are described in this document (lime, portland cement, CKD, Class C fly ash and Class F fly ash with lime) react with clay materials in both ways, but to different degrees. The chemical composition of the modifying material and the characteristics of the soil determine which type of reaction is the primary stabilizing mechanism. In general, lime, CKD, and Class F fly ash modification rely primarily on ion exchange, while Class C fly ash modification occurs primarily through a pozzolanic reaction. Stabilization of clay soils with portland cement is a combination of both reaction types. Class F fly ash is not self-cementing, so it requires lime as an activator; together, Class F fly ash and lime create a cementitious product through a pozzolanic reaction (ACAA 2006).

■ *Material Selection and Dosage Rates*

Lab tests should be performed to determine appropriate dosage rates for each modifying material that is being considered. Suggested lab procedures for each material are shown in Table 6.

Table 6. Common Lab Procedures for Evaluation of Soil Modification

Modifying Material	Atterberg Limits (PI) (ASTM D4318)	Expansion Index of Soils (ASTM D4829)	CBR (ASTM D1883)	Unconfined Compressive Strength (UCS) (ASTM D1633)
Lime	✓	✓	✓	✓
Portland Cement	✓	✓	✓	✓
Cement Kiln Dust	✓	✓	✓	✓
Class C Fly Ash	✓	✓	✓	✓
Class F Fly Ash with Lime	✓	✓	✓	✓

Any of the modifying materials can be used for controlling the volume change of expansive soils. However, the effectiveness of each modifying material is a function of the soil properties and the dosage rate. Soil modification material selection should be based upon lab test results and economic factors. For example, lab test results of ASTM D4318 may show that 4 percent lime modification will reduce the PI of a soil to 10 and that 16 percent fly ash modification will reduce the expansion index to 30 when tested in accordance with ASTM D4829. Based on these results, a comparison between the estimated costs of the lime and the fly ash material can be made to determine which material is most cost effective. In cases where the material costs for each alternative are similar, one can assume that construction costs for lime modified subgrade will be slightly higher than the other materials because the lime-soil mixture must be manipulated twice (see Figure 19).

This document is not intended to define appropriate dosage rates for soil modification materials. These decisions are project/soil specific and should be based on lab testing procedures using soil samples that are anticipated to be found in the upper layers of the subgrade. A geotechnical engineer should provide guidance on the material dosage rate that will adequately control the volume change of an expansive subgrade soil. Reference documents published by cement, lime, and fly ash industry organizations often include normal ranges for dosage rates. These suggested dosage ranges should not be used in lieu of lab testing of the soil to be modified. For most soil types, more than one type of modifying material will adequately control the volume change. Thus, the cost of each available material at the lab tested dosage rate should be estimated and compared to optimize the design.

NOTE: *Modifying sulfate bearing soils with any of the above materials can result in a detrimental volume change of the soil. Soils with sulfate levels above 0.3 percent may react with the calcium in the modifying materials (NLA 2000). Consult with a geotechnical engineer for projects that may potentially have soils containing sulfate.*

■ *Constructing Modified/Stabilized Subgrades*

The process for constructing a lime-modified subgrade is slightly different than for portland cement, CKD and fly ash modified subgrades. Lime requires a mellowing period to react with the soil. In contrast, the cementitious materials must be completely incorporated into the natural soil and fully compacted as quickly as is reasonable to take full advantage of the pozzolanic reaction.

The pozzolanic reaction bonds soil particles together, which restricts their potential to change volume. Disturbing the portland cement, CKD, Class C fly ash or Class F fly ash with lime and soil mixture after the soil particles have bonded together essentially breaks those bonds and decreases the modifying material's capability to control the expansive soil. A requirement that the modified soil mixture be fully compacted within 1 hour of the soil-water-fly ash mixing process is common in specifications for Class C fly ash subgrade modification. While portland cement, CKD and Class F fly ash with lime do not react as quickly as Class C fly ash, it is advisable that a compaction requirement time of not more than 2 hours be applied to these stabilized materials. Details of the subgrade preparation process, with special considerations and steps for chemical modification, are shown in Figure 19.

Special Methods for Controlling Expansive Soils

Where the potential exists for extreme soil volume changes, several special treatments have been used with success. These include ponding (pre-swelling), membrane encapsulation, horizontal geomembranes, and vertical moisture barriers (Gordon and Waters 1984; Luttrell and Reeves 1984; Picornell and Lytton 1987 and 1989; Ramaswamy and Aziz 1987; Reed 1987; Snethen 1979; Steinberg 1981; Watt and Steinberg 1972; Weston 1980). Electro-osmotic chemical stabilization and pressure injection of chemicals have also been used, with mixed results (TRB 1990, Petry and Armstrong 1989). Information on these specialized treatments is beyond the scope of this publication; details of the techniques are given in the cited references.

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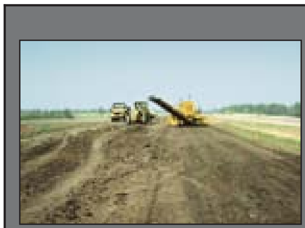


Initial Trimming

Mixing Untreated Subgrade

Spreading Materials

Mixing in Modifying Agent

Compacting

Finish Trimming

Steps/Description

Unstabilized Subgrades

Initial Grading, Compaction, and Finish Grading

Grade the subgrade soil to the line and grade required by the roadway plans. Cross haul materials to avoid abrupt changes in subgrade character. Compact the subgrade soil, adding water, as needed to achieve the optimum moisture content for compaction (density).

Identify excessively soft spots and then, either undercut and replace the soils, or pre-treat with a stabilizing agent. Compact the subgrade again in areas where soft pockets are replaced with improved fill.

Protect the subgrade from rain by “tight blading” and finishing with a smooth drum roller.

Fine grade the subgrade to the shape of the typical section and to plan elevation within grade tolerance. Finish grading operations, which may take place anytime after final compaction occurs.

Chemically Stabilized Subgrades

Initial Grading and Compaction

Trim the subgrade. Finish the grade below the final grade elevation to allow for the increased volume from addition of the subgrade modifying material. Consider the density of the untreated subgrade and the volume of stabilizing material when estimating how far below finish grade to be after the initial shaping. Failure to leave the grade low after initial shaping will result in a modified subgrade layer that is thinner than designed, because it will need to be trimmed more during finish grading operations to meet grade elevation tolerances.

Spreading and Mixing Modifying/Stabilizing Materials and Compacting

Spread stabilizing agent as evenly as possible. Uniform spreading is vital to uniformly controlling the volume change of expansive soils and to achieving uniform support for the subbase and pavement layers. As dosage rates decrease, uniform spreading becomes even more critical with respect to constructing a consistent and uniform subgrade.

For Soil Modification with Lime:

- Use either pebble quicklime spread in a dry state or hydrated lime, slaked and spread as a slurry. Regardless of which form is used, metering the application from the equipment is preferable.
- Mix and add water simultaneously to ensure complete hydration of the lime before final mixing occurs. Target a moisture content from optimum to optimum plus 5 percent.
- Lightly compact the modified soil and grade to drain excess water.
- Let the stabilized soil sit idle for a 24 to 72 hour mellowing period.
- Re-mix the grade, adding water as necessary and recompacting. Target a moisture content of optimum plus 3 percent.
- When prepared properly, a minimum of 60% of the modified soil mixture should pass a #4 (4.75 mm) sieve.

For Soil Modification with Cement:

- Mix, add water, and compact the stabilized soil mixture in a continuous operation to assure that final compaction is achieved in 2 hours or less.
- Target a moisture content within 2 percent optimum.
- When prepared properly, a minimum of 60% of the modified soil mixture should pass a #4 (4.75 mm) sieve. Most modern equipment is capable of achieving this gradation requirement in one pass. If premixing is required, it should be done without the addition of water. The 2 hour working period begins when substantial water is added to the modified soil mixture during the final mixing operation.
- Matching of multiple longitudinal passes should be done carefully to avoid excessive overlap between passes. Areas that are mixed twice are subject to breaking the soil particle bonds and to addition of water twice, which can lead to non-uniform results.
- Attempts to further compact soils after the 2 hour time frame can be detrimental to the strength (capacity to control volume change) of the modified soil mixture. Strict adherence to the 2 hour working period should take precedence over strict adherence to density requirements.

Finish Grading

The final thickness of the modified subgrade layer which impacts uniform support of the subbase and pavement is dependent upon the accuracy of initial shaping of the subgrade and the finish grading operations.

Maintain moisture in the modified subgrade before, during and after (until subbase/pavement is placed up to 7 days) finish grading operations.

Curing

In lieu of continuous sprinkling, a bituminous prime coat may be placed to as a curing coat to maintain the moisture in the modified subgrade until succeeding layers are constructed.

Figure 19. Construction processes for subgrades, with special considerations for lime and cement modified soils.

Frost Action

Frost action is a phenomenon that occurs in the winter and early spring in northern climates. Practically all surface soils undergo some frost action, the magnitude of which is dependent upon the locally prevailing climate and precipitation. Frost action divides into two phases: 1) freezing of the soil water and 2) thawing of the soil water. For pavements, frost action becomes critical when either:

- The freezing phase is accompanied by noticeable heaving of the road surface, or
- The thawing phase is accompanied by a noticeable softening of the roadbed.

It is important to understand that the design considerations for controlling frost heave are not necessarily identical to those for controlling subgrade softening. For example, a soil with high frost-heave potential will not necessarily exhibit the maximum degree of subgrade softening. Even though both mechanisms are typically present in frost-susceptible soils, it is important to recognize how their affects on the performance of concrete pavements differ. Field experience with concrete pavements has shown that frost action damage due to frost heave, in the form of abrupt differential heave, has affected performance more than subgrade softening. A typical crack from frost heaving is shown in Figure 20.

Subgrade softening due to frost action is not a primary concern for subgrade design because uniform support from a subgrade is more important than its strength. However, subgrade softening can aggravate pumping in pavements that are constructed without adequately addressing pumping potential. In short, subgrade softening due to frost action is not a concern if the pavement has been designed to prevent pumping.

Figure 20. Common edge-to-edge crack attributable to differential frost heaving.

Frost design for concrete pavements is concerned with providing uniform subgrade conditions. This is achieved by eliminating the moisture conditions that lead to objectionable differential frost heave:

- Where subgrade soils vary abruptly from non-frost-susceptible sands to highly frost-susceptible silts.
- At cut-fill transitions or at silt pockets.
- Where ground-water is close to the surface.
- Where water-bearing strata are encountered.

Frost Heave

Heaving of the road from frost action is termed “frost heave.” Frost heave, particularly when in isolated areas, induces uneven support of a pavement. When heavy loads pass over the area of uneven support, a crack may form in the pavement surface layer.

There are at least three conditions that must exist before frost heaving can occur. They are:

1. A sufficiently cold climate to allow freezing temperatures to penetrate below the road surface and into the subbase and subgrade.
2. A supply of water from below, above and/or laterally into the freezing zone.
3. A soil material that is frost susceptible and is lying within the freezing zone.

The areas of the United States most susceptible to frost heave are those identified as wet-freeze (WF) in Figure 21, because two of the three conditions listed above (cold climate and supply of water) are common during the winter in these areas.

It should be noted that, because a supply of water is required for frost heave to occur, frost heaving is not generally a concern if the water table is more than 10 ft (3 m) below the surface of the pavement structure.

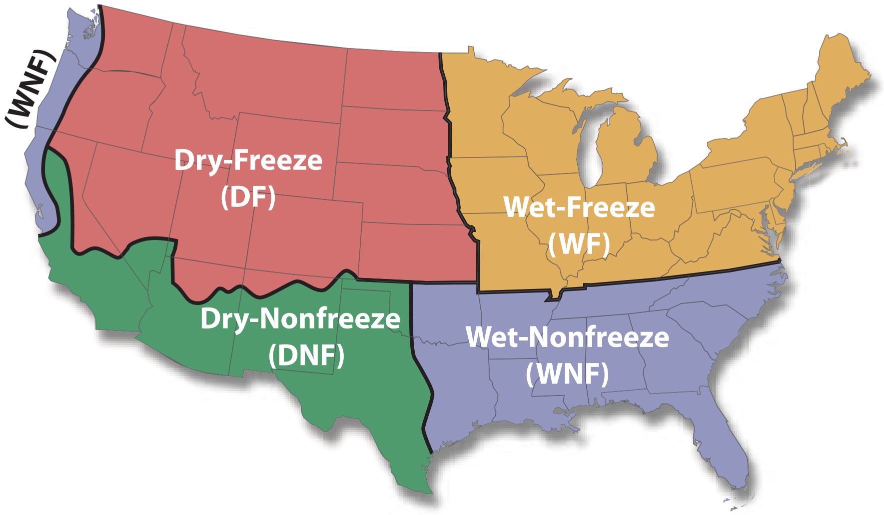


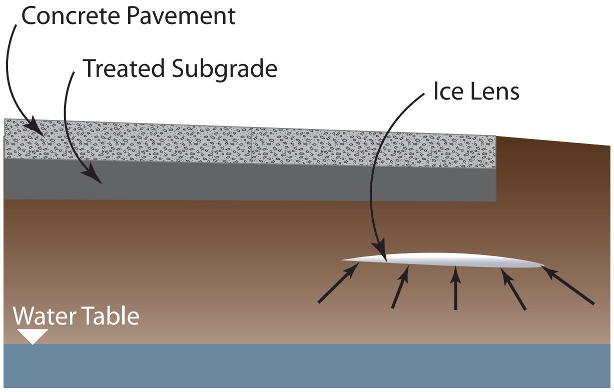
Figure 21. Four climatic zones as identified in the Long-Term Pavement Performance program (NCHRP 2004).

Heaving is caused by the formation of ice lenses in the soil below the pavement (Figure 22). Water expands 9 percent by volume when frozen. When freezing temperatures penetrate a subgrade soil, water from the unfrozen portion of the subgrade is attracted to the frozen zone. If the soil is susceptible to capillary action, the water migrates to previously formed ice crystals and freezes.

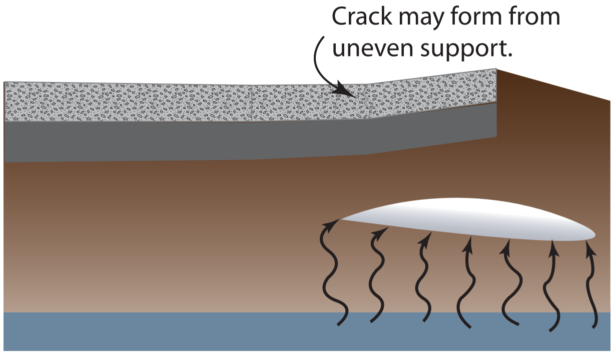
The size of the ice lens depends upon the quantity of free water available within the soil and from the water table, and time. When the soil freezes, the free water freezes and expands. Once started, ice lenses continue to grow as long as a source of free water is available. Free water migrates through the soil to a forming ice lens by capillary action. This migration of water can be as far as 30 ft (9 m) for certain frost-susceptible soils. If the rate of frost penetration into the subgrade is slow, thicker ice lenses will be developed because there is more time for water to migrate from the unfrozen zone before all the free water in the subgrade freezes.

Eliminating the supply of water to the soil below the pavement is virtually impossible. However, good drainage can partially reduce the quantity of water available to feed an ice lens and cause frost heave. Much of this supply of water from below can be cut off with combinations of sand blankets and tile drains.

Some soils are more susceptible to the formation of ice lenses than others. Silts or silty clay soils (AASHTO groups A-4 and A-6 or Unified Classification ML and MH) are considered among the most susceptible to ice lens formation (NMDOT 2006, ASTM M145). Silts encourage the flow of water by capillary action through its pores because the pore size distribution is small enough to drive capillary action but large enough to allow the migration of pore water. Consequently, silts supply the water necessary to promote the formation of ice lenses in



(a) Ice lens begins to form from free moisture in the soil.



(b) Ice lens grows as it is fed from water by capillary movement through frost-susceptible soil causing the pavement to heave and sometimes crack.

Figure 22. Formation of an ice lens, causing frost heave.

the freezing zone. Other soils considered frost-susceptible will also promote formation of ice lenses.

Frost heave is most often found at the following locations:

- Transitions from cut to fill.
- Where ditches are inadequate or non-existent.
- Over culvert pipes.
- Adjacent to driveways that dam roadside ditches and/or collect water.
- Where there is an abrupt change in subgrade material.

Not all frost heaving is detrimental to a pavement. Uniform heaving will likely not be noticeable to the eye or to vehicle passengers. If uniform heaving occurs, there are no bumps or rolls in the pavement surface and, therefore, uniform heaving does not present a maintenance problem. Heaving is destructive and troublesome only during the freezing or frozen phase, when it varies sharply, causing uneven support to the pavement.

To prevent frost heave, highly susceptible soils should be replaced or stabilized. Susceptible areas should be drained with tile drains and/or ditches should be kept clean and free of clutter that prevents flow of water away from the pavement.

Frost-Susceptible Soils

Criteria and soil classifications for identifying frost-susceptible soils usually reflect susceptibility to softening on thaw as well as to heaving (Army 1985, ASCE 1984, Chamberlain 1981, and TRB 1953 and 1974). For a concrete pavement, the major concern is to reduce heaving; control of spring softening is not as much of a consideration. Thus, differentiation should be made in classifications between soils susceptible to heave and those susceptible to thaw softening.

There is a wide diversity in frost susceptibility determination methods; almost all of the methods are unique for individual state, provincial, and federal agencies. Most of the methods are based on soil particle size determination, and several have criteria similar to that of Casagrande (1931) — more than 3% smaller than 0.8 mils (0.02 mm) in non-uniformly graded soils. However, these methods seldom differentiate between frost heave and thaw softening. One method that differentiates the two factors is the freeze-thaw test of the U.S. Army Corps of Engineers (Chamberlain 1987), but the test and equipment are not simple.

In general, the degree of frost susceptibility can be explained by two hydraulic properties of soils:

- *Capillarity* — the soil's ability to pull moisture by capillary forces. The smaller the pore size distribution of a pore network, the greater the driving force (capillary action) and the greater the capillarity.
- *Permeability* — the soil's ability to transmit water through its voids. The permeability of any material is heavily dependent on the connectivity of its pore network. For example, if a material contains many tortuous pores that abruptly end, it will have less permeability than a material with very open pores that pass completely and directly through the material. The more connected and the larger the pore network is, the greater the permeability.

The relation of these properties to frost susceptibility is visualized in Figure 23. Heavy clays have a very

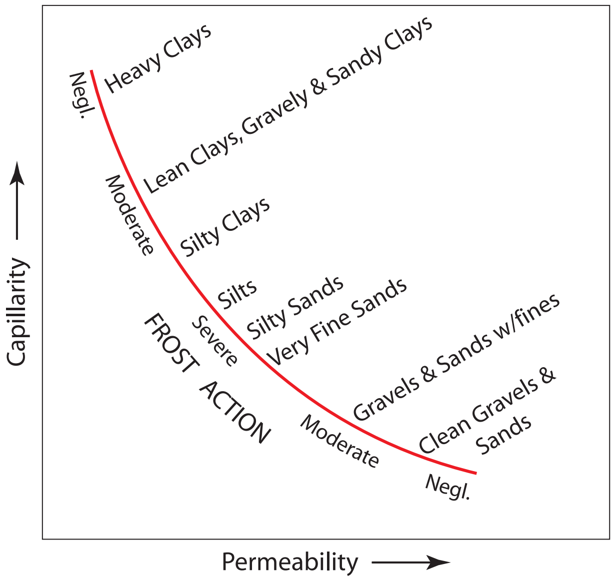


Figure 23. The relationship between frost action and hydraulic properties of soils.

high capillarity but they are practically impermeable. Thus, heavy clays will not allow enough water to be transported to the ice lense for excessive heaving to occur (Fredrickson). Gravels and sands, however, have a very high permeability, allowing water to be easily transported through their pore network, but they lack a pore distribution conducive of capillary action, so they cannot lift enough moisture for heaving to occur. When a right combination of capillarity and permeability occur in a soil, such as with silty materials, severe frost heaving may occur.

Low-plasticity, fine-grained soils with a high percentage of silt-size particles (in the range of 0.02 to 2 mils (0.0005 to 0.05 mm)) are particularly susceptible to frost heave. Other soils considered frost-susceptible include loams, sandy loams, clayey loams, fine sands, clayey gravel, and rock flour. Moderately frost-susceptible soils include dirty sands and gravels and glacial tills. The only soils that can be considered to be non-frost-susceptible are very clean mixtures of sand and gravel.

Spring Subgrade Softening

Except in permafrost regions, a frozen subgrade thaws both from the surface downward and from the bottom upward. As a result, thawing is usually more rapid than freezing. When thawing begins, the moisture content of the subgrade may be high due to the previous moisture increase during freezing and surface water infiltration. This water in the upper thawed layer cannot drain downward because of the frozen zone below. In addition, expansion due to heaving has caused a temporary loss in density. Under these conditions, there is a sharp reduction in subgrade support during the thaw period. Studies by the Material Committee of the Highway Research Board show that the period of greatest strength loss is brief — usually two to three weeks — followed by a period of recovery after thawing is completed and the subgrade material is recompacted. Figure 24 shows a typical increase of subgrade strength on freezing and loss of subgrade strength on thawing over the course of a year.

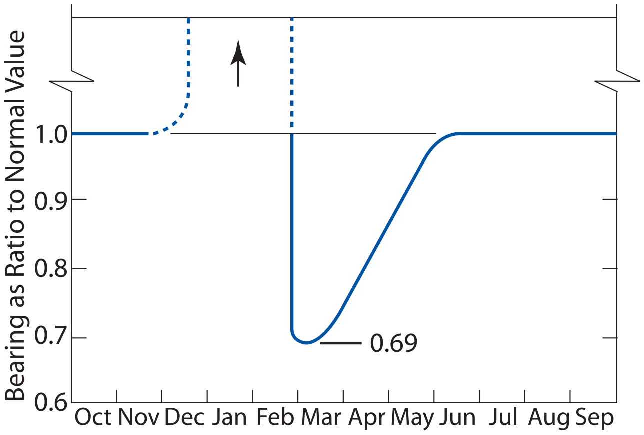


Figure 24. Typical loss in bearing value on thaw.

The period of reduced subgrade support that accompanies thawing has little effect on concrete pavements. This is because concrete reduces pressures to safe limits by distributing loads over large areas and because concrete pavements are designed for fatigue stresses due to load repetitions. Fatigue effects during the period of reduced subgrade strength are offset by reduced fatigue during the longer period that the subgrade is frozen and offers very high support.

Concrete pavements designed on the basis of normal weather subgrade strengths have ample reserve capacity for the periods of reduced support during spring thaw. Tests on concrete airfield and highway pavements in frost areas show maximum reductions in subgrade support of 25 to 45 percent during spring thaw periods (PCA 1975). When these reduced values are used in design analyses, the results show that additional pavement thickness is not required. Because of their inherent load carrying capacity and ability to distribute loads over larger areas, concrete pavements are exempted from load restriction during periods of spring thaw, unlike many asphalt pavements.

Field experience and design analyses verify that subgrade softening is not a factor in design considerations for the control of frost action for concrete pavements. Instead, it is the abrupt, differential frost heave that must be controlled.

Control of Frost Heave

The performance of older concrete pavements in frost-susceptible areas under today's increasingly heavy traffic shows that extensive, costly controls are not necessary to prevent frost damage. Surveys of these pavements indicate that control is needed only to reduce excessive heave and, more critically, to prevent differential heave by achieving reasonably uniform subgrade conditions. As in the case of expansive soils, a large degree of frost heave control is attained most economically by appropriate grading operations and by controlling subgrade compaction and moisture.

Grade and Water Table Elevation

The most fundamental design aspect of controlling frost heave potential is to set the grade lines high enough and construct side ditches deep enough so that highly frost-susceptible soils are always above the capillary range of groundwater tables. If possible, where groundwater is near the surface, the grade should be kept 4 or 5 ft (1.2 or 1.5 m) above the ditch bottom in cut sections and natural ground in fills (embankment sections). Since elevation of the grade is not typically possible for streets and roadways, as it is with highways, other frost heave mitigation techniques should be considered for these applications.

Selective Grading and Mixing

Selective grading operations are beneficial to place highly frost-susceptible soils in the lower portions of embankments, and to cross-haul less frost-susceptible soils form the lower portion of the subgrade towards the top. Cross-hauling and mixing are also useful at cut-full transitions to correct abrupt changes in soil character and type. Where soils vary widely or frequently in character, mixing them is effective in preventing differential frost heave. Figure 25 illustrates a typical cut-fill section; the transition section is removed and mixed with the fill section only to promote uniformity of the finished subgrade surface.

With modern construction equipment, the mixing of non-uniform soils to form a uniform subgrade is often more economical than importing select materials from borrow pits. Chemical modification will also impart some benefit towards the goal of uniformity of the subgrade, but it also is likely less economical than select grading and mixing.

Removal of Silt Pockets

When the grade includes only a few pockets of silt or other frost-susceptible soils, the best option is to excavate and backfill these pockets with soils similar to the surrounding subgrade. To ensure that a condition of uniform support will be created for the pavement, it will be important to compact the backfill materials to the same moisture and density conditions of those found in the adjacent soils. The replacement soil should be mixed with the surrounding soil to form a tapered transition zone at the edges of the pocket, just as in cut-fill transitions.

Compaction and Moisture Control

Once reasonable soil uniformity is created through grading operations, compaction at controlled moisture levels will further improve the subgrade. As previously discussed, subgrade uniformity can be obtained by compacting the subgrade materials slightly wet of the AASHTO T99 optimum moisture content. Treating most fine-grained soils in this

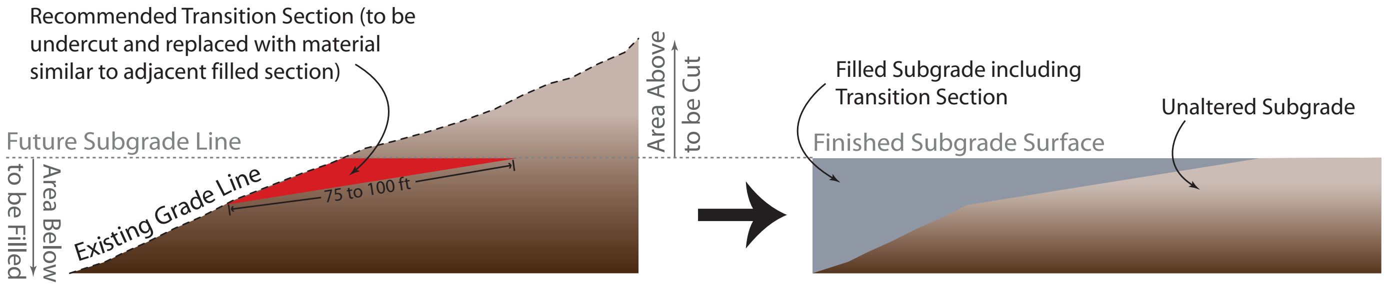


Figure 25. Tapered transition used when embankment material differs from the natural subgrade in the cut section.

manner substantially reduces soil permeability, which retards the rate of moisture flow to the frozen zone. Research confirms that less frost heave occurs when soils are compacted at higher moisture contents (Beskow 1947, Springenschmid 1965).

Furthermore, compaction at slightly wet of AASHTO T99 optimum moisture makes the subgrade less susceptible to nonuniform moisture changes (changes due to saturation and drying) at the pavement edges and joints.

Experience shows that, over time, subgrade moistures will naturally increase to slightly above optimum moisture for frost-susceptible soils in the climates where frost action is a problem. Resistance to frost heave is enhanced when subgrades are initially compacted at moisture contents above optimum, rather than when compacted dry and later saturated by natural forces.

■ Drainage

Where elevating the pavement grade is impractical, underdrains may be used to lower groundwater tables. The drains must be placed so that the groundwater level is lowered beyond the subgrade soil's capillary range since capillary water cannot be effectively drained.

Where wet spots are encountered in the grade, due to seepage through a permeable stratum underlain by an impervious material, intercepting drains may be considered.

The backfill placed around and above pipe underdrains should be open-graded to permit rapid flow into the slotted pipe. Underdrain trenches should be wrapped with a geotextile fabric to prevent infiltration and clogging by adjacent soils.

■ Protection for Utilities Located in the Subgrade

Placing a utility such as a culvert, drain or duct under a concrete pavement with a frost-susceptible subgrade can be problematic and should be avoided if possible. If, however, it is necessary to place a utility into the pavement structure then special consideration should be taken to protect the utility and the pavement structure above it.

Figure 26 shows several examples of frost heave protection methods for a culvert at various depths with respect to the frost line (boundary of the freezing zone). If a culvert is located above the freezing zone (cases a and b in Figure 26), measures should be taken to adequately isolate the culvert from the potential expansion of the surrounding frost-susceptible subgrade material. As the depth of a culvert increases with respect to the freezing zone, less protection is necessary. If a culvert is placed completely in the unfrozen zone, no isolation is necessary because all of the expansion of the frost-susceptible soil will occur above the culvert, in the frozen and freezing zones.

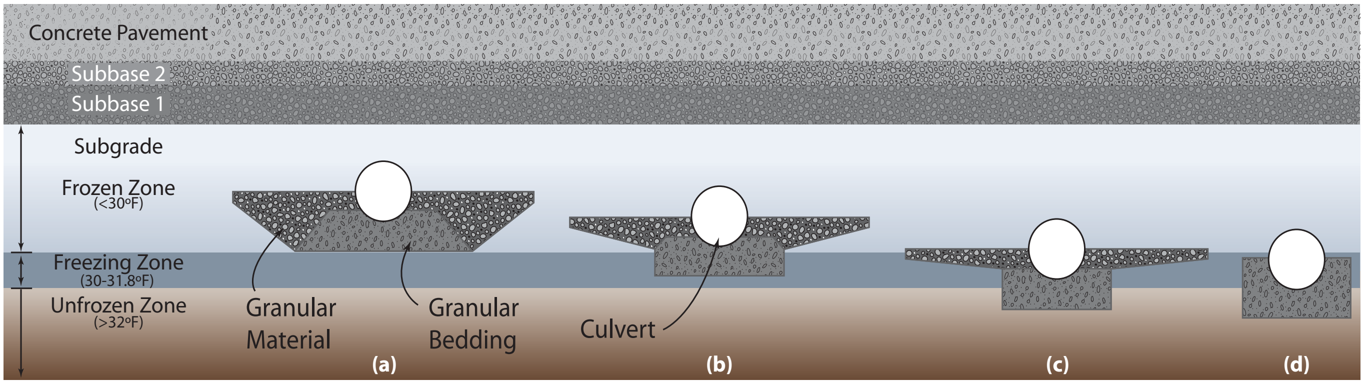


Figure 26. Freezing sequence in a typical pavement profile and example frost heave protection methods for culverts at various depths.

Non-Frost-Susceptible Cover

Layers of clean gravel and sand will reduce frost heave, but they are not required for this purpose if frost heave can be mitigated by proper grading operations.

When an unstabilized granular subbase layer is used to prevent pumping, it also provides some protection against frost action. However, that protection is minimal since coarse-grained soils permit somewhat deeper frost penetration than do fine-grained soils because of a difference in thermal properties due to the higher in-place moisture contents of the fine-grained soils.

An example of the effect of subbase thickness on frost heave for a road in Minnesota is shown in Figure 27 (Nowlen 1959). Although the amount of heave is not great, the data shows that it is not eliminated at subbase thickness up to 18 in. (460 mm). Subbase layers are more effective in preventing loss in subgrade support on thaw, which is not a primary design consideration for concrete pavements.

Proper grade design, selective grading and compaction control will produce uniform support and resistance to rapid moisture flow into the upper part of the subgrade. These are effective methods for preventing differential or excessive heaving. If a subbase layer is used, it is not necessary for it to be any thicker than the nominal thickness required to prevent pumping because it is not an effective means of preventing frost heave and should not be treated as such.

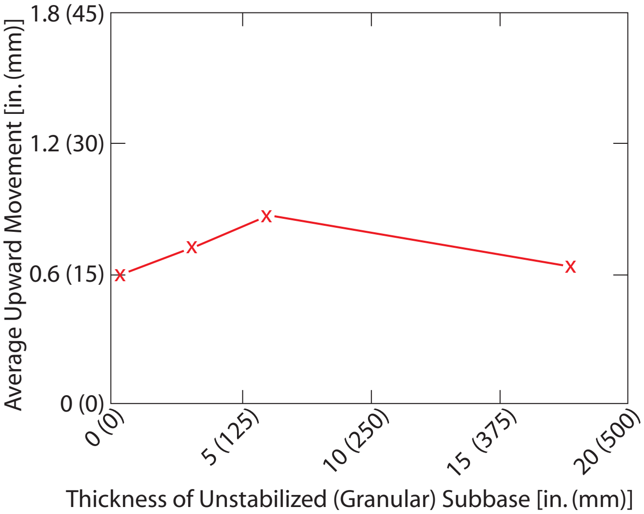


Figure 27. Effect of unstabilized (granular) subbase thickness on frost heave.

Wet Soils

Wet soils may be encountered during construction for reasons ranging from a naturally high water table to seasonal rainfall, and even changes in drainage conditions due to construction. Regardless of the cause, in-situ wet soils must be addressed before constructing a subbase or concrete pavement on the subgrade.

The simplest ways to mitigate problems due to wet soils are to construct drains before construction or to let the subgrade dry out prior to constructing a subbase or concrete pavement on the subgrade. However, construction scheduling and costs may make these solutions ineffective [Burak 2007]. Other procedures that may be used fall into three categories:

- Enhancement – A method of removing excessive moisture in wet soils by providing drainage via trenches or toe drains at the lowest point(s); compacting the subgrade using heavy equipment, which forces the excess moisture out of the subgrade due to high applied pressures; or adjusting the moisture content through chemical modification (soil stabilization). (See the section entitled *Chemical Modification* earlier in this chapter for more discussion on chemical modification.)
- Reinforcement/separation – A method of removing excessive moisture in wet soils by using geosynthetics. Geosynthetics are thin, pliable sheets of textile material of varying permeability. The varieties of geosynthetics include geotextiles, geogrids, geonets, geocells, and geomembranes. The usefulness and effectiveness of geosynthetics directly depends on the type of geosynthetic, the intended function (filtration, separation and/or reinforcement), in-situ soil conditions, and installation techniques.
- Substitution – A method of removing excessive moisture in wet soils is removing unsuitable,

unstable or excessively wet soils and replacing it with select borrow material or, alternatively, covering the wet soil with a suitable material to develop the necessary uniformity and stability. (See the sections entitled *Selective Grading* and *Selective Grading and Mixing* earlier in this chapter for more discussion on cross-hauling and selective grading.)

More detailed information regarding special consideration of wet soils is available elsewhere [MNDOT 2003].

SPECIAL CONSIDERATIONS OF THE SUBGRADE DURING RECONSTRUCTION DUE TO INTERSECTION REPLACEMENT, UTILITY CUTS OR INLAYS

A reasonably uniform subgrade, with no abrupt changes in support, is ideal for any concrete pavement. Achieving this condition after pavement removal operations will require some effort especially in the relatively confined work area of an intersection. The first step is to ensure that the subgrade soils are of uniform material and density.

Compacting the subgrade surface adequately requires a compactor heavy enough to achieve 95 percent of AASHTO T99 density, the same as with other pavement construction. However, it may be difficult to maneuver large compactors in a trench created by removing an older pavement for an intersection. A more effective strategy in a confined area may be to apply more compaction effort using smaller equipment. Because final trimming disturbs the subgrade surface slightly, additional compaction rolling is usually necessary after trimming.

The soil moisture content should be reasonably uniform during compaction; excessively wet or dry spots require correction to produce reasonable uniformity. For most soils, compaction should be done at moisture contents at or slightly above optimum, as previously discussed.

Soft spots in the subgrade often become visible after removing an old pavement. It is not acceptable to merely place a granular layer over these soft areas; excavation is necessary to remove the suspect soils. Ideally, the replacement soil should be of the same type as in the surrounding subgrade to develop uniform support.

Contractors must pay particular attention to sections of the subgrade overlying any utility installations such as sewers, telephone and power conduits and water lines. Careless compaction of fill materials in these trenches often causes soft spots in the subgrade. Controlled low-strength fill (flowable-fill) materials are an economical alternative for these areas.

Flowable-fill materials do not need compaction and flow easily to fill a trench. The mixtures contain portland cement, sand, fly ash and water and typically develop 28-day compressive strengths of about 50 to 100 psi (0.35 to 0.70 MPa). Flowable-fill materials provide enough strength to prevent settlement, but are easy to remove using a bucket on a backhoe or front-end loader if future excavation is necessary.

Chapter 4. Subbases

A subbase provides benefits to both design and construction. From the design perspective, the essential function of a subbase is to prevent pumping of fine-grained soils. From the construction perspective, the function of a subbase is to provide a stable working platform for construction equipment, which enables a contractor to provide a smoother pavement and achieve a more consistent pavement thickness than might be possible if constructing on just a subgrade.

Secondary benefits of subbases are that they aid in controlling volume changes for expansive or frost-susceptible subgrade soils, and they can reduce excessive differential frost heave. However, these factors can most likely be more economically and better controlled through proper subgrade preparation treatments. Subbases can also be used as a drainage layer; however, when doing this, the right balance of drainage and stability must be obtained.

PUMPING

Pumping is defined as the forceful displacement of a mixture of soil and water through slab joints, cracks and pavement edges. Continued, uncontrolled pumping eventually displaces enough soil so that uniformity of support is lost, leaving slab corners and ends unsupported. This non-uniform support condition often results in premature cracking at slab corners and pavement roughness, generally in the form of faulted transverse joints. In the worst case, loads deflect concrete slabs enough to pump water and fine soil particles through joints and onto the surface of the pavement, where visible stains become evident. Figures 28 and 29 show a pumping joint in action and the subsequent deposit of subbase/subgrade material onto the shoulder.

Figure 28. Photograph of pumping.

Figure 29. Stains on shoulders due to pumping.

Cooperative studies by state highway departments and the Portland Cement Association during the 1930's and 1940's first determined the basic factors necessary for pumping to occur. Further experience determined that all of the following conditions must be present:

- Fast moving, heavy loads to deflect the slabs (trucks, not automobiles).
- Undoweled joints or joints with poor load transfer.

- The presence of water between the pavement and the subgrade or subbase.
- A fine-grained subgrade or erodible subbase material.

Figure 30 illustrates the mechanics of pumping. First, a heavy-wheel load forces the leave-slab down as it approaches a joint or crack. When the wheel load crosses the joint or crack, the leave slab rebounds up quickly and the approach slab is forced down quickly, causing a rapid differential deflection at the joint or crack. This rapid differential deflection pushes water and soils from underneath the approach slab toward the leave slab and may expel the mixture of soil and water out from beneath the slabs. Eventually, after thousands of heavy load applications, a void may develop under the slabs, causing uneven, non-uniform support. The most common distresses resulting from this action are corner breaks and faulted joints (Figures 31 and 32).

The subgrade materials that are most prone to pumping are high-plasticity silts and clays. Unstabilized (granular) subbase materials prone to pumping are generally considered to be those with 15% or more fines passing the No. 200 (75 µm) sieve. Pumping can be mitigated by using a non-erodible or stabilized subbase. Unstabilized (granular) subbases meeting AASHTO M155 requirements will effectively prevent pumping in pavements carrying even the highest volumes of traffic, assuming that other design features are appropriately selected.

Regardless of subbase selection, experience has shown that the most influential design factor for preventing pumping is using dowelled transverse pavement joints. However, any step that can be taken to remove any one or more of the causal factors necessary for pumping is advisable. Using a properly graded subbase (unstabilized or stabilized) eliminates the fines in soil that will go into suspension, while using dowels eliminates the rapid differential deflection caused by frequent heavy wheel loads; this combination of mitigation strategies is the most

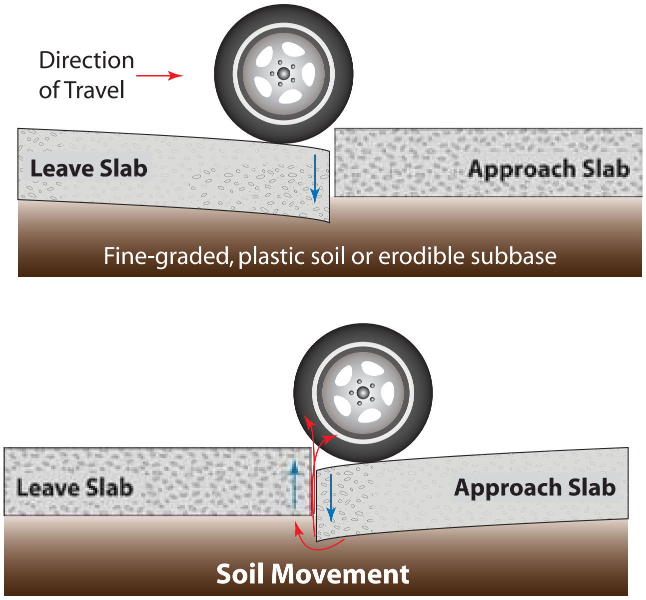


Figure 30. Mechanics of pumping.

Figure 31. Corner break from void under corner of concrete slab.

Figure 32. Faulted joint.

often used because it isolates the two causal factors that are the easiest and most reliable to address by choices in pavement design.

WHEN TO USE A SUBBASE

Engineered subbases are appropriate when a stable and uniform construction platform will benefit construction and/or when the combination of subgrade soil type, water availability, and high-speed, heavy vehicle traffic are at a level that is conducive to cause pumping and any associated distresses. Therefore, a subbase is a required element for concrete pavements designed for major, heavily-traveled pavements, particularly those carrying large numbers of trucks.

Pavements for slow-moving trucks or light-traffic pavements, such as residential streets, secondary roads, parking lots, and auto-only high-speed roadways, are not prone to the development of pumping. A subbase is not warranted for pumping protection in such applications because these facilities are not subject to the pavement deflection and rebound that high-speed, heavy wheel loads cause. Specifically, there are several exceptions to the advice on using a subbase to prevent pumping as presented earlier in this chapter:

- *Traffic** — A pavement expected to carry 200 trucks† per day or fewer generally does not require a subbase to prevent pumping. Also, pavements that are designed to carry less than 1,000,000 18-kip (80 kN) ESAL's over the course of their service life do not require subbases to prevent pumping damage.
- *Natural Drainage* — A subgrade soil that is naturally free draining typically will not pump because water percolates through the subgrade and does not remain under the pavement where it can transport fine materials in suspension. Pavements may be built directly on natural subgrade soils with this character as long as the soil is satisfactory in other critical regards (e.g., frost action and expansion).
- *Qualified Subgrade Soils* — Subgrade soils with less than 45% passing a No. 200 (75 µm) sieve and with a PI of 6 or less are adequate for moderate volumes of heavy truck traffic without the use of a subbase layer. In these cases, it is advisable to use dowelled joints — even in slabs less than 8 in. (200 mm) — to prevent differential deflections at slab joints.

It should be noted that these exceptions, which allow for a concrete pavement to be placed directly on a subgrade, are extremely dependent on the designer's estimate of heavy truck-traffic volumes over the life of the pavement.

In no case is increasing the thickness of a concrete pavement slab an acceptable measure to prevent pumping. Without proper preventive measures, pumping occurs on even the thickest of pavement slabs if the right combination of factors exists. A non-erodible subbase and load transfer dowels at the transverse joints are necessary whenever heavy truck volumes are anticipated.

To further define when a subbase is warranted, Table 7 gives serviceability data and pumping factors from the AASHO Road Test for sections with no subbase versus a 6 in. (150 mm) subbase. In this data, loops 2 and 3 are typical of many city streets, county roads, and light-traffic highways. As can be seen, under these low volume conditions, the pavements without subbases gave similar performance as those pavements with subbases. Table 7 also shows that a 6 in. (150 mm) subbase provides adequate protection against pumping for very heavy loadings.

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* These guidelines were developed from the AASHO Road Test and cooperative surveys with state agencies covering more than 2,000 miles of concrete pavements in ten states representing a wide range of climates, soils, traffic conditions. While developed many years ago, these guidelines remain applicable today. Included in the studies were pavements with and without joint load transfer devices and projects carrying as may as 700 axle loads per day of more than 18,000 lb (80 kN) and projects with tractor-semi-trailer counts of 1,000 to 2,000 per day.

† Two-way traffic, not including panel and pickup trucks, and other four-tire single units.

Table 7. Performance and Heavy Pumping Factor for No-subbase and 6 in. (150 mm) Subbase Sections, 3rd Level Concrete Design — All Traffic Loops

Loop No.	Axle type	Axle load [kips (kN)]	Slab thick. [in. (mm)]	Subbase thick. [in. (mm)]	P at end of tests	Repetitions at P = 1.5 (in 1,000s)	Heavy pumping factor[1]
2[2]	Single	2 (9)	5.0 (130)	0 (0) 6 (150)	4.1 4.1	— —	0 0
2	Single	6 (27)	5.0 (130)	0 (0) 6 (150)	4.1 4.0	— —	0 0
3[3]	Single	12 (53)	6.5 (165)	0 (0) 6 (150)	4.2 4.1	— —	0 0
4	Single	18 (80)	8.0 (200)	0 (0) 6 (150)	4.5 4.4	— —	0 0
5	Single	22.4 (100)	9.5 (240)	0 (0) 6 (150)	3.9 3.7	— —	25 15
6	Single	30 (130)	11.0 (280)	0 (0) 6 (150)	4.2 4.2	— —	0 0
3[3]	Tandem	24 (110)	6.5 (165)	0 (0) 6 (150)	4.0 4.1	— —	0 0
4	Tandem	32 (140)	8.0 (200)	0 (0) 6 (150)	2.4 4.2	— —	100 12
5	Tandem	40 (180)	9.5 (240)	0 (0) 6 (150)	— 40	658 —	907 148
6	Tandem	48 (210)	11.0 (280)	0 (0) 6 (150)	— 43	907 —	925 0

[1] Pumping data obtained from AASHO Road Test Data System 4243, “Rigid Pavement Pumping Surveys”

[2] Loop 2 data for Design 1 sections

[3] Loops 3 – 6 data for Design 3 sections

Also of significance to the decision to use a subbase is the influence it may have on construction of the surface pavement. Subbases provide a stable, smooth track-line or pad-line for the paving machine and stable support for fixed form construction. The track or pad lines for slipform paving machines are about 3 ft (1 m) to either edge of the width of the pavement. These are the paths along which a slipform paving machine’s tracks will ride while placing the pavement (Figure 33). Many agencies recognize the value of constructing on a stable, uniform track-line, so they require an extension of the subbase beyond the edge of the pavement in their concrete pavement design template. Extending the prepared subgrade and subbase layers beyond the edge of the pavement slabs also contributes to edge support, which reduces edge stresses and prevents settlement of shoulders or curb-and-gutter sections.

Figure 33. Trackline for slipform paving machine.

SUBBASE TYPES

Several different types of subbases have been successfully used under concrete pavements. These include:

- Unstabilized (granular) subbases.
- Stabilized subbases, which include:

- cement-stabilized subbases (cement-treated subbases or lean concrete subbases, both of which may include fly ash) and
- asphalt-treated subbases.

With any subbase, it is possible to utilize recycled concrete (either from an existing concrete pavement or another source) or a variety of waste materials as aggregate.

Regardless of specific subbase considerations, the best results are obtained by:

- Selecting subbase materials and combinations of layers that adequately prevent pumping of subgrade soils for the life of the pavement.
- Selecting subbase materials that will not contribute to excessive pavement deflections under traffic loadings, and will remain stable over time.
- Treating the subbase surface to ensure that it does not cause excessive friction or induce bonding to the pavement slabs.
- Specifying gradation or material controls that will ensure a reasonably consistent subbase material quality across an individual project.
- Building the subbase to grade controls that foster a pavement of consistent thickness and smoothness.

Unstabilized (Granular) Subbases

Unstabilized subbases, also known as granular subbases, are the most common type of subbase for applications such as streets, roadways and highways. A wide variety of soils and aggregates make excellent constituents for unstabilized subbases. The types of materials that have been used successfully include crushed stone, bank run sand-gravels, sands, soil-stabilized gravels, bottom ash, crushed or granulated slag, and local materials such as crushed wine waste and sand-shell mixtures. Any number of combinations of all these materials that would provide a proper subbase could alternatively be used. Recycled crushed concrete is also an excellent source material for an unstabilized subbase.

Unstabilized subbases have long been the most common type of subbase, but they fell out of favor with some highway agencies at a time when jointed reinforced concrete (JRC) pavements and undowelled (plain) concrete pavements were the norm. Both of these pavement designs were subject to deterioration by pumping and faulting — at the cracks that occurred by design between dowelled joints in JRC pavements and at each transverse joint in plain undowelled pavements. The faulting, corner cracking and roughness that developed on the pavements designed in this era is primarily attributable to a lack of positive joint (or crack in the case of JRC pavements) load transfer and the unanticipated increase in truck traffic experienced on the road network, and not due to any general negative characteristic of unstabilized subbases.

Since the 1980’s, however, the practice of dowelling transverse joints has become the norm for plain concrete pavements and the use of JRC pavement designs for roadways or highways has fallen out of favor. Thus, unstabilized subbases have once again become a preferred means of mitigating pumping for most highway agencies.

When designed and constructed properly, unstabilized subbases make an outstanding support layer for concrete pavements for all types of roadways and highways. Their primary advantage is their relatively low cost when compared to stabilized subbases.

Material Requirements

As a minimum, an unstabilized subbase material must meet the requirements of AASHTO M147 (alternatively, AASHTO M155 might be used if pumping is of significant concern). The following factors generally define materials that make a good unstabilized subbase:

- Maximum particle size of no more than one third the subbase thickness.
- Less than 15% passing the No. 200 (75 µm) sieve.
- Plasticity Index of 6 or less.
- Liquid limit of 25 or less.

- Los Angeles abrasion resistance (AASHTO T96 or ASTM C131) of 50% or less.
- Target permeability of about 150 ft/day (45 m/day), but no more than 350 ft/day (107 m/day), in laboratory tests.

The principal criterion[†] for creating a good unstabilized subbase is to limit the amount of fines passing the No. 200 (75 µm) sieve. If there are too many fines, the unstabilized subbase may hold water more readily and will be prone to erosion, pumping and frost action. If the local climate and soil dictates that it is necessary to prevent damage by frost action, it is better to use materials at or near the minimum fines content defined by the material specification.

Soft aggregate materials also are not satisfactory for unstabilized subbases because additional fines may be created under the abrasion or crushing action of compaction equipment and construction traffic. These fines will decrease uniformity in the layer and may contribute to frost action and other problems.

Gradation Control

Although a wide range of materials (and gradations) have performed well as unstabilized subbases under concrete pavements, it is important on each project for the subbase to have a reasonably constant gradation that allows compaction equipment to produce the uniform and stable support that is essential for excellent pavement performance. As with the subgrade, any abrupt changes in the character of a subbase can lead to reduced performance of a concrete pavement.

As a guide, Table 8, taken from AASHTO M147, shows typical unstabilized subbase material gradations (ASTM D1241 is similar). AASHTO M147 divides various unstabilized subbase materials into six separate gradations that all permit a wide range in the percentage passing the various sieves. As a result, all gradations encompass unstabilized granular subbases that can be either open-graded and slightly-to-moderately permeable, or dense-graded and relatively impermeable.

All of the gradations included in AASHTO M147 will perform satisfactorily if properly graded to permit compaction to such a density that minimal increases in densification will occur after the pavement is in service. Conversely, an unstabilized subbase with abrupt or uncontrolled variations between open and dense gradations — even within the specification bands — can result in variable pavement perfor-

Table 8. Grading Requirements for Soil-Aggregate Materials (ASTM M147)

Sieve size		Percent passing					
		Grading A	Grading B	Grading C	Grading D	Grading E	Grading F
2 in.	50 mm	100	100	—	—	—	—
1 in.	25 mm	—	75 – 95	100	100	100	100
⅜ in.	9.5 mm	30 – 65	40 – 75	50 – 85	60 – 100	—	—
No. 4	4.75 mm	25 – 55	30 – 60	35 – 65	50 – 85	55 – 100	70 – 100
No. 10	2.00 mm	15 – 40	20 – 45	25 – 50	40 – 70	40 – 100	55 – 100
No. 40	425 µm	8 – 20	15 – 30	15 – 30	25 – 45	20 – 50	30 – 70
No. 200*	75 µm	2 – 8	5 – 20	5 – 15	5 – 20	6 – 20	8 – 25

* Limit material passing the No. 200 (75µm) sieve to 15% maximum for all Grading (A – F) for an unstabilized (granular) subbase.

[†] It is important to understand that it is possible for an unstabilized subbase material to pump if it is a poorly graded material that erodes easily and/or it contains an excess of fine material. Pumping of unstabilized subbase materials may also occur on structurally under-designed pavements due to excessive deflections caused by frequent loads on slabs of inadequate thickness. This was observed at the AASHO Road Test (HRB 1962) and the recommendations in this publication are predicated on adequate structural design.

mance due to the resultant non-uniform character along the grade of the project.

Careful examination of the allowable percentage passing each sieve for gradings A through F in Table 8 reveals that only Grading A and C limit the maximum percentage passing the No. 200 (75 µm) sieve to less than 15%. It is important to bear in mind that AASHTO M147 gradings were developed for general pavement construction including both concrete and asphalt pavements. Therefore, the application of AASHTO M147 for use with concrete pavement is likely to require more careful development of the granular material combination in order to limit the percent passing the No. 200 (75 µm) sieve to a lower requirement (again, the recommended maximum percent passing the No. 200 (75 µm) sieve is 15%).

■ *Discussion on Drainage of Unstabilized (Granular) Subbases*

It is important to draw a distinction between open-graded and free-draining subbases. In this publication, the term free-draining designates materials similar to that shown as grading A in Table 8, where the percent of fines passing the No. 200 (75 µm) sieve is considerably below 15%, but the fines are not eliminated altogether. The recommended target permeability of a free-draining subbase is around 150 ft/day (45 m/day) in laboratory tests, which is all that is necessary for an effectively draining subbase. Although materials as coarse and open-graded as ASTM No. 57 stone have been used as draining layers, they are not recommended for concrete pavement due to their lack of adequate stability for construction operations and their susceptibility to long-term settlement under heavy truck traffic. It is better to design the gradation of the unstabilized granular subbase to include more fines for the sake of stability than to omit the fines for the sake of drainage.

The term 'free-draining' used to be synonymous with an older term — open-graded — that persists in literature and specifications. However, the reader is cautioned that, in practice, unstabilized subbases designated as 'open-graded' are also often associated with 'permeable' or 'drainable' subbases, a form of very porous subbase that became a popular design element through the 1990's. Permeable subbases — unstabilized subbases with the amount of fines reduced to a level that increases the permeability of the subbase to 500 to 20,000 ft/day (152 to 6,100 m/day) in laboratory tests — are no longer recommended for concrete pavement because these subbases are not stable over time and violate the fundamental requirement to maintain a uniform, stable foundation for the life of the pavement. See the section entitled *Permeable Subbases: Reasons to Avoid Their Use* later in this publication or the section entitled *Pavement System Drainage* earlier in this publication for more discussion on permeable subbases.

■ *Quality Control*

Project specifications should clearly identify the grading option(s) for any specific project, or allow the contractor to select an unstabilized subbase source that complies with any of the gradings in AASHTO M147 that also meets the specifier's criteria (such as percentage passing the No. 200 (75 µm) sieve). An effective way to ensure gradation control is to allow wide latitude in the selection of an unstabilized subbase from gradation limits known to be satisfactory.

Prior to construction, the contractor should submit a target gradation that fits within the specified gradation band. For quality control, plus and minus tolerances should be established from the submitted target gradation. Typical job control tolerances from the target gradation are:

- ±10% for materials 1 in. (25 mm) and larger.
- ±8% for materials between 1 in. and No. 4 (25 mm and 4.75 mm).
- ±5% for materials No. 4 (4.75 mm) and smaller.

Consolidation

Granular materials are subject to some consolidation from the action of heavy traffic once a pavement is placed into service. Thorough compaction of the unstabilized subbase will minimize post-construction consolidation, keeping it within a tolerable range

Figure 34. Example of a concrete pavement failure due to inadequate compaction of the subbase.

(less than about 10 percent). Figure 34 shows a localized failure from inadequate compaction.

Research results document the need for a high degree of compaction for unstabilized subbases with heavy-duty pavements, as shown in Figure 35 (Colley and Nowlen 1958). The research shows that as few as 50,000 load repetitions can produce excessive consolidation where densities are very low (less than 85 percent). According to the research, densities approaching 95 percent of AASHTO T99 density will prevent detrimental consolidation of a dense-graded granular (unstabilized) subbase.

Note that standard laboratory tests do not provide adequate density controls for some cohesionless or nearly cohesionless subbase materials. In such cases, an equivalent degree of compaction should be established by the tests for the relative density of cohesionless soils (ASTM D4253 and D4254).

Thickness and Compaction

Since the primary purpose of a subbase is to prevent pumping, it is neither necessary nor economical to use a thick subbase in an attempt to increase support or elevate the grade with respect to the water table. Experimental projects have shown that a 3 in. (75 mm) thick unstabilized subbase will prevent pumping under very heavy traffic. Similarly, slit-trench excavations made at pavement edges reveal that an unstabilized subbase thickness of just 2 in. (50 mm) can prevent pumping, even on projects that have carried heavy traffic for 10 years or more. Therefore, the maximum recommended unstabilized subbase thickness is 4 in. (100 mm) for regular construction projects. This recommendation is a practical means of securing the thickness of 2 to 3 in. (50 to 75 mm) that is necessary to prevent pumping.

Another matter of practical concern in considering the required unstabilized subbase thickness is the potential for consolidation under traffic. As the thickness of an unstabilized subbase increases, the same continuing rate of consolidation from repetitive loads will produce even greater total amounts of consolidation (i.e., a 10 percent post-construction consolidation of a 6 in. (150 mm) unstabilized subbase would be 50% high than that of a 4 in. (100 mm) unstabilized subbase due solely to the 50 percent increase in thickness). Figure 36 shows the results of repetitive load tests on unstabilized sub-

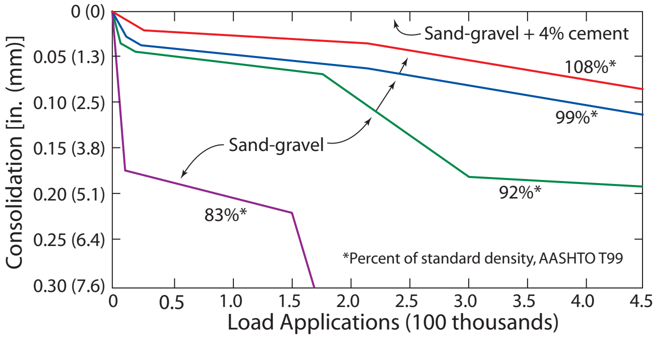

Figure 35. Subbase consolidation under repetitive loading.

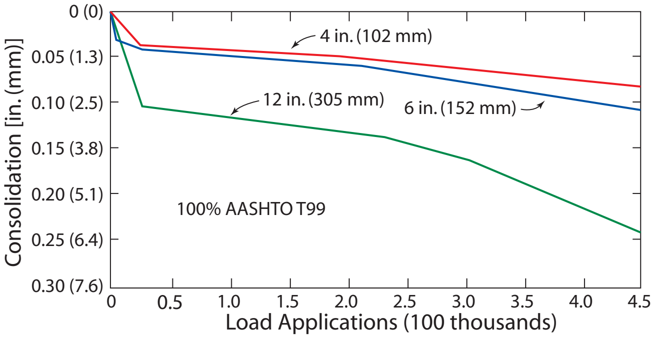

Figure 36. Influence of unstabilized subbase thickness on consolidation.

base that are 4, 6 and 12 in. (100, 150 and 300 mm) thick, placed on a clay-loam subgrade and compacted to 100 percent AASHTO T99 density. After 450,000 load repetitions, there was more than twice as much consolidation on the 12 in. (300 mm) unstabilized subbase as on the 4 or 6 in. (100 or 150 mm) unstabilized subbases. The least amount of combined subgrade-subbase consolidation occurred on the 4 in. (100 mm) unstabilized subbase.

Full-scale static load tests of slabs on various types and thicknesses of unstabilized subbases also reveal that strains and deflections are not affected appreciably by the unstabilized subbase thickness (Childs, Colley, Kapernick 1957). For a load positioned at transverse joint edges, these tests show only slight reductions in strains and deflections when unstabilized subbase thicknesses are greater than 4 to 6 in. (100 to 150 mm). Repetitive load tests have also demonstrated that the slight reductions in strain and deflection possible from the use of a 9 to 15 in. (225 to 450 mm) thick unstabilized subbase will be offset by the excessive consolidation of these thick layers (Colley 1958).

For these reasons, the following two guidelines should be followed with respect to unstabilized subbases for concrete pavements:

- A minimum of 95 percent of AASHTO T99 density should be developed for unstabilized subbase materials. On projects that will carry large volumes of heavy traffic, a minimum specified density of 98 percent of AASHTO T180 is warranted.
- Unstabilized subbase thicknesses should not exceed about 4 in. (100 mm). The additional material and construction cost of providing thicker unstabilized subbases is not justified. When unstabilized subbase thicknesses are increased beyond 4 in. (100 mm), there is an increased risk of poor pavement performance due to post-construction consolidation due to heavy traffic.

Unstabilized (Granular) Subbase Construction

Figure 37 shows the basic steps in constructing an unstabilized (granular subbase). The construction of unstabilized subbases can be accomplished in many ways. The keys to proper consolidation, however, are to ensure a homogeneous blending of the unsta-


Placing


Grading


Rewetting Immediately before Paving

Steps/Description

Mixing

The key to proper unstabilized subbase construction is placing a uniformly moist material that is homogenously blended. The water and aggregate may be mixed using many different methods, including using a standard mixer or a pugmill mixer. The unstabilized subbase could alternatively be mixed on the roadway using motorgraders.

Placing and Compacting

Once mixed, the unstabilized material may be placed to elevation with a paving machine; placed and trimmed with a hopper-converted auto-trimmer; or placed from trucks, spread with a motorgrader, and then cut to grade and cross-slope with an auto-trimmer. No matter which method is used, the material should be compacted to the required density (typically 95 percent of AASHTO T99 or 98 percent of AASHTO T180) and with minimal compaction effort to avoid segregation.

Grading

The unstabilized subbase should be trimmed to the shape of the typical cross section and to plan elevation within grade tolerance. The moisture in the unstabilized subbase must be monitored and kept near optimum before, during and after finish grading operations. Obtaining the optimum moisture content immediately before paving is extremely important (especially if recycled concrete aggregates are used) to prevent early-age cracking.

Figure 37. Construction Processes for Unstabilized Subbases.

bilized subbase material and to have all material uniformly moist prior to and during compaction.

The materials can be mixed in either a standard mixer or pugmill mixer, both of which must have an accurate control mechanism for the proportions of water and aggregate. An alternate method is to place and mix aggregate on the roadway using motor graders or other similar equipment and to add water during the mixing operation.

Once mixed, it is acceptable for unstabilized subbase material to be placed by the following means:

- Placed from trucks, spread with a blade on a motor-grader, and then cut to grade and cross-slope with an auto-trimmer.
- Placed and trimmed with a hopper-converted auto-trimmer.
- Placed to elevation with a paving machine.

After placing the unstabilized subbase material, the contractor must shape the layer to the desired cross section, condition with water to develop the optimum moisture content and compact the subbase to the specified density.

Free-draining subbase material may also be placed with a jersey spreader, trimmer or motor grader. Regardless of the equipment, it is important to spread and shape the material to the specified thickness in the typical section so that adequate density may result from minimal compaction effort. One to three passes of a 4 to 10 ton (4 to 10.2 metric ton) steel-wheel roller in the static mode will typically suffice. Over-rolling may cause degradation of the material, with a resulting loss of permeability.

Trimming operations appear to contribute the most to unstabilized subbase aggregate segregation, leading to spatial variations. Trimmers add to segregation problems in several ways: they shake the aggregate, causing fine particles to migrate to the bottom of the layer, and they remove the top, relatively coarse aggregate and leave behind finer aggregate. Aggregate placement and spreading operations are also likely contributors to segregation of fines and, therefore, a contractor's operational consistency is the key to producing a layer with consistent properties (White 2004).

The final unstabilized subbase surface should be smooth and uniform, free from ruts, humps, or other abrupt elevation changes and graded to the desired cross slope. The finished tolerance of the unstabilized subbase should be ±½ in. (± 12 mm) of the design profile grade. It is common practice to initially place an unstabilized subbase thicker than designed and then finish-grade the surface with an automated trimmer or motor grader. Materials removed during this finish-grading process are suitable for salvage and re-use.

Paving Precautions

The contractor should wet a unstabilized subbase prior to paving. A dry, unstabilized subbase may contribute to early age, uncontrolled cracking in the concrete pavement. A dry subbase draws moisture from the concrete, which may dry the lower portion of the slab before the middle or the top. This condition induces differential shrinkage (warping) similar to surface drying from high winds except at the bottom of the slabs and not the top of the slab. Any subbase that has the potential to absorb water from the fresh concrete should be moistened prior to paving. Moistening efforts are especially important with slag and recycled concrete subbase materials due to the high absorptive capacity of these aggregates.

Stabilized Subbases

Stabilized subbases generally refer to subbase materials that are bound by either cement or asphalt binders. Stabilized subbases fall into three general categories: cement-treated, lean concrete, and asphalt-treated. The primary benefit of stabilized subbases is that they provide relatively strong, uniform support and are resistant to erosion (pumping). Table 9 lists the erosion potential of various subbase materials under undowelled joints.

Compared to unstabilized subbases, stabilized subbases provide a higher degree of support to the pavement slabs (i.e., higher k-value). While this does not alter the required pavement slab thickness for a given load appreciably (see the section entitled *Influence of Foundation Strength of Concrete Pavement Thickness* earlier in this publication), it does strengthen the overall pavement structure. Plate-bearing tests on stabilized subbases produce

Table 9. Erosion Potention of Various Stabilized Subbase Materials (after Ray and Christory 1989)

Erosion Potential	Material Types
Extremely resistant	Lean concrete with 7-8% cement. Asphalt-treated subbase with 6% asphalt or greater.
Resistant	Cement-treated subbase with 5% cement.
Resistant under certain conditions	Cement-treated subbase with 3-5% cement. Asphalt-treated subbase with about 3% asphalt.
Fairly erodible	Cement-treated subbase with less than 3% cement. Unstabilized granular subbase.
Very erodible	Contaminated untreated granular materials. Unstabilized fine subbase.

extremely high k-values and these high k-values reduce stresses, strains and deflections from vehicle loadings in the overlying concrete slab. As an example, Figure 38 shows the strains measured in concrete slabs under a 9,000-lb (40-kN) load on a clay subgrade, an unstabilized subbase and a cement-treated subbase, and the k-values computed from these data. Computed k-values are in close agreement with those determined by the plate-bearing tests made directly on subgrades and subbases. It should be noted that although increased foundation stiffness via increased strength is beneficial from an applied loads point-of-view, it could potentially have a negative impact on environmentally induced stresses and strains. (See the section, *Influence of Foundation Stiffness on Stresses and Strains in Concrete Pavement Slabs*, for more information on this concept.)

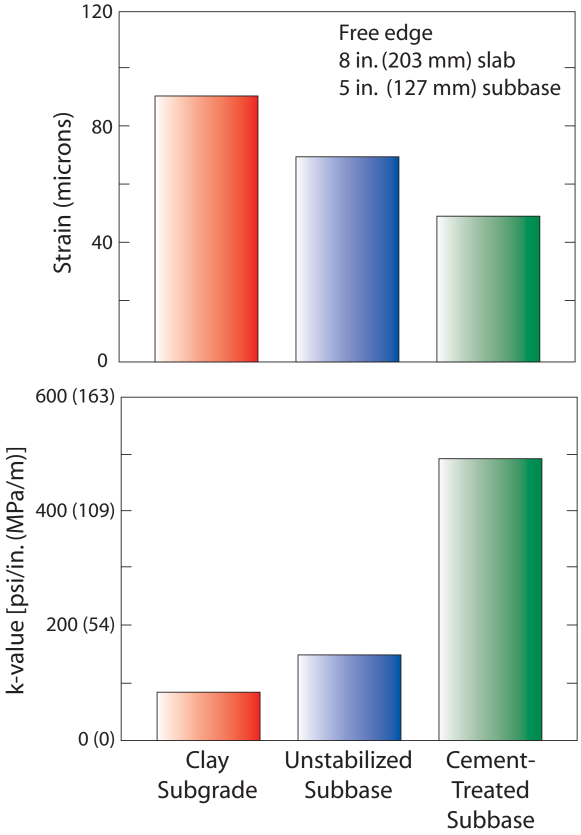

Figure 38. Measured strains and computed k-values, 9-kip (4,100 kg) plate load.

Another structural benefit of stabilized subbases is that they improve load transfer at pavement joints, especially for pavements with undowelled joints and plain concrete slabs (Colley and Nowlen 1967; Henrichs, et al. 1989; Ionnides and Korovesis 1990). Research results for plain concrete slabs cast on the plain subgrade, an unstabilized subbase and a cement-treated subbase are shown in Figure 39. As load applications accumulate on a slab supported by

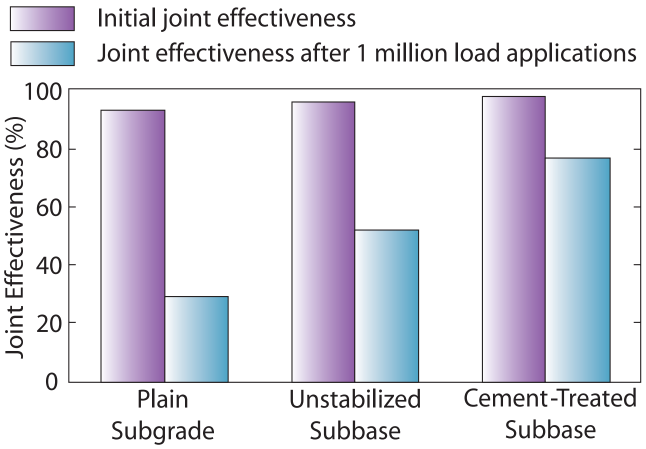

Figure 39. Joint effectiveness for a plain subgrade, an unstabilized subbase, and a cement-treated subbase (based on a 9 in. (250 mm) concrete slab).

the plain subgrade or an unstabilized subbase, load transfer (joint effectiveness) gradually decreases. On the cement-treated subbase, however, the loss occurs at a much slower rate and stabilizes around one-half million load applications; even after 1 million loads, joint effectiveness remains at a level of almost 80 percent (Figure 39). These results indicate that a cement-treated subbase will contribute more to maintaining effective load transfer over a longer period than will the plain subgrade or an unstabilized subbase, when all other factors are the same.* Similar results would be expected for lean concrete subbases and asphalt-treated subbases, although the level of contribution will likely be different than that indicated for a cement-treated subbase due to their differences in strength, modulus of elasticity and resistance to erosion.

Stabilized subbases provide an excellent construction platform for constructing concrete pavement. The bound subbase surface drains water quickly, providing an all-weather working platform that expedites construction operations after rainfall. Stabilized subbases also aid in improving the final pavement smoothness because they provide firm, stable support for the concrete forms or the slipform paver's trackline.

Other benefits of stabilized subbases include: minimizing post-construction subbase consolidation under traffic; minimizing intrusion of hard granular particles into the bottom of pavement joints; providing a more erosion resistant subbase material; and permitting greater use of local materials, substandard aggregates, and recycled materials (recycled concrete from either an existing concrete pavement or another source, reclaimed asphalt pavement, etc.), which can result in conservation of aggregates and savings in material and hauling costs (FHWA 2004, PCA 2003, Yrjanson 1989).

The mixture design for stabilized-material layers is driven by the property or properties that are desired. Sometimes, stabilized subbases are required simply to provide a construction platform, and are not intended to provide additional long-term strength. When this is the case, the minimum additive percentage that will result in the required performance is determined and it is not necessary to test for strength or durability requirements (FAA 1999).

Cement-Stabilized Subbases

Subbases that are stabilized with portland cement fall into two general categories: cement-treated subbases (CTB) and lean concrete subbases (LCB). Fly ash also may be included in either a CTB (giving a cement-plus-fly-ash-treated subbase) or a LCB (giving a lean-concrete-plus-fly-ash subbase), and slag may be used in a CTB. Cement-treated materials are distinguished from lean concrete (also referred to as econocrete) in that they have a much drier consistency, contain less cement, and are best controlled using compaction and/or density requirements instead of strength requirements. Each material also requires different placement techniques. CTB placement is similar to other unstabilized subbase materials.

Contractors can elect to mix the cement with the granular material using a pugmill or standard central mix plant and then haul it to the paving site. To achieve adequate final results, CTB materials, because of their drier consistency, require compaction by rollers for density. LCB materials, however, are placed with a slipform paver or modified-concrete spreader in essentially the same manner as conventional concrete mixtures, requiring no additional compaction effort. As a result of these fundamental differences, the specification requirements for each material also are different.

For a lean concrete, typical specifications require a 7-day compressive strength from 750 to 1,200 psi (5.2 to 8.3 MPa) and an air content from 4.0 to 12.0%. The air content of an LCB may be used to prevent exceeding the maximum strength, as well as for freeze-thaw durability.

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* Regardless of the benefits of improved support and contribution to load transfer, stabilized subbases are not an alternative to dowelling joints. Any pavement that is expected to have significant truck traffic requires dowelled transverse joints. The thickness of the concrete pavement slab, as required by a thickness design procedure such as ACPA's StreetPave or the Mechanistic Empirical Pavement Design Guide (MEPDG), is the most rational factor to determining whether dowels are warranted. Generally, slabs greater than 8 in. (200 mm) thick require dowels because of expected truck loadings.

Because a CTB layer is best controlled using compaction and/or density requirements, common requirements are a level of compaction between 96 and 100 percent of the maximum density. The maximum density (determined by AASHTO T134 or ASTM D558) is determined by a representative field sample taken from the moist mixture at the time compaction begins. Although there is typically no strength requirement on CTB material, targeting a 7-day compressive strength from 300 to 800 psi (2.1 to 5.5 MPa) assures long-term durability (PCA 2006). Contractors may elect to build a test strip to demonstrate that their construction methodology meets the required density specification and that the resultant compressive strength falls within the desired target strength range.

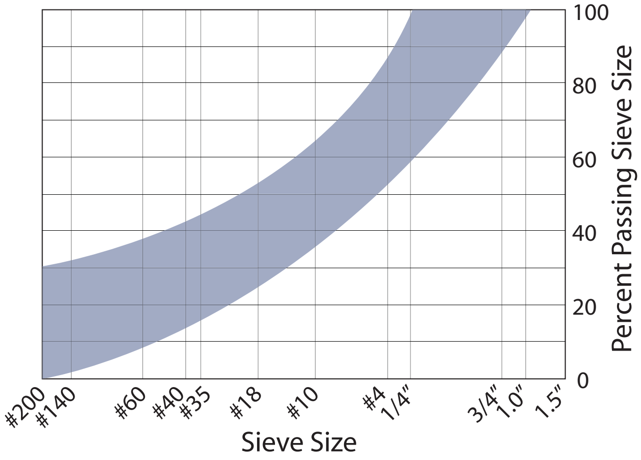

Figure 40. Gradation for minimum cement requirements of cement-treated subbases (from PCA IS029).

Cement-Treated Subbases

MATERIAL REQUIREMENTS

Cement-treated subbases (CTB) typically require about 2 to 5% cement by weight. Granular materials, as specified in AASHTO M147 or Soil Classification Groups A-1, A-2-4, A-2-5, and A-3 work well for a CTB.

The granular material typically has no more than about 35 percent passing the No. 200 (75 µm) sieve, a Plasticity Index of 10 or less, and may be either pit-run or manufactured. A maximum particle size of ¾ to 1 in. (19 to 25 mm) is preferable to permit accurate grading of the subbase.

In many instances, dirty granular materials or recycled concrete aggregates may not be acceptable for unstabilized subbase specifications because of excess fines or plasticity, but such materials may be acceptable to use as a subbase if they are treated with cement (PCA 2003). These inexpensive materials often require less cement than the cleaner, more expensive aggregates. Gradations falling within the broad band shown in Figure 40 usually require minimal cement contents. Also, the use of materials within the band will result in cost savings due to lower material and cement costs.

To determine the optimal cement content for a CTB requires standard laboratory wet-dry and freeze-thaw tests and PCA weight-loss criteria or lab molded compressive strength results (PCA EB052). No matter the derivation of the cement content, CTB acceptance testing should be based on the field measured percent of maximum density.

When specified, a 7-day compressive strength of 300 to 800 psi (2.1 to 5.5 MPa) (PCA 2006) is the typical target strength range for CTB layers. At this strength, the long-term durability of the CTB subject to repeated cycles of wetting and drying or freezing and thawing is virtually assured (i.e., Figure 41

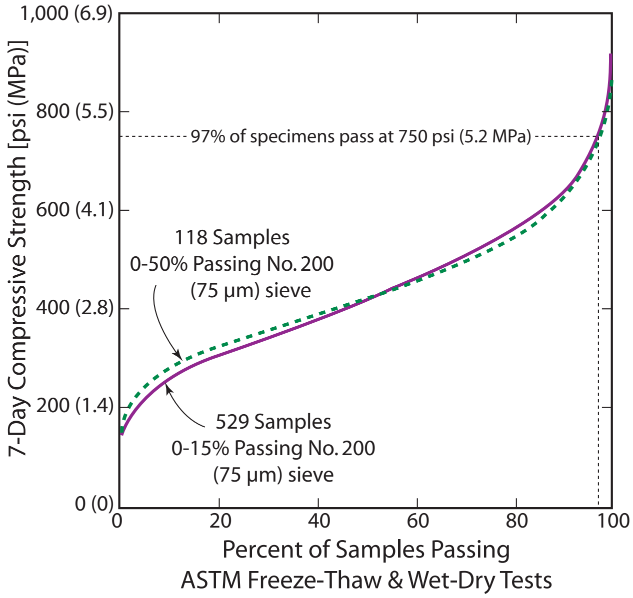

Figure 41. Relationship between strength and durability for CTB. (PCA EB052).

shows that about 97 percent of test specimens passed ASTM D559 and D560 freeze-thaw and wet-dry testing with a strength of 750 psi (5.2 MPa)).

CONSTRUCTION

Figure 42 shows the basic steps in constructing a cement-treated subbase. Contractors may select to use either road-mix or central-mix methods for constructing a CTB. In road-mixing, the material is processed on the subgrade. The proper quantity of cement is spread onto the soil/aggregate with a cement spreader and mixed either with a multiple-pass mixer or a single-pass mixer. Multiple-pass mixers require one pass for dry mixing the cement and soil/aggregate and a second pass for moist mixing the materials. Single-pass mixers complete the operation simultaneously, in one pass.

In a central mixing operation, cement and soil/aggregate for the CTB are mixed in a pugmill or a central-plant mixer. After mixing, the moist mixture is hauled in dump trucks, where the contractor dumps it onto the grade and then spreads it with a mechanical spreader. The subgrade should be moist when the cement treated material is placed and operators should dump and spread the mixture in a manner that will minimize segregation.

Soon after the granular material, cement and water are uniformly blended and spread to the target thickness and width, the contractor must compact the material with rollers, followed closely by a trimmer, which will finish the material to grade. Any surface moisture lost through evaporation during finishing operations must be replenished by a light fog spray.

A reasonable surface grading tolerance for cement-treated subbase after trimming is ±0.5 in. (±12 mm), longitudinally or transversely, as measured by a 10 ft (3 m) straightedge. Methods for finishing the CTB to proper grade are similar to those for finishing unstabilized subbase materials. However, because of the

Placing (PCA EB003)

Compacting

Curing (PCA EB003)

Steps/Description

Mixing and Placing

If central-mixing, the cement, soil/aggregate, and water are mixed in either a central-plant mixer or a pugmill. The mixture is then placed on the grade and spread with a mechanical spreader. Often times, the subbase surface is moistened before placing the material if a central-mixing method is used; this helps prevent differential drying in the subbase layer. If road-mixing, the cement is spread evenly across the soil/aggregate material on the grade and mixed using either a multiple-pass (requiring one pass for dry mixing and one for wet mixing) or single-pass mixer (mixes the soil/aggregate, cement and water in one pass).

Compacting and Trimming

Soon after placing, the cement-treated subbase should be compacted with rollers and trimmed to the specified grade. A typical tolerance for a cement-treated subbase after trimming is ±0.5 in. (±12 mm) as measured by a 10 ft (3 m) straightedge. It is important place and trim a cement treated subbase within 4 hours from the time the cement comes in contact with the water because it will begin to cure and subsequent compaction might be deleterious to the strength. If placed in an environment with high ambient temperatures or high winds, the window for placement, compaction and trimming becomes even smaller.

In the event that harsh ambient conditions or construction staging requires the CTB to be trimmed after an initial curing period, curing compound must be reapplied after trimming to prevent bonding between the concrete pavement and the CTB.

Curing

Cement-treated subbases are typically cured with a light fog spray of water (to replenish any water that has evaporated from the surface since placement) followed by an application of bituminous curing material at a rate between 0.15 and 0.25 gal/yd^2 (0.68 and 1.1 l/m^2).

Figure 42. Construction processes for cement-treated subbases.

cementitious nature of CTB, time influences finishing and trimming to some extent. To gain full advantage of the benefits imparted by the cement, about 4 hours of working time are available for placing and finishing CTB once the cement comes into contact with water. High winds and extreme heat may reduce the working time available, so the contractor is encouraged to be mindful of the working conditions.

CTB requires a curing application once finishing operations are completed. A light fog spray of water and an application of a bituminous curing material help contain moisture so the cement may hydrate properly. Typical applications rates for the bituminous curing agent are from 0.15 to 0.25 gal/yd^2 (0.68 to 1.1 l/m^2).

In some cases, trimming CTB subbases prior to paving disturbs the subbase's surface character. After trimming, the surface may be rough in certain locations, creating an unwanted condition that promotes bonding between the CTB and the pavement. One of the following methods will minimize bonding in trimmed areas:

- Reapplication of asphalt curing agent and spreading of a thin layer of sand before paving.
- An application of two coats of wax-based curing compound before paving.

Lean Concrete Subbases

MATERIAL REQUIREMENTS

Lean concrete subbase mixtures contain more cement and water than cement-treated subbase materials, but they contain less cement than conventional concrete. Lean concrete has the same appearance and consistency as conventional concrete, and it also requires consolidation by vibration like conventional concrete.

It is acceptable to relax some of the restrictive requirements for conventional concrete in a specification for lean concrete. Certain requirements that relate to the performance characteristics of concrete as an exposed pavement surface are not as critical for a lean concrete subbase, such as minimum cement content or aggregate abrasion resistance. Loss of surface texture or polishing of aggregate, lack of abrasion resistance, popouts, surface scaling, or other undesirable qualities for a pavement surface are acceptable for lean concrete as a lower course in the pavement structure. Lean concrete is designed for use as a subbase only and, in general, makes use of aggregates that do not necessarily meet quality standards* for unstabilized subbases or conventional concrete, thus some engineers have adopted the term “econocrete” when referring to lean concrete (ACPA 1975).

Data from laboratory test programs and lean concrete construction projects indicate that a rather wide range of aggregates will work well in LCB mixtures (ACPA 1975). Some of these aggregates are materials not processed to the same degree as normal concrete aggregates. Most have more fine material passing the No. 100 (150 μm) and No. 200 (75 μm) sieves than is acceptable for normal concrete, but this is not necessarily objectionable for lean concrete because the extra fines supply needed workability.

On some projects, existing concrete and asphalt pavements have been recycled and used as aggregates for lean concrete subbases. In fact, the slight decrease in flexural and compressive strength, as is typically observed when using recycled aggregates over virgin, is of no concern for a lean concrete subbase. A special precaution might be warranted, however, for the gradation of the recycled aggregate because the recycled fines have a much higher absorption capacity than typical fine aggregates; if a concern, the fines from the recycled aggregate may be removed during the crushing and sorting process and replaced by virgin fine aggregate (Cho and Yeo 2004).

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* To reduce pavement costs and preserve high-quality aggregates, the U.S. Federal Highway Administration issued Notice N5080.34, which says: “The use of lower quality, locally available aggregates is encouraged for econocrete (lean concrete). The use of recycled pavement material serving as aggregate is encouraged. The limits to lower aggregate quality should be determined by the state, based on local experience, or by tests of econocrete (lean concrete) designs.” (FHWA 1975)

Normal procedures and tests for concrete mixtures are applicable for lean concrete, with the following exceptions:

- A single aggregate may be used rather than a combination of coarse aggregate and fine aggregate, stockpiled separately.
- The cement content may be considerably less than that for conventional concrete, and must be controlled to keep the compressive strength of the lean concrete between 750 and 1,200 psi (5.2 and 8.3 MPa), as detailed later.
- Material combinations must produce lean concrete that is workable, capable of adequate consolidation by vibration and cohesive enough to resist excessive edge slumping when placed with a slipform paver.
- Workability may be enhanced by the existence of extra fines in the aggregate; higher than normal amounts of entrained air; addition of fly ash, water-reducing admixtures or workability agents; or any combination of these additions.

Past recommendations limited the maximum strength of LCB to 1,500 psi (10.3 MPa) while current recommendations limit strength to 1,200 psi (8.3 MPa) (ACPA 1975). The purpose of limiting strength is to avoid problems associated with high curling and warping stresses in the pavement slabs. Where the stiffness or strength of an LCB subbase becomes excessive, a fabric interlayer may be used to mitigate problems associated with the additional stiffness.

STRENGTH PROPERTIES

Laboratory investigations and field installations indicate that the desirable properties of lean concrete used as a subbase course are achieved with cement factors in the range of 200 to 350 lb/yd^3 (119 to 208 kg/m^3), slumps from 1 to 3 in. (25 to 75 mm), average 7-day compressive strength between 750 and 1,200 psi (5.2 and 8.3 MPa) and air contents somewhat greater than normal concrete (6% to 8% air for concrete made with a maximum size aggregates of 1 to 2 in. (25 to 50 mm) in freeze-thaw areas).

The strength of LCB layers is also important to the performance of the pavement over time. Counter to intuition, the stronger an LCB layer becomes, the more problematic it may become for pavement performance. Long-term performance studies reveal increased levels of cracking on LCB layers compared to unstabilized subbases. This result is attributable to the stiffness of the LCB, which becomes excessive if the strength of the lean concrete is not kept in check. Also, cracks may reflect from the LCB subbase into the pavement slabs if the LCB strength becomes excessive and drying shrinkage cracks exist in the LCB.

Higher LCB strength generally increases the layer stiffness and, although this might lower the stresses and strains due to applied loads, this typically leads to higher curling stresses in the pavement slabs. A similar increase in support stiffness is attributable to the thickness of LCB layers. Therefore it is also important for LCB layers not be too thick. Higher environmental stresses (curling and warping) have a more damaging impact when the concrete is relatively young, when the slab had not yet developed the strength and fracture toughness necessary to resist cracking. For more on this, see the section, *Influence of Foundation Stiffness on Stresses and Strains in Concrete Pavement Slabs,* earlier in this publication or the section, *Stabilized Subbase Precautions,* later in this chapter.

The engineer must recognize that targeting a compressive strength range such as 750 to 1,200 psi (5.2 to 8.3 MPa) may be difficult to achieve by the contractor due to normal variations in project materials. Contractors must recognize the importance not to become overzealous with achieving strength in an LCB subbase for purposes of expediting construction or other reasons. In some cases, higher subbase stiffness is not from a misapplication of the specification, but only as a matter of the passage of time. Project sequencing and strength development must be properly factored into the LCB mixture design.

CONSTRUCTION

Figure 43 shows the basic steps in constructing a lean concrete subbase. A lean concrete subbase permits the concrete paving contractor to use his own mixing and placing equipment for the subbase, thus spreading out move-in (mobilization) costs over a greater volume of work. The scheduling of the paving contractor's work would be more definite than when a subbase of a different type (e.g., asphalt-treated) is sublet to another contractor. In some cases, the work schedule maintained by the subbase subcontractor does not fit with the paving contractor's schedule, possibly resulting in delays.

Lean concrete subbases are constructed in essentially the same manner and with the same equipment as normal concrete pavements. The only two differences are jointing practice and treatment of the lean concrete subbase surface.

Installing joints is generally not necessary in a lean concrete subbase. Shrinkage cracks will develop, but experience has shown that, for LCB strengths — 750 to 1,200 psi (5.2 to 8.3 MPa) — and with the interlayer treatment discussed below, the cracks usually will not reflect through the overlying concrete pavement. In the event the strength of the LCB is of concern (i.e., strength of the LCB is too high), joints could be scored or sawed into the lean concrete subbase surface at the location where joints will be placed in the concrete pavement. If reflective cracking is of concern, tar paper or any other applicable material may be placed over any shrinkage cracks before application of a bond breaker to further reduce the likelihood of reflective cracking.

The recommended interlayer treatment is to leave the surface of the lean concrete untextured to prevent a mechanical bond to the concrete surface. A further step to preventing bond is to apply two heavy coats of wax based curing compound as a bond breaker. The first coat is applied immediately, as a cure coat, and the second coat is applied shortly before the surface concrete is placed, to refresh the coverage.

Placing

Properly Cured LCB

Steps/Description

Mixing

Because lean concrete is of a comparable consistency as conventional concrete, lean concrete subbases are typically mixed in a central-plant mixer.

Placing and Finishing

Again, because of the similarities in properties between lean concrete and conventional concrete, it is typically placed in the same manner as conventional concrete: usually by slipformed paving. Due to its consistency, it is relatively easy to keep the surface finish within the typical specified tolerance of 0.25 in. (6 mm) by a 10 ft (3 m) straightedge. There is no need for additional finishing work as with conventional concrete because the surface is not a riding surface; the surface of the lean concrete subbase also should not be textured: this helps prevent it from developing a mechanical bond with the concrete pavement.

Curing and Jointing

Typical curing procedures for lean concrete subbases include the application of two heavy coats of wax based curing compound. This procedure prevents evaporation of water from the subbase surface to promote thorough hydration of the mixture and mitigates uncontrolled cracking in the subbase layer. The curing compound also serves as a bond breaker between the subbase and the concrete pavement.

Figure 43. Construction processes for lean concrete subbases.

In Germany, current practice is to use a 0.2 in. (5 mm) thick non-woven geotextile fabric to separate the concrete pavement and lean concrete subbase. This practice has considerable merit and is currently being used in portions of the United States and elsewhere in the world.

The surface finish tolerances for lean concrete subbases are better on average than for any other type of subbase due to the placement techniques; tolerances are often specified as low as ±0.25 in. (±6 mm), longitudinal or transverse, by a 10 ft (3 m) straightedge. This minimizes the occurrence of concrete overruns (yield losses) because of the contractor's need to meet minimum pavement depth requirements (ACPA 1975).

Asphalt-Treated Subbases

Asphalt-treated subbases (ATB) provide another option as a supporting layer for concrete pavement.

■ *Design & Material Requirements*

The design criteria for asphalt-treated soils and aggregate combinations focus almost exclusively on compaction/stability and gradation parameters.

An asphalt coating on granular materials provides a membrane, which prevents or hinders the penetration of water and thereby reduces the tendency of the material to lose strength in the presence of water. Because an asphalt-treated subbase relies on adhesion to bind aggregate particles together, stripping is a primary concern. Stripping is the breaking of the bond between the asphalt cement and the aggregates by the action of water or water vapor (SHRP 1993). The result of stripping is a breakdown of the hot-mix asphalt into particles without any binding medium. Although there are many causes identified for stripping, the most plausible cause in a subbase layer is from decreased asphalt contents in the asphalt mixture, which reduces the binder film thickness. Anti-stripping agents may prevent this potential problem. The moisture susceptibility test used to evaluate asphalt for stripping is AASHTO T283. This test serves two purposes: to identify whether a combination of asphalt binder and aggregate is moisture susceptible and to measure the effectiveness of anti-stripping additives.

The thickness requirement for an asphalt-stabilized subbase depends upon the support from the subgrade. A thicker subbase is necessary for weak soil conditions to prevent construction equipment from deforming the asphalt layer, especially on softer or more yielding subgrades. A 2 in. (50 mm) thick asphalt stabilized subbase may be sufficient for stiffer foundations, such as those modified with lime, fly ash or cement, or if the ATB is being placed on an unstabilized subbase.

The following considerations and stipulations are advisable for using asphalt-treated subbases under concrete pavements:

- Asphalt mixes for a subbase may use a lower grade of asphalt cement than is required for asphalt surfaces.
- An asphalt cement content of about 4 to 4.5% is considered typical for asphalt-treated subbases.
- Durable aggregates remain an important uncompromising requirement for asphalt-treated subbases and their appropriate size depends upon the subbase thickness. The maximum size aggregates are typically ¾ in. (19 mm).
- Aggregates meeting moderate soundness requirements perform satisfactorily in asphalt-treated subbases. A maximum freeze-thaw loss in water of 10 and freeze-thaw loss in a water alcohol solution as high as 45 according to AASHTO T103 are considered adequate. Some agencies do not require freeze-thaw and wet-dry durability tests for asphalt-treated subbase mixtures (Army 1994).
- Density requirements of the specifying agency must be maintained for an asphalt-treated subbase mixture.
- The surface of an asphalt-treated subbase may range from rough to smooth. Rougher surfaces may induce a high degree of friction with the concrete pavement and require an additional technique to mitigate this friction.

- Because the surface of an asphalt-treated subbase can reach 140°F (60°C) or more, it should be sprinkled with water or whitewashed with a water-lime solution prior to concrete paving to reduce the surface temperature (IPRF 2003).

■ *Construction*

Construction methods for asphalt-treated subbases are the same as for constructing any asphalt layer. Contractors place the material using an asphalt paving machine and compact the layer to a specified density with rollers. The layer must conform to the typical section in the plans, and provide for uniform support and resistance to erosion or stripping.

Grade control with an asphalt-treated subbase is also a primary factor in construction. Surface deviations that do not exceed ±0.25 in. (±6 mm), longitudinal or transverse, by a 10 ft (3 m) straightedge are acceptable for an asphalt-treated subbase. Often, it more difficult to place an asphalt-treated subbase close to the desired grade than a cement- treated subbase, resulting in unnecessary cost overruns in the concrete paving portion of the job.

Further details on constructing asphalt-treated subbases can be found in other sources.

Stabilized Subbase Precautions

Despite the advantages of stabilized subbases, one can not simply substitute a stabilized subbase for an unstabilized subbase and expect enhanced performance. There are well-documented occurrences of erratic uncontrolled cracking on projects with lean concrete, cement-treated, asphalt-treated and permeable treated subbases that were known to have bonded to the concrete pavement (Halm, Yrjanson, Lokken 1985; Voigt 1992 and 1994). Cores examined from these projects typically revealed that the cracks traveled around coarse aggregate particles, indicating very early formation. These cracks are usually due to two factors:

1. High friction between the pavement and the subbase — Plastic concrete shrinks due to concrete drying and/or temperature contraction causing the concrete pavement to slide along the subbase. As the stiffness of the subbase increases, the coefficient of friction between the subbase and the slab increases, which induces higher tensile stresses and increases the risk of cracking. Table 10 shows a typical coefficient of friction for various subbase materials.
2. Increased curling stress in the pavement — Stabilized subbase materials increase stresses in the concrete slab because they cause the value of the radius of relative stiffness* of the pavement to decrease. This reduces the ability of the slabs to spread out stress from the load and, for equivalent panel sizes, it increases the stress conditions in the pavement. Due to this effect, curling stresses on stabilized subbases may be up to

Table 10. Coefficient of Friction for Various Subbase Materials

Subbase	Coefficient of Friction
Natural subgrade	1.0
Chemically-modified clay soil	1.5
Unstabilized granular subbase	1.5
Bituminous surface treatment	3.0
Unstabilized crushed stone subbase	6.0
Asphalt-treated subbase (smooth)	6.0
Cement-treated subbase	10.0
Asphalt-treated subbase (rough)	15.0
Asphalt-treated open-graded subbase	15.0
Cement-treated open-graded subbase	15.0
Lean concrete subbase (econocrete)	15.0

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* The radius of relative stiffness, ℓ, is affected by the modulus of elasticity of the concrete (E_c), the thickness of the pavement (h), the Poisson's ratio of the concrete (υ), and the modulus of subgrade reaction (k-value). As the strength and thickness of the subbase increase, the k-value increases, and the radius of relative stiffness decreases. A lower radius of relative stiffness causes higher stresses in the pavement.

$$\ell = \sqrt[4]{\frac{E_c h^3}{12(1-\nu^2)k}}$$

two times higher than curling stresses on conventional unstabilized subbases. For more on this, see the section entitled *Influence of Foundation Stiffness on Stresses and Strains in Concrete Pavement Slabs* earlier in this publication.

By themselves, the above factors may not be significant enough to cause random, uncontrolled cracking on a new construction project. However, when combined with other factors such as improper materials selection, poor concrete mixture design and/or too much distance between transverse joints, the risk for unwanted cracking increases.

To minimize the potential for random, uncontrolled cracking, the following three factors must be considered in selecting materials for stabilized subbases, and for designing of concrete pavements with stabilized subbases:

- Potential bonding of plastic concrete to the subbase surface.
- Strength of stabilized subbase materials.
- Joint spacing (panel size dimensions).

The potential for bonding between the concrete and subbase can be minimized with the application of a bond-breaking medium. For lean concrete subbases, current practice includes two heavy spray applications of wax-based curing compound on the subbase surface. Though there are no common bond-breaker recommendations for cement-treated subbases or asphalt-treated subbases, Table 11 provides some alternatives for reducing friction and preventing bonding of concrete pavement to stabilized subbases.

Alternative Subbase Materials

In some cases, virgin coarse aggregate is not readily available in close proximity to a concrete paving project. In other cases, virgin coarse aggregate might not be the most economical choice. When such cases arise, recycled concrete (either from an existing concrete pavement or another source) or other waste materials might be used as aggregate in subbase layers.

Recycled Concrete

Using recycled concrete as unstabilized subbase or in a cement-stabilized subbase is common practice. There are many benefits to using recycled concrete, most of which fall into the area of sustainability, including:

- **Performance:** The angularity of recycled concrete aggregate, coupled with potential residual cementation, provides a strong and durable platform for construction and improves load carrying capacity over the life of the pavement. Furthermore, the crushing and sizing operations can be modified to accommodate any desired aggregate gradation (FHWA 2004).
- **Economics:** Savings are realized in the cost of transporting new aggregates, and in the cost of hauling and disposing of the old pavement.

Table 11. Alternatives for Reducing Friction or Bond Between Concrete Pavement and Stabilized Subbase Materials

Material	Comments
Curing compound	Two coats of white pigmented wax-based compound works well.
Sand	Dusting about 12 lb/yd^2 (5.5 kg/m^2) works well.
Bladed fines	Recycled jobsite material works well as thin layer.
Asphalt emulsion	Works well on smoother subbase surfaces. Must be even coating.
Non-woven geotextile	Works well for CTB and LCB. Must be 0.2 in. (5 mm) thick, fastened to surface.
Polyethylene sheets	Works well but difficult to use when windy; could pose traffic hazard in urban areas.
Tar paper	Works well as debonding medium directly over shrinkage cracks in subbase. Not recommended for application on entire subbase area.
Choker stone	For stabilized open-graded materials only — chip-size material to fill near-surface voids and minimize penetration of concrete into subbase.

- **Resource Conservation:** Reusing existing material is helpful where quality aggregate supplies are scarce (Yrjanson 1989). Also, using recycled concrete aggregates in either a subbase or in the concrete mix conserves virgin aggregates.
- **Environmental Consideration:** Recycling existing pavement materials as an aggregate subbase reduces dumping and land disposal (FHWA 2004). Using valuable landfill space for disposal of concrete would be questionable when it can easily be recycled.

The cost of using recycled aggregates for subbase material includes only the cost of crushing operations. The costs for breaking, removal, steel separation, and transport are incidental to any reconstruction project.

Although the aforementioned construction processes used for unstabilized or stabilized subbases do not change, there are some precautions that must be considered when using a recycled concrete as aggregate.

■ *Aggregate Characteristics*

Research and experience has established the various physical properties of coarse and fine aggregates made by recycling in-place concrete pavements. The properties have also been verified through agency testing where recycled concrete aggregates have been specified for reuse. Generally, the tests performed on materials made from recycled concrete pavements are the same as for virgin aggregates, with only a few exceptions.

A contractor can produce nearly any desired gradation using crushed, recycled concrete. Table 12 provides typical recycled unstabilized subbase layer gradations (ACPA 1993). A lower yield of recycled coarse material will result when the target gradation requires smaller top-size material. Coarse aggregates are those particles which are at least ⅜ in. (9.5 mm) at their narrowest width. The gradation of the fine aggregate portion depends upon the type of crushing operation employed. The material will be very angular, requiring somewhat more effort to place than virgin-based granular material.

A small amount of fine particles cling to coarse aggregates during crushing and sizing operations. Studies of this condition conclude that, for most cases, the aggregates do not need washing to remove this fine material. However, some agencies require washing to reduce the potential of leaching calcium carbonate or calcium oxide when the aggregate is used for unstabilized subbase.

Recycled aggregates produced from all but the poorest quality material should be able to meet the L.A. Abrasion Test (AASHTO T96 or ASTM C131) requirement of 50% or less for subbase materials.

Normally, on a highway project that employs recycled concrete into the subbase, the source material

Table 12. Typical Recycled Unstabilized Subbase Gradations

Sieve Sizes		Percent Passing Sieve	
2 in.	50 mm	100	100
1 in.	25 mm	—	—
⅜ in.	9.5 mm	40 – 75	—
No. 4	4.75 mm	25 – 60	35 – 70
No. 10	2.00 mm	—	—
No. 40	425 µm	15 – 45	—
No. 200	75 µm	3 – 12	3 – 10

is the old pavement at the project site, which is processed without any contaminants or inclusions. In urban areas, the concrete that is to be recycled may be from a variety of sources and can include materials such as plaster, soil, wood, gypsum, plastic and vinyl, or rubber. Tests for contaminants are particularly important for generally recycled source materials. Agencies should apply the contamination percentage limits normally permitted for virgin coarse aggregates as a means to control the volume of these contaminants in recycled concrete subbase material.

■ *Precautions*

As mentioned, crushing and sizing operations may produce dust and fine material that clings to the larger aggregate particles. In a free-draining subbase, water that seeps through the recycled concrete particles may wash the dust off the large aggregates over time. The water and fine material sometimes drains through the layer and, if an edge drainage system exists along the pavement, the fines may be expelled from it. Some agencies report observing leachate at drain outlets due to this action (TRB 1993). The fine material may also settle on filter fabric or drain pipes before reaching the outlets.

Over time, the leachate can clog edge drain pipes and blind filter fabrics, if they surround the pipe trench. To prevent this from occurring, it is important to use a daylighted drainage design or to ensure that the filter fabric for the edge drain pipe does not completely surround the trench (see the section entitled *Daylighting the Subbase,* earlier in this publication). In either case, there is no potential obstruction to the free flow of water and fine material, which allows it to flow through the subbase to the outlet pipes or side ditches.

Although the leachate from a recycled concrete aggregate subbase is initially extremely alkaline (high pH due to high concentration of hydroxyl ions in solution), it is not harmful to the environment. In the event that the effluent from the pavement system is of a high enough pH to be of any concern, it is usually heavily diluted by the time it reaches the drainage outlets, restricting environmental concerns to small regions surrounding the outlets (MNDOT 1995). Furthermore, some states (including Minnesota, Virginia, California and Texas) have taken a proactive stance by lowering regulatory burdens on recycled concrete aggregates to effectively promote their use. These states realize the environmental benefits of not having the expired concrete pavement placed in a landfill and the subsequent conservation of virgin aggregates (FHWA 2004).

Waste Materials

The need to recycle waste materials into pavement construction has never been greater than it is at this time. Many United States and international road agencies have studied the use of different waste materials in subbase layers. Through such study, it is well known that reclaimed asphalt pavement (RAP), mill tailings, and other rock can be used as a unstabilized subbase in concrete pavement construction applications.

- *RAP* — Reclaimed asphalt pavement (RAP) will perform satisfactorily as a subbase aggregate (TFHRC 2007). The materials must be processed properly, and in most cases it must be blended with conventional aggregates and soils to develop an effective subbase gradation.
- *Mill Tailings* — Mill tailings may be used as a partial addition to unstabilized subbase layers (TFHRC 2006). However, only the coarser-sized particles are acceptable as long as there are no harmful or reactive chemical components concentrated from the host rock.
- *Other Rock* — Other rock, sometimes called waste rock, includes igneous or metamorphic rocks, as well as properly consolidated limestone, sandstone, and dolomitic rocks, that are generally acceptable for granular subbase even if not classified for use in concrete (TFHRC 2006).

Permeable Subbases: Reasons to Avoid Their Use

Permeable subbases, also known as "drainable subbases" or "open-graded subbases," became a very popular design element for concrete highway pavements in the 1990's (FHWA 1992). These subbases are generally characterized as a crushed aggregate (often stabilized with cement or asphalt) with a reduced amount of fines to increase the permeability of the subbase up to levels from 500 to 20,000 ft/day (152 to 6,100 m/day) in laboratory tests. Despite the intuitive advantage of an ability of the permeable subbase to remove excess water from the pavement rapidly, permeable subbases have had a problematic history due to:

- Instability as a construction platform during construction.
- Inherent instability and associated destructive deflection of concrete slabs under repeated loads.
- Early mid-panel cracking on properly sized slabs.
- Early erratic pavement cracking due to high friction between the subbase and the pavement.
- Early faulting from non-uniform support caused by consolidation of unstabilized permeable layers.
- Intrusion of concrete into the voids in the permeable subbase, altering the structural section and the required jointing pattern.
- Infiltration of fines from underlying layers into the permeable subbase voids, clogging the system, and trapping water within the subbase.
- Settling, crushing, and plugging of retrofitted edge drain pipes during and after installation.
- Deferred or no planned maintenance to the drain pipe system, causing water to be trapped within the pavement structure.
- An initial cost of up to 25 percent more than other conventional subbases.

Permeable subbases — permeability greater than about 350 ft/day (107 m/day) in laboratory tests — are no longer considered a cost effective design element for concrete pavement. This conclusion was reached through experiences with poorly performing pavements built on permeable subbase layers. It is further supported by several performance evaluation studies that concluded that these systems do not have a significant positive influence on concrete pavement performance for many design conditions (Elfino and Hossain 2007; Hall and Crovetti 2007; NCHRP 2002). Without contributing appreciably to the performance of concrete pavement, there is no way to justify the high-cost of these rapid-draining systems. Studies show the cost of concrete pavement increases as much as 25% with rapid-draining permeable subbases systems compared to a design with a conventional unstabilized subbase (Cole and Hall 1996).

The following sections discuss the mechanism behind several of the aforementioned problems with permeable subbases, as well as results from the most comprehensive review of the performance of concrete pavement structures that include permeable subbases.

Loss of Support Due to Breakdown of the Aggregate

Starting in 1996, cracks started to appear in the field on pavements placed on unstabilized permeable subbases that with coefficients of permeability around 1,000 ft/day (305 m/day) or higher. The cause of this cracking was the breakdown of material at the joints, which created a non-uniform support condition between the ends of the slab (joints) and the center of slab. The mechanism for the deterioration is crushing of the aggregate in the subbase below pavement joints because of high deflections* and high point-to-point contact pressure between the particles of the unstabilized permeable subbases (Figure 44). When this occurs, the crushed aggregate particles fall into the open void structure of the permeable subbase and, after enough repetitions, the subbase at the joint consolidates, leaving the ends of the slab unsupported.

Though this phenomenon has primarily occurred on unstabilized permeable bases, it has also occurred on asphalt-treated permeable subbases that have stripped. Theoretically, it could also occur on a cement-stabilized permeable subbases if the cementing action between particles were to break down, although this has yet to be recorded in the field.

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* Deflections at slab joints are typically between 2 and 5 times higher than the deflections at the slab center.

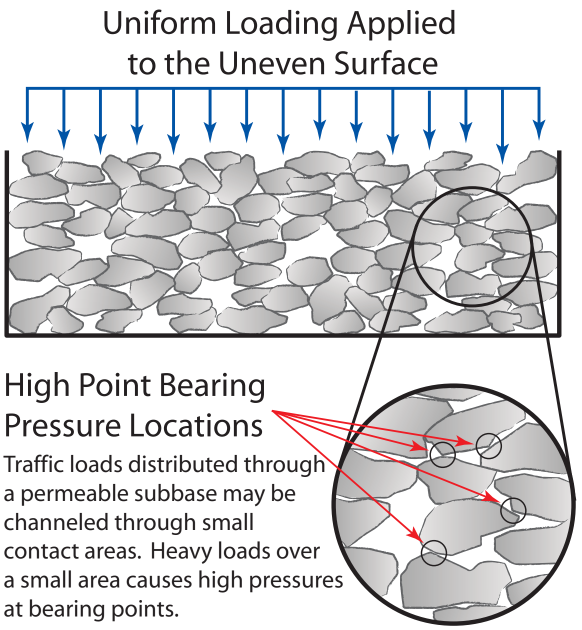

Figure 44. Schematic of unstabilized permeable subbase and potential for high bearing stress.

Because of their increased fines content, free-draining subbase materials will mitigate this mechanism of support loss by increasing the points of contact between aggregate particles and reducing point-to-point bearing pressures between particles.

Loss of Support Due to Infiltration of the Subgrade into the Subbase

Loss of support due to infiltration of the subgrade into the subbase occurs because the subbase under the entire slab consolidates, causing the entire slab to settle (Figure 45). The most common reason for this is having a poor or no filter-separator layer that does not prevent the migration of fines (minus No. 200 (75 µm) material) into the permeable subbase from the subgrade. When this infiltration occurs, the pavement section settles to a degree that matches the infiltration. Though this can occur with both unstabilized and stabilized permeable subbases, stabilized subbases can worsen the effect by “cheese grading” themselves into the subgrade material as the pavement system expands and contracts due to temperature changes throughout the year.

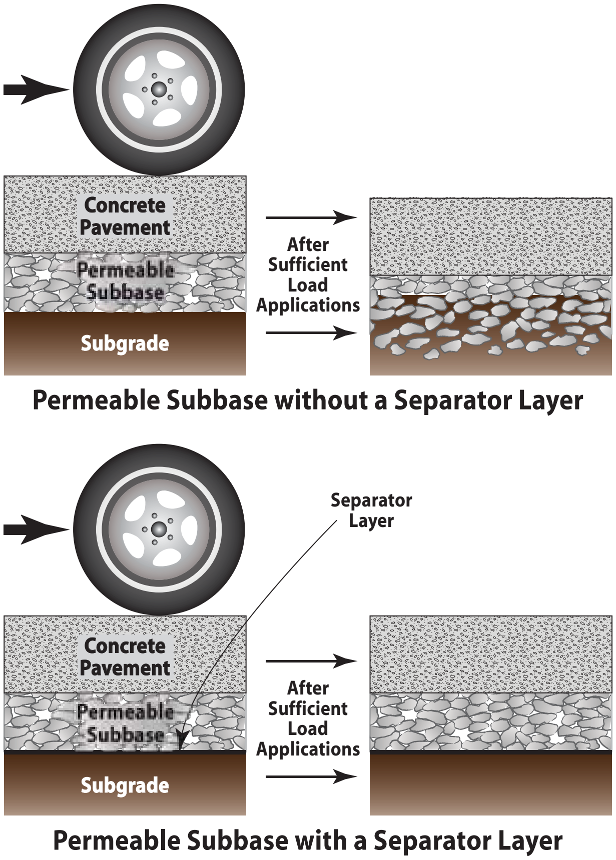

Figure 45. A permeable subbase with and without a separator layer. Note the infiltration of the subgrade and resultant settlement of the pavement in the case without a separator layer.

Early Age Cracking Due to Penetration of Mortar from the Concrete Pavement into the Subbase

Early age cracking due to penetration of mortar from the concrete pavement into the subbase is a problem that can occur on permeable subbases. Because of the openness of the permeable subbase structure, mortar works its way into the voids as the concrete is vibrated and consolidated. This penetration into the subbase restricts slab movement, which increases the risk of both early-age and long-term cracking in the pavement.

Instability as a Construction Platform

Subbase material stability is another important consideration. Dense-graded or free-draining granular materials and materials stabilized with cement or asphalt create firm support for construction equipment. Unstabilized permeable layers, however, have caused some placement problems.

The profile pan (the part of a slipform paver that controls the pavement surface) typically references its position from sensors following stringlines placed along the grade, usually on both sides of the paver. The stringlines are not necessarily parallel to the grade, but rather are set to form the surface regardless of the grade elevation. A well-positioned stringline can help to overcome some minor surface deviations in a subbase or track line, but it is not a substitute for smooth, stable track lines built to a tolerance. The hydraulic systems that control a slipform paving machine's profile pan cannot adjust quickly enough to significant variations in the machine's vertical position caused by settlement of an unstable subbase or track line. An unstable track line causes the profile pan to continually attempt to adjust its position relative to the machine's frame. If too abrupt or frequent, these types of mechanical adjustments are known to cause bumps or dips in the pavement surface.

Layers with high permeability coefficients do not have the in-place stability necessary to enable contractors to build consistently smooth surfaces. Also, agencies must consider if specifying an unstabilized permeable subbase will limit the option to haul concrete to the paving site due to the high potential of rutting of the surface.

Overall Field Performance

The most comprehensive study of the performance of permeable subbases and concrete pavement drainage systems came to the following conclusions (NCHRP 2002):

- *For properly designed, doweled, jointed concrete pavements, joint faulting in general is fairly low and a permeable subbase has a relatively small effect on reducing joint faulting further. When a dense-graded subbase exists, edgedrains were not found to have a significant effect on reducing doweled joint faulting. Dowel bars greatly minimize differential deflections across joints, thus reducing the potential for pumping and erosion.*
- *For non-doweled, jointed concrete pavements, joint faulting in general is much higher and a permeable subbase has a significant effect in reducing joint faulting. However, the permeable subbase must be well designed or it can become contaminated by fines, allowing faulting to develop. The edgedrains must also be maintained properly or they will clog and any potential benefits in pavement performance will be lost.*
- *A significant reduction in D-cracking was identified at an experimental site in Michigan that contained an asphalt-treated permeable subbase (0-, 6-, and 12-percent deteriorated joints on three sections), as compared with sites with dense-graded, asphalt-treated subbases and full depth AC shoulders (79- to 100-percent deteriorated joints on two). When observed over the entire database, concrete sections with permeable subbases averaged less than one-half of the deteriorated joints of concrete sections with dense-graded subbases. A likely reason is that a concrete slab with a permeable subbase may be less saturated than with a dense-graded subbase, resulting in a lower amount of freeze-thaw during saturation to cause D-cracking. This finding is based on very limited data, but, if valid generally, it would have significant implications for concrete pavements constructed in freeze thaw areas with aggregates that are susceptible to D-cracking*.*

Cost Effectiveness

The final consideration is the cost of permeable subbases versus the incremental improvement in pavement performance. Figure 46 shows the relative cost comparisons for different types of subbases that are used under concrete pavements (Cole and Hall 1996). On average, unstabilized permeable subbases add approximately 15% to the cost of concrete pavement relative to a traditional dense-graded

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* The importance of material selection, in particular aggregate selection, for durable concrete cannot be overemphasized. Design feature selection, such as permeable subbases, is no substitute for appropriate control and selection of materials.

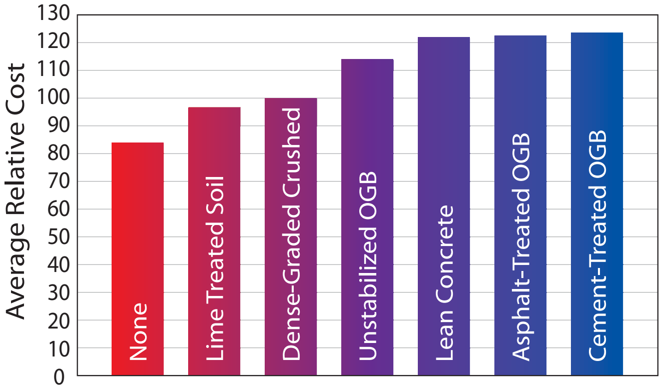

Figure 46. Effects base type have on total construction cost, with dense-graded crushed aggregate base assigned the relative cost of 100 percent.

unstabilized subbase; stabilized permeable subbases add approximately 25% to the cost of concrete pavement due to their additional requirements for layers, materials and edge drain systems. Other studies estimate the cost differential at over 30% (Hoerner, Smith, Bruinsma 2004). A cost-benefit analysis shows that permeable subbases would need to extend pavement life between 8 and 15 years in a life cycle cost analysis to be considered cost effective. Experience over the past two decades indicates that permeable subbases do not provide that level of impact, and the positive impacts of drainage can be provided more effectively with a free-draining subbase layer. Therefore, installation of a permeable subbase design carries with it a substantial risk that the system will not function properly over the life of the pavement and will not extend pavement life enough to be considered cost effective, negating the beneficial concept of this drainage feature (NCHRP 2002).

SPECIAL CONSIDERATIONS OF THE SUBBASE DURING RECONSTRUCTION DUE TO INTERSECTION REPLACEMENT, UTILITY CUTS OR INLAYS

Once the subgrade has been prepared with the special considerations for the subgrade discussed earlier in this publication, a new or replacement subbase must be placed. All placement techniques, compaction requirements, trimming tolerances, etc. are the same as for a new construction, but some consideration must be taken for the size of the work area.

On large intersections, contractors may use automatic trimming equipment to shape the subbase and deposit any excess material outside the paving area. For fixed-form paving, the automatic trimming machine rides on the forms after they are fastened into place. For slipform paving, the trimming machine references the stringline(s) for the slipform paving machine.

On small projects and in confined work zones it may not be practical to use automatic trimming equipment and the contractor will probably trim the grade with a motor grader or small loader.

Because final trimming disturbs the subbase surface slightly, additional compaction rolling is usually necessary after trimming.

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Appendix

Glossary

Because the terminology used in regards to subgrades and subbases is unique and often unfamiliar to pavement design engineers, this extensive Glossary has been included as a means to quickly define many of the terms used inside of this publication. This Glossary is, however, not intended to cover all terms used in the vernacular of subgrades and subbases but several other extensive sources of terms are readily available, such ACI Committee 116 and ASTM standards.

A

AASHTO Soil Classification System – A soil classification system developed to categorize soils according to their load carrying capacity and resultant service life when used as part of a pavement structure.

Absorbed Moisture – The moisture held in a material and having physical properties not substantially different from those of ordinary water at the same temperature and pressure.

Absorption – The amount of water absorbed under specific conditions, usually expressed as a percentage of the dry weight of the material; the process by which the water is absorbed.

Adsorbed Water – Water held on surfaces of a material by physical and chemical forces, and having physical properties substantially different from those of absorbed water or chemically combined water at the same temperature and pressure. Essentially, it is water retained by soil after gravitational and capillary moisture are removed; it can be described as the water associated with the air-dry moisture content.

Adsorption – Development at the surface of a solid of a higher concentration of a substance than exists in the bulk of the medium; especially in concrete and cement technology, formation of a layer of water at the surface of a solid, such as cement, or aggregate, or of air-entraining agents at the air-water boundaries; the process by which a substance is adsorbed.

Aggregate – Granular material, such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast furnace slag, used alone in an unstabilized subbase or with a hydraulic cementing medium or asphalt binder in a stabilized subbase.

Aggregate Blending – The process of intermixing two or more aggregates to produce a different set of properties, generally, but not exclusively, to improve grading.

Aggregate Gradation – The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).

Asphalt-Treated Subbase (ATB) – A stabilized subbase that is bound by asphalt binder.

ASTM (Unified) Soil Classification System – A soil classification system developed to categorize soils according to their textural and plasticity qualities with respect to their performance as engineering construction materials.

B

Base – A layer within an asphalt pavement structure; usually a granular or stabilized material, either previously placed and hardened or freshly placed, on which the pavement surface is placed in a later operation.

Base Course – (also known as *Binder Course*) – The layer(s) of hot mix asphalt immediately below the surface course, generally consisting of less asphalt and larger aggregates than the surface course.

Binder Course – See *Base Course*.

C

California Bearing Ratio (CBR) – The ratio of the force per unit area required to penetrate a soil mass with a 3 in.^{2} (19 cm^2) circular piston. The index (CBR) value is the percent of an established reference value for 0.1 in. (2.5 mm) and 0.2 in. (5.0 mm) penetration. The reference value of 100 was originally considered to represent the resistance of a well-graded crushed stone. Typical CBR values may range from 2 to 8 for clays and 70 to 90 for crushed stones.

Capillarity – (also known as *Capillary Action* or *Capillary Absorption*) – The action by which a liquid (water) rises or wicks in a channel above the horizontal plane of the supply of free water (water table) by way of surface tension forces and without appreciable external pressures. The number and size of the channels in a soil determine its pore size distribution and thus its capillarity. This soil property is measured as the distance (ranging from zero to 30 ft (9.1 m) or more) moisture will rise above the water table by this action.

Capillary – Void space in a sample (i.e., in soil) with microscopic channels small enough to draw liquid water through them by way of molecular attraction of the water adsorbed on the inner surfaces.

Capillary Action – See *Capillarity*.

Capillary Absorption – See *Capillarity*.

Capillary Water – Water held in the soil pores or “capillaries” by “capillary action.”

Cement-Treated Subbase (CTB) – A stabilized subbase that is bound by portland cement with a general dosage of about 4 or 5 percent cement by weight. CTB are best controlled using compaction and/or density requirements, but typical target strengths for a CTB layer are between 300 and 800 psi (2.1 and 5.5 MPa) compression at 7 days.

Cement-Stabilized Subbase – A class of stabilized subbases that includes cement-treated subbases (CTB) and lean concrete.

Centrifuge Moisture Equivalent (CME) – The moisture content of a soil after a saturated sample is centrifuged for one hour under a force equal to 1,000 times the force of gravity. Low values, such as 12 or less, indicate soils of low capillarity such as permeable sands and silts; high values, such as 25, indicate soils of high capillarity such as impermeable clays.

Chemical Modification – Treatment of a sub-ideal subgrade material with lime, portland cement, cement kiln dust, Class C fly ash, or Class F fly ash in conjunction with lime to provide shrink-swell resistance and the uniform stability necessary for an ideal working platform.

Clay – A soil texture method classification category. A fine-textured soil that breaks into very hard clods or lumps when dry and is plastic and unusually sticky when wet. When a ball of moist soil is pressed between the thumb and finger, it will form a long ribbon.

Classification Systems – See Soil Classification Systems.

Cone Penetrometers – Devices used to measure the strength of in place soil; examples include the WES Cone Penetrometer and the Dynamic Cone Penetrometer (DCP). The penetrometers are driven into the ground at either a constant rate (WES) or by dropping a specific hammer weight over a given distance (DCP). Measured values are correlated to CBR, shear strength, or soil modulus value.

Cross-hauling – Replacement of sub-ideal soils with ideal soils at critical points in a pavement structure by either preferentially relocating the sub-ideal material to a lower elevation and subsequently bringing more ideal material towards the surface or removing portions of the subgrade and replacing with more ideal materials.

Crushed Gravel – The product resulting from the artificial crushing of gravel with a specified minimum percentage of fragments having one or more faces resulting from fracture.

Crushed Stone – The product resulting from the artificial crushing of rocks, boulders, or large cobblestones, substantially all faces of which possess well-defined edges and have resulted from the crushing operation.

Crusher-run Aggregate – Aggregate that has been broken in a mechanical crusher and has not been subjected to any subsequent screening process.

Cut-fill Transition – A location in which an area of isolated non-uniformity is eliminated by blending or cross-hauling the sub-ideal subgrade material with a more ideal material to yield a more gradual and uniform transitional area.

D

Daylighted Subbase – (also known as *Daylighting*) – An edge drainage system in which a subbase is extended through the edge of the pavement system to a point where it is capable of freely carrying water to side ditches, hence being daylighted.

Daylighting – See *Daylighted Subbase*.

Degree of Saturation – The ratio of the volume of water in a material (i.e., in aggregate) to the volume of voids, usually expressed as a percentage.

Density – The weight of a unit volume of soil. It may be expressed either as a wet density (including both soil and water) or as a dry density (soil only).

Drainage – The interception and removal of water from, on, or under an area or roadway; the process of removing surplus ground or surface water artificially; a general term for gravity flow of liquids in conduits.

Drainable Subbase – See *Permeable Subbase*.

E

Econocrete – See *Lean Concrete*.

Edge Drainage System – A system designed to carry water that has infiltrated the pavement surface to a side ditch. The two most common types of edge drainage systems are collector pipes with redundant outlets and daylighted subbases.

Enhancement – A method of removing excessive moisture in wet soils by providing drainage via trenches or toe drains at the lowest point(s); compacting the subgrade using heavy equipment, which forces the excess moisture out of the subgrade due to high applied pressures; or adjusting the moisture content through chemical modification (soil stabilization).

Expansive Soil – Soils that change volume with changes in moisture content; expansive soils that may swell enough to cause pavement problems are generally clays falling into the AASHTO A-6 or A-7 groups, or classified as CH, MH or OH by the Unified Classification System, and with a Plasticity Index greater than about 25 by ASTM D4318.

F

Faulting – Differential vertical displacement of a slab or other member adjacent to a joint or crack; often caused by pumping.

Fat Clay – A soil texture method classification category. Highly plastic clay; strongly exhibits the characteristics indicated for clay.

Field Moisture Equivalent (FME) – The minimum moisture content at which a smooth surface of soil will absorb no more water in 30 seconds when the water is added in individual drops; the FME reports the moisture content required to fill all the pores in sands, when the capillarity of cohesionless expansive soils is completely satisfied and when cohesive soils approach saturation.

Fine Aggregate – Aggregate passing the ⅜ in. (9.5 mm) sieve and almost entirely passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (75 µm) sieve.

Fineness Modulus – A measure of the fineness or coarseness of an aggregate sample, usually the fine aggregate (sand). It is determined by adding the cumulative percent retained on each of a specified series of sieves, and dividing the sum by 100.

Fly Ash – The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the fire box through the boiler by flu gasses; used as mineral admixture in cement-treated subbases.

Flowable-fill – Controlled low-strength fill materials that do not need compaction and flow easily to fill a trench. The mixtures contain portland cement, sand, fly ash and water and typically develop 28-day compressive strengths of about 50 to 100 psi (0.35 to 0.70 MPa). Flowable-fill materials provide enough strength to prevent settlement, but are easy to remove using a bucket on a back hoe or front-end loader if future excavation is necessary.

Free-draining Subbase – A subbase with a target permeability between 50 and 150 ft/day (15 and 46 m/day) in laboratory tests; the maximum permeability for a free-draining subbase is approximately 350 ft/day (107 m/day) in laboratory tests and any materials that provide higher permeability rates should be considered permeable subbases.

Free Moisture – (also known as *Free Water*) – Moisture having essentially the properties of pure water in bulk; moisture not absorbed by aggregate.

Free Water – See *Free Moisture*.

Frost Action – A phenomenon in which freezing and thawing of a soil in winter and early springtime might cause uneven support below a pavement surface. The freezing phase of frost action might cause noticeable heaving of the road surface (see *Frost Heave*) and the thawing phase of frost action might cause noticeable softening of the roadbed (see *Subgrade Softening*)

Frost Heave – (also known as *Frost Heaving*) – Heaving of the road surface due to frost action. Frost heave, particularly when in isolated areas, induces uneven support of a pavement.

Frost Heaving – See *Frost Heave*.

Frost-Susceptible Soils – Low-plasticity, fine-grained soils with a high percentage of silt-size particles 0.02 to 2 mils (0.0005 to 0.05 mm). Other soils considered frost-susceptible include loams, sandy loams, clay loams, fine sands, clayey gravel and rock flour. Moderately frost-susceptible soils include dirty sands and gravels and glacial tills. The only soils that can be considered to be non-frost-susceptible are very clean mixtures of sand and gravel.

G

Geosynthetics – Thin pliable sheets of textile material of varying permeability. The varieties of geosynthetics include geotextiles, geogrids, geonets, geocells and geomembranes. The usefulness and effectiveness of geosynthetics directly depends on the type of geosynthetic, the intended function (filtration, separation and/or reinforcement), in-situ soil conditions and installation techniques.

Gradation – See *Grading*.

Grading – The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).

Granular Subbase – See *Unstabilized Subbase*.

Gravel – Granular material predominantly retained on the No. 4 (4.75 mm) sieve and resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

Gravitational Water – Water free to move under the influence of gravity. This is the water that will drain from a soil. For in-situ soils it is water at and below the ground water table and is often termed “groundwater.”

H

Heavy Clay – See *Fat Clay*.

Hygroscopic Water – See *Adsorbed Water*.

I

Illinois Bearing Ratio (IBR) – A measure of the support provided by the roadbed soils or by unbound granular materials. The IBR test is a slight modification of the California Bearing Ratio (CBR) procedure and is a soaked laboratory test. The IBR is considered to be equal to CBR in most cases.

Ion Exchange Stabilization – The chemical mechanism of chemical modification of a subgrade soil in which flocculation and agglomeration of clay particles results in granular particles with a lower PI and lower sensitivity to moisture fluctuation.

J

K

k-value – See *Modulus of Subgrade Reaction*.

L

Lean Clay – A soil texture method classification category. Moderately plastic clay; shows the characteristics indicated for clay, but to a lesser degree.

Lean Concrete Subbase – A subbase that is bound by portland cement and with higher cement and water contents than cement-treated subbases, but they less cement than conventional concrete and an average 7-day compressive strength between 750 and 1,200 psi (5.2 and 8.3 MPa). The aggregates used in lean concrete subbases do not necessarily meet conventional quality standards for aggregates used in pavements.

Lighter Clay – See *Lean Clay*.

Liquid Limit (LL) – This limit separates the plastic state from the liquid state. It is represented by the moisture content at which soil, when separated by a standard groove [0.04 in. (1 mm)] in a standard cup, will flow back together [0.4 in. (1 cm) length] under 25 standard taps or blows [0.4 in. (1 cm) fall impacts]. The liquid limit is considered to relate directly to soil compressibility; the higher the LL, the greater the compressibility.

M

Maximum Size Aggregate – See *Nominal Maximum Size.*

Mill Tailings – A mineral processing waste that may be used as a partial addition to unstabilized subbase layers. However, only the coarser-sized particles are acceptable as long as there are no harmful or reactive chemical components concentrated from the host rock.

Modulus of Subgrade Reaction (k-value) – A bearing test, conducted in the field, which provides an index to rate the support provided by a soil or subbase layer directly beneath a concrete slab; the reaction of the subgrade per unit of area of deformation typically given in psi/in. (MPa/m).

Moist – Slightly damp but not quite dry to the touch; the term wet implies visible free water, damp implies less wetness than wet, and moist implies not quite dry.

Moisture Content – The ratio of the mass of water in a given granular aggregate sample to the dry weight of the mass.

N

Natural Sand – Sand resulting from natural disintegration and abrasion of rock.

Nominal Maximum Size – In specifications for and descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass; sometimes referred to as maximum size (of aggregate).

Nonplastic Soil – A soil that is composed almost entirely of sand sizes, gravel or coarse silt that will show no significant consistency variations with moisture variations.

O

Open-graded Subbase – See *Permeable Subbase*.

P

Pavement Structure – The combination of asphalt/concrete surface course(s) and base/subbase course(s) placed on a prepared subgrade to support the traffic load.

Pea Gravel – Screened gravel the particle sizes of which range between 3⁄16 and ⅜ in. (4.75 and 9.5 mm) in diameter.

Percent Fines – Amount, expressed as a percentage, of material in aggregate finer than a given sieve, usually the No. 200 (75 µm) sieve.

Permeable Subbase – (also known as *Drainable Subbase* or *Open-graded Subbase*) – Unstabilized layer consisting of crushed aggregates with a reduced amount of fines to promote drainage and increase the permeability of the subbase above 350 ft/day (107 m/day) in laboratory tests, although typical levels range from 500 to 20,000 ft/day (152 to 6,100 m/day) in laboratory tests. Despite their intuitive advantage to quickly be able to remove excess water, permeable subbases are no longer considered a cost effective design element for concrete pavements due to their very problematic history.

Permeability – A soil's ability to transmit water through its voids. The permeability of any material is heavily dependent on the connectivity of its pore network; the more connected and the larger the pore network is, the greater the permeability.

Plastic Limit (PL) – This limit separates the semi-solid state from the plastic state. It is represented by the moisture content at which the soil, when rolled into a ⅛ in. (3.2 mm) cylindrical ribbon, will begin to break into short sections.

Plastic Soil – A soil that contains a fine fraction of silt or clay, or a combination of the two, that will pass from a solid to semisolid to plastic and eventually to a liquid state with the gradual addition of water.

Plasticity Index (PI) – The numerical difference between the liquid limit (LL) and the plastic limit (PL), each expressed as moisture content in percent. Low PI soils are very sensitive to moisture change since the addition of only a few percent moisture can change the soil from a plastic to a liquid state.

Porosity – The ratio of the volume of voids to the total volume of the mass regardless of the amount of air or water contained in the voids. Porosity may also be expressed as a percentage.

Pozzolanic Stabilization – The physical mechanism of chemical modification of a subgrade soil in which direct cementitious effects bond soil grains together.

Pumping – The forceful displacement of a mixture of soil and water that occurs under slab joints, cracks and pavement edges which are depressed and released quickly by high-speed heavy vehicle loads; occurs when concrete pavements are placed directly on fine-grained, plastic soils or erodible subbase materials. This nonuniform support condition often results in premature cracking at slab corners and pavement roughness, generally in the form of faulted transverse joints.

Q

R

R-value – See *Resistance Value*.

Radius of Relative Stiffness – A character or property of a concrete slab which measures the stiffness of the slab in relation to that of the subbase/subgrade.

Reclaimed Asphalt Pavement (RAP) – Previously existing asphalt pavement that has been processed for reuse, typically as aggregate in a subbase layer.

Recycled Concrete – Previously existing, hardened concrete that has been crushed and sorted for reuse, typically as aggregate in a subbase layer. Recycled concrete can come from any number of sources, not just concrete pavements, and sorting processes can be adjusted to remove contaminants such as reinforcing steel.

Reinforcement – A method of removing excessive moisture in wet soils by using geosynthetics.

Relative Humidity – The ratio of the quantity of water vapor actually present to the amount present in a saturated atmosphere at a given temperature; expressed as a percentage.

Resistance Value (R-value) – A measure of the stiffness of the subgrade/subbase material by way of resistance to plastic flow. Typical R-values for heavy clays are 0 to 5, for high plasticity silts are 15 to 30 and for well-graded crushed stone base are 80 or more.

Resilient Modulus of Subgrade Soil ($\mathbf{M_{RSG}}$ or $\mathbf{M_R}$ or $\mathbf{E_{SG}}$) – A measure of the stiffness of a subgrade as an estimate of the modulus of elasticity (E) of a material; modulus of elasticity is the stress divided by strain for a slowly applied load and resilient modulus is the stress divided by strain for a rapidly applied load.

S

Sand – The fine granular material (usually less than 3⁄16 in. (4.75 mm) in diameter) resulting from the natural disintegration of rock, or from the crushing of friable sandstone. Also, a soil texture method classification category. Squeezed in the hand when dry, this soil will fall apart when the pressure is released. Squeezed when moist, it will form a cast that will hold its shape when the pressure is released but will crumble when touched.

Sand Equivalent (SE) – A means to quantify the presence of undesirable claylike materials in soils and aggregate materials; this method tends to magnify the volume of clay present in a sample somewhat in proportion to its detrimental effects. Concrete sands and crushed stone have SE values of about 80; very expansive clays have SE values of zero to 5.

Saturated Surface-Dry – Condition of an aggregate particle or other porous solid when the permeable voids are filled with water but there is no water on the exposed surface.

Saturation – 1) In general, the condition of the coexistence in stable equilibrium of either a vapor and a liquid or a vapor and solid phase of the same substance at the same temperature. 2) As applied to aggregate or concrete, the condition such that no more liquid can be held or placed within it.

Selective Grading – Grading operations in which highly frost-susceptible soils are moved to lower portions of embankments and less susceptible soils are cross-hauled to from the lower portion of the subgrade towards the top.

Separation – A method of removing excessive moisture in wet soils by using geosynthetics.

Separator – (also known as *Separator Fabric*) Geotextile fabrics and dense-graded granular layers that prevent the migration of fines from the subgrade into a free-draining subbase.

Separator Fabric – See *Separator*.

Sieve – A metallic plate or sheet, a woven-wire cloth, or other similar device, with regularly spaced apertures of uniform size, mounted in a suitable frame or holder for use in separating granular material according to size.

Sieve Analysis – The classification of particles, particularly of aggregates, according to sizes as determined with a series of sieves of different openings.

Silt – A soil texture method classification category. Consists of a large quantity of silt particles with none to small amounts of sand and clay. Lumps in a dry, undisturbed state appear quite cloddy, but they can be pulverized readily; the soil then feels soft and floury. When wet, silt loam runs together and puddles. Either dry or moist casts can be handled freely without breaking. When a ball of moist soil is pressed between thumb and finger, its surface moisture will disappear, and it will not press out into a smooth, unbroken ribbon but will have a broken appearance.

Silty-clay – A soil texture method classification category. Consists of plastic (cohesive) fines mixed with a significant quantity of silt. It is a fine-textured soil that breaks into hard clods or lumps when dry. When a ball of moist soil is pressed between the thumb and finger, it will form a thin ribbon that will break readily, barely sustaining its own weight. The moist soil is plastic and will form a cast that will withstand considerable handling.

Silty-sand – A soil texture method classification category. Consists largely of sand, but has enough silt and clay present to give it a small amount of stability. Individual sand grains can be seen and felt readily. Squeezed in the hand when dry, this soil will fall apart when the pressure is released. Squeezed when moist, it forms a cast that will not only hold its shape when the pressure is released but will also withstand careful handing without breaking. The stability of the moist cast differentiates this soil from sand.

Shrinkage Limit (SL) – This limit separates the solid state from the semisolid state. It is represented by the point in a drying process at which no further shrinkage takes place while drying continues.

Soil Classification Systems – Systems created to group soil materials in categories according to their physical properties. Two widely used soil classification systems are the ASTM Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) system.

Soil Moisture Suction – See *Capillarity*.

Specific Gravity – The ratio of the weight in air of a given volume of material at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature.

Specific Gravity Factor – The ratio of the weight of aggregates (including all moisture), as introduced into the mixer, to the effective volume displaced by the aggregates.

Stabilized Subbase – A subbase layer that is bound by either portland cement or asphalt binders. Stabilized subbases fall into three general categories: cement-treated, lean concrete and asphalt-treated. The primary benefit of stabilized bases is that they provide relatively strong, uniform support and are resistant to erosion (pumping).

Subbase – The layer(s) of select or engineered material of planned thickness placed between the subgrade and a concrete pavement that serve one or more functions such as preventing pumping, distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction.

Subgrade – The natural ground, graded and compacted, on which a pavement structure is built.

Subgrade Softening – The sharp reduction in subgrade support that occurs when a subgrade thaws both from the surface downwards and from the bottom upward. Typically of little concern for a concrete pavement structure that is adequately designed to resist frost heave.

Substitution – A method of removing excessive moisture in wet soils is removing unsuitable, unstable or excessively wet soils and replacing it with select borrow material or, alternatively, covering the wet soil with a suitable material to develop the necessary uniformity and stability.

Surface Moisture – See *Absorbed Water*.

Surface Tension – The property that, due to molecular forces, exists in the surface film of all liquids and tends to prevent the liquid from spreading.

T

U

Unified Soil Classification System – See *ASTM Soil Classification System.*

Unstabilized Subbase – (also known as *Granular Subbase* or *Untreated Subbase*) – A subbase layer composed of crushed stone, bank run sand-gravels, sands, soil-stabilized gravels, bottom ash, crushed or granulated slag, recycled concrete aggregate, or local materials such as crushed wine waste and sand-shell mixtures and not including any stabilizing agent (i.e., cement or asphalt binders). These are the most common type of subbase for applications such as streets, roadways and highways. The principal criterion for creating a good unstabilized subbase is to limit the amount of fines passing the No. 200 sieve (75 µm) to 15%; if there are too many fines, the unstabilized subbase may hold water more readily and will be prone to erosion, pumping and frost action.

Untreated Subbase – See *Unstabilized Subbase*.

V

Void Ratio – The ratio of the volume of voids to the volume of soil particles. The porosity and void ratio of a soil depend upon the degree of compaction or consolidation. Therefore, for a particular soil in different conditions, the porosity and void ratio will vary and can be used to judge relative stability and load carrying capacity with these factors increasing as porosity and void ratio decrease.

W

Water Content – See *Moisture Content*.

Well-Graded Aggregate – Aggregate having a particle size distribution that will produce maximum density; i.e., minimum void space.

Wet Soil – An in-situ soil condition in which the soil has an excessively high moisture content. Wet soils may be encountered during construction for reasons ranging from a naturally high water table to seasonal rainfall, and even changes in drainage conditions due to construction.

X

Y

Z

AASHTO Standards

All American Association of State Highway and Transportation Officials (AASHTO) documents references in the text of this publications are listed as follows and can be obtained at www.aashto.org; please consult the AASHTO website to ensure that you have obtained the most recent version of any AASHTO standard before using it.

M145	Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes
M147	Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses
M155	Standard Specification for Granular Material to Control Pumping under Concrete Pavement
M252	Standard Specification for Corrugated Polyethylene Drainage Pipe
M278	Standard Specification for Class PS46 Poly (Vinyl Chloride) (PVC) Pipe
T89	Standard Method of Test for Determining the Liquid Limit of Soils
T90	Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
T93	Standard Specification for Determining the Field Moisture Equivalent of Soils (Discontinued)
T96	Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
T99	Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop
T103	Standard Method of Test for Soundness of Aggregates by Freezing and Thawing
T134	Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures
T176	Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test
T180	Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop
T190	Standard Method of Test for Resistance R-Value and Expansion Pressure of Compacted Soils
T193	Standard Method of Test for The California Bearing Ratio
T221	Standard Method of Test for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements
T222	Standard Method of Test for Nonrepetitive Static Plate Load Test of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements
T265	Standard Method of Test for Laboratory Determination of Moisture Content of Soils
T273	Standard Method of Test for Soil Suction
T283	Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
T307	Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials

ASTM Standards

All American Society for Testing and Materials (ASTM) documents references in the text of this publication are listed as follows and can be obtained at www.astm.org; please consult the ASTM website to ensure that you have obtained the most recent version of any ASTM standard procedure before using it.

C131	Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
D422	Standard Test Method for Particle-Size Analysis of Soils
D425	Standard Test Method for Centrifuge Moisture Equivalent of Soils
D426	Method of Test for Field Moisture Equivalent of Soils (Withdrawn 1958)
D427	Test Method for Shrinkage Factors of Soils by the Mercury Method
D558	Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures
D559	Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures
D560	Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures
D698	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))
D1195	Standard Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements
D1196	Standard Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements
D1241	Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses
D1633	Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders
D1883	Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils
D2216	Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2419	Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate
D2487	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D2488	Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)
D2844	Standard Test Method for Resistance R-Value and Expansion Pressure of Compacted Soils
D3152	Standard Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure-Membrane Apparatus
D3282	Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes
D4253	Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table
D4254	Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density
D4318	Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D4546	Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils
D4829	Standard Test Method for Expansion Index of Soils

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