Subgrade Design and Construction

A. General Information

The subgrade is that portion of the pavement system that is the layer of natural soil upon which the pavement or subbase is built. Subgrade soil provides support to the remainder of the pavement system. The quality of the subgrade will greatly influence the pavement design and the actual useful life of the pavement that is constructed. The importance of a good quality subgrade to the long term life of the pavement cannot be understated. As the pavement reaches design life, the subgrade will not have to be reconstructed in order to support the rehabilitated subgrade or the reconstructed pavement. In urban areas, subgrade basic engineering properties are required for design. This section summarizes the design and construction elements for subgrades.

B. Site Preparation

Site preparation is the first major activity in constructing pavements. This activity includes removing or stripping off the upper soil layer(s) from the natural ground. All organic materials, topsoil, and stones greater than 3 inches in size should be removed. Removal of surface soils containing organic matter is important not only for settlement, but also because these soils are often moisture-sensitive, they lose significant strength when wet and are easily disturbed under construction activities. Most construction projects will also require excavation or removal of in-situ soil to reach a design elevation or grade line.

C. Design Considerations

Subgrade soil is part of the pavement support system. Subgrade performance generally depends on three basic characteristics:

1. **Strength:** The subgrade must be able to support loads transmitted from the pavement structure. This load-bearing capacity is often affected by degree of compaction, moisture content, and soil type. A subgrade having a California Bearing Ratio (CBR) of 10 or greater is considered essential and can support heavy loads and repetitious loading without excessive deformation.

2. **Moisture Content:** Moisture tends to affect a number of subgrade properties, including load-bearing capacity, shrinkage, and swelling. Moisture content can be influenced by a number of factors, such as drainage, groundwater table elevation, infiltration, or pavement porosity (which can be affected by cracks in the pavement). Generally, excessively wet subgrades will deform under load.

3. **Shrinkage and/or Swelling:** Some soils shrink or swell, depending upon their moisture content. Additionally, soils with excessive fines content may be susceptible to frost heave in northern climates. Shrinkage, swelling, and frost heave will tend to deform and crack any pavement type constructed over them.

Pavement performance also depends on subgrade uniformity. However, a perfect subgrade is difficult to achieve due to the inherent variability of the soil and influence of water, temperature, and construction activities. Emphasis should be placed on developing a subgrade CBR of at least 10. Research has shown that with a subgrade strength of less than a CBR of 10, the subbase material will deflect under traffic loadings in the same manner as the subgrade. That deflection then impacts the pavement, initially for flexible pavements, but ultimately rigid pavements as well.

To achieve high-quality subgrade, proper understanding of soil properties, proper grading practices, and quality control testing are required. However, pavement design requirements and the level of engineering effort should be consistent with relative importance, size, and cost of design projects. Therefore, knowledge of subgrade soil basic engineering properties is required for design. These include soil classification, soil unit weight, coefficient of lateral earth pressure, and estimated CBR or resilient modulus. Table 6E-1.01 summarizes the suitability of different soils for subgrade applications, and Table 6E-1.02 gives typical CBR values of different soils depending on soil classification.

Table 6E-1.01: Suitability of Soils for Subgrade Applications

Subgrade Soils for Design	Unified Soil Classifications	Load Support and Drainage Characteristics	Modulus of Subgrade Reaction (k), psi/inch	Resilient Modulus (M_R), psi	CBR Range
Crushed Stone	GW, GP, and GU	Excellent support and drainage characteristics with no frost potential	220 to 250	Greater than 5,700	30 to 80
Gravel	GW, GP, and GU	Excellent support and drainage characteristics with very slight frost potential	200 to 220	4,500 to 5,700	30 to 80
Silty gravel	GW-GM, GP-GM, and GM	Good support and fair drainage, characteristics with moderate frost potential	150 to 200	4,000 to 5,700	20 to 60
Sand	SW, SP, GP-GM, and GM	Good support and excellent drainage characteristics with very slight frost potential	150 to 200	4,000 to 5,700	10 to 40
Silty sand	SM, non-plastic (NP), and >35% silt (minus #200)	Poor support and poor drainage with very high frost potential	100 to 150	2,700 to 4,000	5 to 30
Silty sand	SM, Plasticity Index (PI) <10, and <35 % silt	Poor support and fair to poor drainage with moderate to high frost potential	100 to 150	2,700 to 4,000	5 to 20
Silt	ML, >50% silt, liquid limit <40, and PI <10	Poor support and impervious drainage with very high frost value	50 to 100	1,000 to 2,700	1 to 15
Clay	CL, liquid limit >40 and PI >10	Very poor support and impervious drainage with high frost potential	50 to 100	1,000 to 2,700	1 to 15

Source: American Concrete Pavement Association; Asphalt Paving Association; State of Ohio; State of Iowa; Rollings and Rollings 1996.

D. Strength and Stiffness

Subgrade materials are typically characterized by their strength and stiffness. Three basic subgrade stiffness/strength characterizations are commonly used in the United States: California Bearing Ratio (CBR), modulus of subgrade reaction (k), and elastic (resilient) modulus. Although there are other factors involved when evaluating subgrade materials (such as swell in the case of certain clays), stiffness is the most common characterization and thus CBR, k-value, and resilient modulus are discussed here.

1. **California Bearing Ratio (CBR):** The CBR test is a simple strength test that compares the bearing capacity of a material with that of a well-graded crushed stone (thus, a high-quality crushed stone material should have a CBR of 100%). It is primarily intended for, but not limited to, evaluating the strength of cohesive materials having maximum particle sizes less than 0.75 inches. Figure 6E-1.01 is an image of a typical CBR sample.

Figure 6E-1.01: In-situ CBR

Source: ELE International

The CBR method is probably the most widely used method for designing pavement structures. This method was developed by the California Division of Highways around 1930 and has since been adopted and modified by numerous states, the U.S. Army Corps of Engineers (USACE), and many countries around the world. Their test procedure was most generally used until 1961, when the American Society for Testing and Materials (ASTM) adopted the method as ASTM D 1883, CBR of Laboratory-Compacted Soils. The ASTM procedure differs in some respects from the USACE procedure and from AASHTO T 193. The ASTM procedure is the easiest to use and is the version described in this section.

The CBR is a comparative measure of the shearing resistance of soil. The test consists of measuring the load required to cause a piston of standard size to penetrate a soil specimen at a specified rate. This load is divided by the load required to force the piston to the same depth in a standard sample of crushed stone. The result, multiplied by 100, is the value of the CBR. Usually, depths of 0.1 to 0.2 inches are used, but depths of 0.3, 0.4, and 0.5 inches may be used if desired. Penetration loads for the crushed stone have been standardized. This test method is intended to provide the relative bearing value, or CBR, of subbase and subgrade materials. Procedures are given for laboratory-compacted swelling, non-swelling, and granular materials. These tests are usually performed to obtain information that will be used for design purposes. The CBR value for a soil will depend upon its density, molding moisture content, and moisture content after soaking. Since the product of laboratory compaction should closely represent the results of field compaction, the first two of these variables must be carefully controlled during the preparation of laboratory samples for testing. Unless it can be ascertained that the soil being tested will not accumulate moisture and be affected by it in the field after construction, the CBR tests should be performed on soaked samples.

Relative ratings of supporting strengths as a function of CBR values are given in Table 6E-1.02.

Table 6E-1.02: Relative CBR Values for Subbase and Subgrade Soils

CBR (%)	Material	Rating
> 80	Subbase	Excellent
50 to 80	Subbase	Very Good
30 to 50	Subbase	Good
20 to 30	Subgrade	Very good
10 to 20	Subgrade	Fair-good
5 to 10	Subgrade	Poor-fair
< 5	Subgrade	Very poor

The higher the CBR value of a particular soil, the more strength it has to support the pavement. This means that a thinner pavement structure could be used on a soil with a higher CBR value than on a soil with a low CBR value. Generally, clays have a CBR value of 6 or less. Silty and sandy soils are next, with CBR values of 6 to 8. The best soils for road-building purposes are the sands and gravels whose CBR values normally exceed 10. Most Iowa soils rate fair-to-poor as subgrade materials.

The change in pavement thickness needed to carry a given traffic load is not directly proportional to the change in CBR value of the subgrade soil. For example, a one-unit change in CBR from 5 to 4 requires a greater increase in pavement thickness than does a one-unit change in CBR from 10 to 9.

2. **Resilient Modulus (M_R):** M_R is a subgrade material stiffness test. A material's M_R is actually an estimate of its modulus of elasticity (E). While the modulus of elasticity is stress divided by strain for a slowly applied load, M_R is stress-divided by strain for rapidly applied loads like those experienced by pavements. Flexible pavement thickness design is normally based on M_R. See Table 6E-1.01 for typical M_R values.

   The resilient modulus test applies a repeated axial cyclic stress of fixed magnitude, load duration, and cycle duration to a cylindrical test specimen. While the specimen is subjected to this dynamic cyclic stress, it is also subjected to a static confining stress provided by a triaxial pressure chamber. It is essentially a cyclic version of a triaxial compression test; the cyclic load application is thought to more accurately simulate actual traffic loading.

   The M_R is a slightly different measurement of somewhat similar properties of the soil or subbase. It measures the amount of recoverable deformation at any stress level for a dynamically loaded test specimen. Both measurements are indications of the stiffness of the layer immediately under the pavement.

   The environment can affect pavement performance in several ways. Temperature and moisture changes can have an effect on the strength, durability, and load-carrying of the pavement and roadbed materials. Another major environmental impact is the direct effect roadbed swelling, pavement blowups, frost heave, disintegration, etc. can have on loss of riding quality and serviceability. If any of these environmental effects have a significant loss in serviceability or ride quality during the analysis period, the roadbed soil M_R takes the environmental effects into account if seasonal conditions are considered.

The purpose of using seasonal modulus is to qualify the relative damage a pavement is subject to during each season of the year and treat it as part of the overall design. An effective road bed soil modulus is then established for the entire year which is equivalent to the combined effects of all monthly seasonal modulus values. AASHTO provides different methodology to obtain the effective M_R for flexible pavement only. The method that was selected for use in this manual was based on the determination of M_R values for six different climatic regions in the United States that considered the quality of subgrade soils.

Figure 6E-1.03: Resilient Modulus

Source: Federal Highway Administration

3. **Modulus of Subgrade Reaction (k, k_c):** This is a bearing test that rates the support provided by the subgrade or combination of subgrade and subbase. The k-value is defined as the reaction of the subgrade per unit of area of deformation and is typically given in psi/inch. Concrete pavement thickness design is normally based on the k-value. See Table 6E-1.01 for typical k-values.

   Modulus of subgrade reaction is determined with a plate bearing test. Details for plate bearing tests are found in AASHTO T 221 and AASHTO T 222 or ASTM D 1195 and ASTM D 1196.

   Several variables are important in describing the foundation upon which the pavement rests:

   a. **Modulus of Subgrade Reaction (k):** For concrete pavements, the primary requirement of the subgrade is that it be uniform. This is the fundamental reason for specifications on subgrade compaction. The k-value is used for thickness design of concrete pavements being placed on prepared subgrade.

   b. **Composite Modulus of Subgrade Reaction (k_c):** In many highway applications the pavement is not placed directly on the subgrade. Instead, some type of subbase material is used. When this is done, the k value actually used for design is a "composite k" (k_c), which represents the strength of the subgrade corrected for the additional support provided by the subbase.

4. Correlation of Strength and Stiffness Values:

a. Relationship of CBR and Dynamic Cone Penetrometer (DCP) Index: The dual mass Dynamic cone Penetrometer (DCP) is a method for estimating in-place stability from CBR correlations. As shown in Figure 6E-1.05, the dual mass DCP consists of an upper and lower 5/8 inch diameter steel shaft with a steel cone attached to one end. The cone at the end of the rod has a base diameter of 0.79 plus 0.01 inches. As an option, a disposable cone attachment can be used for testing of soils where the standard cone is difficult to remove from the soil. According to Webster et al. (1992), the disposable cone allows the operator to perform twice the number of tests per day than with the standard cone. At the midpoint of the upper and lower rods, an anvil is located for use with the dual mass sliding hammers. By dropping either a 10.1 or a 17.6 pound hammer 22.6 inches and impacting the anvil, the DCP is driven into the ground. For comparison, the penetration depth caused by one blow of the 17.6 pound sliding hammer would be approximately equivalent to two blows from the 10.1 pound hammer. The 10.1 pound hammer is more suitable for sensitive clayey soils with CBR values ranging from 1 to approximately 10; however, it is capable of estimating CBR values up to 80. In general, the 17.6 pound hammer is rated at accurately measuring CBR values from 1 to 100. At its full capacity, the DCP is designed to penetrate soils up to 39 inches. In highly plastic clay soils, the accuracy of the DCP index decreases with depth due to soil sticking to the lower rod. If necessary, hand-augering a 2 inch diameter hole can be used to open the test hole in 12 inch increments, preventing side friction interference.

CBR and DCP index (PI):

1) For all soils except CL below CBR of 10, and CH soils:

$$CBR = \left(\frac{292}{PI} \right)^{1.12}$$

2) For soils with CBR less than 10:

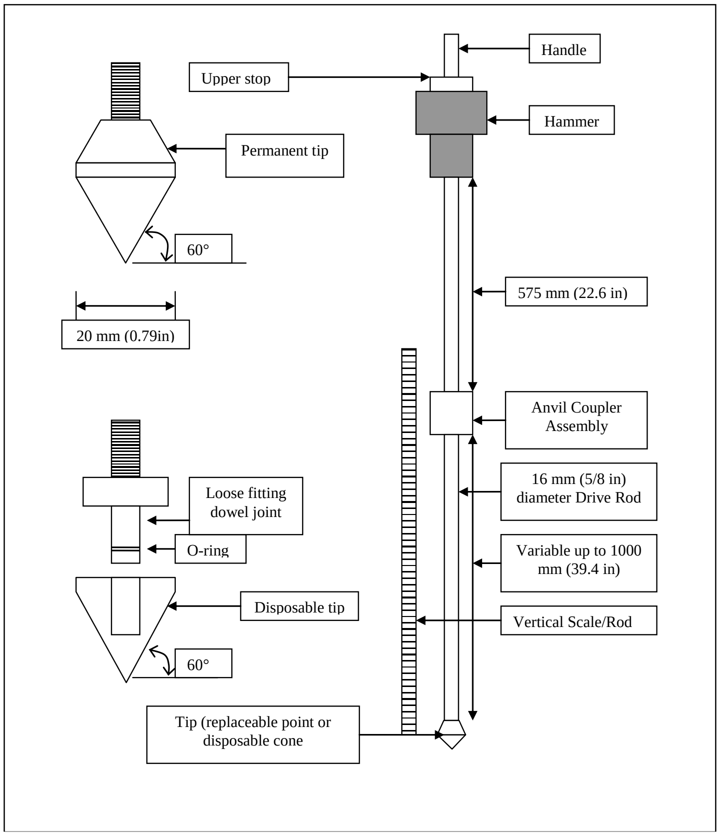
$$CBR = \left(\frac{1}{0.0170019 x PI} \right)^{2}$$

3) For CH soils:

$$CBR = \left(\frac{1}{0.002871 x PI} \right)$$

Where PI = Penetration index from DCP, (mm/blow)

Figure 6E-1.05: DCP Design and Cone Tip Details



b. Relationship of M_R and k-value: An approximate relationship between k and M_R published by AASHTO is fairly straightforward.

$k = M_R/19.4$

where

k = modulus of subgrade reaction (psi/inch)
M_R = roadbed soil resilient modulus of the soil as determined by AASHTO T 274.

c. Relationship of CBR, MR, and k-value: See approximate relationships in Table 6E-1.01.

E. Subgrade Construction

1. **General:** The most critical element for subgrade construction is to develop a CBR of at least 10 in the prepared subgrade using on-site, borrow, or modified soil (see Section 6H-1 - Foundation Improvement and Stabilization). Uniformity is important, especially for rigid pavements, but the high level of subgrade support will allow the pavement to reach the design life.

   In most instances, once heavy earthwork and fine grading are completed, the uppermost zone of subgrade soil (roadbed) is improved. The typical improvement technique is achieved by means of mechanical stabilization (i.e., compaction). Perhaps the most common problem arising from deficient construction is related to mechanical stabilization. Without proper quality control and quality assurance (QC/QA) measures, some deficient work may go unnoticed. This is most common in utility trenches and bridge abutments, where it is difficult to compact because of vertical constraints. This type of problem can be avoided, or at least minimized, with a thorough plan and execution of the plan as it relates to QC/QA during construction. This plan should pay particular attention to proper moisture content, proper lift thickness for compaction, and sufficient configuration of the compaction equipment utilized (weight and width are the most critical). Failure to adequately construct and backfill trench lines will most likely result in localized settlement and cracking at the pavement surface.

2. **Compaction:** Compaction of subgrade soils is a basic subgrade detail and is one of the most fundamental geotechnical operations for any pavement project. The purpose of compaction is generally to enhance the strength or load-carrying capacity of the soil, while minimizing long-term settlement potential. Compaction also increases stiffness and strength, and reduces swelling potential for expansive soils.

   a. **Density/Moisture:** The most common measure of compaction is density. Soil density and optimum moisture content should be determined according to ASTM D 698 (Standard Proctor Density) or ASTM D 4253 and D 4254 (Maximum and Minimum Index Density for Cohesionless Soils). At least one analysis for each material type to be used as backfill should be conducted unless the analysis is provided by the Engineer.

      Field density is correlated to moisture-density relationships measured in the lab. Moisture-density relationships for various soils are discussed in Part 6A - General Information. Optimal engineering properties for a given soil type occur near its compaction optimum moisture content, as determined by the laboratory tests. At this state, a soils-void ratio and potential to shrink (if dried) or swell (if inundated with water) is minimized.

      For pavement construction, cohesive subgrade soil density should satisfy 95% of Standard Proctor tests, with the moisture content not less than optimum and not greater than 4% above optimum. For cohesionless soils (sands and gravel), a minimum relative density of 65% should be achieved with the moisture content greater than the bulking moisture content.

   b. **Strength/Stiffness:** Inherent to the construction of roadway embankments is the ability to measure soil properties to enforce quality control measures. In the past, density and moisture content have been the most widely measured soil parameters in conjunction with acceptance criteria. However, it has been shown recently that density and moisture content may not be an adequate analysis. Therefore, alternate methods of in-situ testing have been reviewed. The dual mass Dynamic Cone Penetrometer (DCP) is a method for estimating in-place stability from CBR correlations.

   c. **Equipment:** Several compaction devices are available in modern earthwork, and selection of the proper equipment is dependent on the material intended to be densified. Generally, compaction can be accomplished using pressure, vibration, and/or kneading action. Different types of field compaction equipment are appropriate for different types of soils. Steel-wheel rollers, the earliest type of compaction equipment, are suitable for cohesionless soils. Vibratory steel rollers have largely replaced static steel-wheel rollers because of their higher efficiency. Sheepsfoot rollers, which impart more of a kneading compaction effort than smooth steel wheels, are most appropriate for plastic cohesive soils. Vibratory versions of sheepsfoot rollers are also available. Pneumatic rubber-tired rollers work well for both cohesionless and cohesive soils. A variety of small equipment for hand compaction in confined areas is also available. Table 6E-1.03 summarizes recommended field compaction equipment for various soil types.

Table 6E-1.03: Recommended Field Compaction Equipment

Soil	First Choice	Second Choice	Comment
Rock fill	Vibratory	Pneumatic	--
Plastic soils, CH, MH	Sheepsfoot or pad foot	Pneumatic	Thin lifts usually needed
Low-plasticity soils, CL, ML	Sheepsfoot or pad foot	Pneumatic, vibratory	Moisture control often critical for silty soils
Plastic sands and gravels, GC, SC	Vibratory, pneumatic	Pad foot	--
Silty sands and gravels, SM, GM	Vibratory	Pneumatic, pad foot	Moisture control often critical
Clean sands, SW, SP	Vibratory	Impact, pneumatic	--
Clean gravels, GW, GP	Vibratory	Pneumatic, impact, grid	Grid useful for over-size particles

Source: Rollings and Rollings 1996

The effective depth of compaction of all field equipment is usually limited, so compaction of thick layers must be done in a series of lifts, with each lift thickness typically in the range of 6 to 8 inches.

The soil type, degree of compaction required, field compaction energy (type and size of compaction equipment and number of passes), and the contractor’s skill in handling the material are key factors determining the maximum lift thickness that can be compacted effectively. Control of water content in each lift, either through drying or addition of water plus mixing, may be required to achieve specified compacted densities and/or to meet specifications for compaction water content.

Proof-rolling with heavy rubber-tired rollers is used to identify any remaining soft areas. The proof-roller must be sized to avoid causing bearing-capacity failures in the materials that are being proof-rolled. Proof-rolling is not a replacement for good compaction procedures and inspection. An inspector needs to be present onsite to watch the deflections under the roller in order to identify soft areas. Construction equipment such as loaded scrapers and material delivery trucks can also be used to help detect soft spots along the roadway alignment. It is very difficult to achieve satisfactory compaction if the lift is not on a firm foundation.

3. **Overexcavation/Fill:** The installation of structural features (e.g., sewer, water, and other utilities) adjacent to or beneath pavements can lead to problems during or following construction. Proper installation of such utilities and close inspection during construction are critical.

   A key element in the installation of these systems is proper compaction around and above the pipe. Granular fill should always be used to form a haunch below the pipe for support. Some agencies are using flowable fill or controlled low strength material (CLSM) as an alternative to compacted granular fill. Without this support feature, the weight above the pipe may cause it to deform, creating settlement above the pipe, and often pipe collapse. Even if a sinkhole does not appear, leaks of any water-bearing utility will inundate the adjacent pavement layers, reducing their support capacity.

   Pavement problems also occur when improper fill is used in the embankment beneath the pavement system. Placement of tree trunks, large branches, and wood pieces in embankment fill must not be allowed. Over time, these organic materials decay, causing localized settlement, and they eventually form voids in the soil. Again, water entering these voids can lead to collapse and substantial subsidence of the pavement section. Likewise, placement of large stones and boulders in fills create voids in the mass, either unfilled due to bridging of soil over the large particles or filled with finer material that cannot be compacted with conventional equipment. Soil above these materials can migrate into the void space, creating substantial subsidence in the pavement section. These issues can be mitigated with well-crafted specifications that will prohibit the use of these types of materials.

Transitions between cut zones and fill zones can also create problems, particularly related to insufficient removal of weak organic material (clearing and grubbing), as well as neglect of subsurface water movements. A specific transition also occurs at bridge approaches. These problems are typically related to inadequate compaction, usually a result of improper compaction equipment mobilized to the site or lack of supervision and care (e.g., lift placement greater than compaction equipment can properly densify).

F. References

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