Optimizing Subgrades & Subbases for Concrete Pavements

National Concrete Pavement Technology Center
Iowa’s Lunch–Hour Workshop
In cooperation with the Iowa DOT
and the Iowa Concrete Paving Association
The performance of a pavement depends on the quality of its subgrade and subbase layers and the drainage of these foundation layers; They can play a key role in mitigating the effects of climate and the stresses generated by traffic.
1. Uniformity
2. Soils
3. Soil Stabilization
4. Subbases (unstabilized)
5. Geosynthetics
Pavement Support Basics

- Firm, uniform, and non-erodible support is essential for concrete pavements
  - Reduces pavement defections from vehicle loadings
  - Avoids stress concentrations
- Must provide a stable working platform to expedite all construction operations
- Subgrade uniformity is more important than strength
Non-Uniform Subgrade Support

- Non-uniform support results in differential deflections, causing stress concentrations in the pavement.
- Have different soil properties.

Concrete Pavement

Stiff Subgrade | Soft Subgrade | Stiff Subgrade

Stress Intensities
SOILS
Soil Particle Size (by themselves)

Sand
- 0.05–2 mm diameter
- High permeability

Silt
- 0.002–0.05 mm diameter

Clay
- less than 0.002 mm diameter
- Low permeability

Source: Thomson Higher Education
<table>
<thead>
<tr>
<th>AASHTO CLASSIFICATION</th>
<th>GENERAL DESCRIPTION</th>
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<tbody>
<tr>
<td>A-1</td>
<td>Well graded coarse to fine; non-plastic or feebly plastic; includes coarse without binder</td>
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<tr>
<td>A-1-a</td>
<td>Mostly stone fragments or gravel</td>
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<tr>
<td>A-1-b</td>
<td>Mostly coarse sand; may need added fines for a firm base; suitable or can be made suitable for granular base coarse</td>
</tr>
<tr>
<td>A-2-4</td>
<td>Granular with binder characteristics of A-4 and A-5 soils</td>
</tr>
<tr>
<td>A-2-5</td>
<td>Granular with binder characteristics of A-6 and A-7 soils</td>
</tr>
<tr>
<td>A-2</td>
<td>Soils are inferior to A-1 soils due to poor grading, inferior binder, or both generally are suitable as a blanket for very plastic subgrades slated to receive concrete pavement</td>
</tr>
<tr>
<td>A-3</td>
<td>Sands deficient in soil binder and coarse material; equigranular; examples are fine beach or desert blown sands. Water has little affect on A-3 soils</td>
</tr>
<tr>
<td>A-4</td>
<td>Composed mostly of silt with only moderate to small amounts of coarse material and only small amounts of clay; can vary texturally from sandy loams to silt to clay loams</td>
</tr>
<tr>
<td>A-5</td>
<td>Similar to A-4 except that they include very poorly graded soils containing such things as mica; is a poor stability soil.</td>
</tr>
<tr>
<td>A-6</td>
<td>Composed predominately of clay with moderate to negligible amounts of coarse material; have low stability at high moisture contents but are pretty stable otherwise; show shrinkage cracks during dry weather; is a good soil other than the fact that it has great affinity for water</td>
</tr>
<tr>
<td>A-7</td>
<td>Composed predominately of clay like A-6 but due to the presence of one-size silt particles, organic matter, mica flakes, or lime carbonate, is elastic</td>
</tr>
<tr>
<td>A-7-5</td>
<td>Moderate plasticity indexes; may be highly elastic. P.I. less than or equal to L.L. –30</td>
</tr>
<tr>
<td>A-7-6</td>
<td>High plasticity indexes P.I. greater than L.L. –30</td>
</tr>
</tbody>
</table>
This is the textural triangle. If you know the percent clay (flat line) and percent sand or silt, you can draw lines into the triangle to figure out what textural category the soil belongs to.
A-4 soils are predominantly silts with variable amounts of granular material or clay and some plasticity. Their strength varies with moisture content. These soils are very susceptible to frost heaving when located over sand pockets holding water in glacial till. They are very susceptible to erosion.

A-5 soils are silty soils with moderate liquid limit (40 max)

A-6 soils are clay soils with higher liquid limit (41 min)

A-7 soils are predominantly clay with variable amounts of granular material or silt. They are highly plastic and their strength varies appreciably with moisture content. They are also expansive.
SL=Shrinkage Limit (While drying, no more shrinkage)
PL=Plastic Limit (Beginning of Plastic State. The higher, the more swelling)
LL=Liquid Limit (Beginning of Liquid State. The higher, the greater compressibility)
PI=Plasticity Index (LL-PL) (The higher, the more plastic the soil and higher swell)
AASHTO Criteria

Plastic Index

Liquid Limit

- **A-7-6**: (High Plasticity Clay)
- **A-7-5**: (Moderate plastic clay)
- **A-2-7**: (Granular with A-7)
- **A-2-6**: (Granular with A-6)
- **A-6**: (Clay)
- **A-4, A-2-4**: Low
- **A-5, A-2-5**: Medium
- **(Granular with A-6)**: High

Plasticity

PI=LL-30
Cohesive Soils (Plastic)

- The consistency of these soils can range from a dry, solid state to a wet, liquid state with the addition of 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.
Organic Soils

Any soil that contains a sufficient amount of organic matter to influence the engineering properties is called organic soil.

As a result, organic soils have the following characteristics:

• Have a lower density than other mineral soils
• May have a low shear strength
• May be highly compressible
• Can be very difficult to compact
• May continue to degrade over time
# Unsuitable Soils

<table>
<thead>
<tr>
<th>Definition</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Peat or Muck.</td>
<td>Slope Dressing Only.</td>
</tr>
<tr>
<td>2. Soils with a plasticity index of 35 or greater.</td>
<td></td>
</tr>
<tr>
<td>3. A-7-5 or A-5 having a density less than 85pcf (1350 kg/m³) (AASHTO T 99 Proctor Density or Materials I.M. 309).</td>
<td></td>
</tr>
<tr>
<td>1. All soils other than A-7-5 or A-5 having a density of 95 pcf (1500 kg/m³) or less (AASHTO T 99 Proctor Density or Materials I.M. 309).</td>
<td>Type C placement placed 3 feet (1 m) below top of subgrade in fills.</td>
</tr>
<tr>
<td>2. All soils other than A-7-5 or A-5 containing 3.0% or more carbon.</td>
<td></td>
</tr>
<tr>
<td>1. A-7-6 (30 or greater).</td>
<td>Type B placement placed 5 feet (1.5 m) below top of subgrade in fills.</td>
</tr>
<tr>
<td>2. Residual clays (overlaying bedrock), Paleosols, gumbo, and gumbotils regardless of classification.</td>
<td></td>
</tr>
<tr>
<td>1. Shale</td>
<td>Type A placement placed in layers 5 feet (1.5 m) below top of subgrade in fills (Alternate layers to consist of suitable soils or Type C placement soils).</td>
</tr>
<tr>
<td>2. A-7-5 or A-5 soils having a density greater than 86 pcf (1351 kg/m³) but less than 95 pcf (1500 kg/m³) (AASHTO T 99 Proctor Density or Office or Materials I.M. 309).</td>
<td></td>
</tr>
</tbody>
</table>

**Iowa DOT Table 2102.02-1: Uses for Unsuitable Soils**
(SUDAS – Not allowed in ROW)
Water Sources

1. **Water Table – 100% Saturation**

2. **Cracking from non-uniform support from differential soil movement.**

   - **Surface Water**
   - **Adsorption Water**
   - **Capillary Fringe**
Water Movement

• Capillary Action; Movement of water in narrow soil pores through intermolecular attractive forces between the soil and water.

• Pore Pressure- During compaction of the soil the pores become smaller and the water bonded to the soil loosens and becomes unbounded free water causing the pressure to rise, resulting in the rising of the free water.
Capillarity, Permeability, and Frost Action

- The finer the grain, the higher the capillarity
  - Very little air content between grains
  - Pore network affect permeability.
  - The simpler the network the higher the permeability
Frost Heave

**Cause**

- Water in large pores freezes at normal freezing temperature
- Water in capillary tubes and small intersects of soil does not freeze and is drawn to ice mass

**Effect**

- Road surface heaved at least as much as combined lens thickness
- Ice Lenses

**Ground Water**

- Road Surface

**Water in large pores**

- Freezes at normal freezing temperature

**Base course**

- Water in capillary tubes and small intersects of soil does not freeze and is drawn to ice mass

**Road surface**

- Heaved at least as much as combined lens thickness
Compaction of Soils

Why compact the soil?

- Removes air and moisture
- Well compacted soils minimize the amount of moisture moving through
- Reduces settlement
- Increases bearing capacity
- Reduces frost heave if soil freezes
- Reduces expansion and contraction

California Bearing Ratio (CBR)
Modulus of Subgrade Reaction (k)
Influence of Moisture on Engineering Properties

- Want to achieve
  - High strength
  - Low compressibility
  - Low Shrink/Swell potential

Dry of Optimum
Strength (Higher)
Stability (Higher)
Compressibility (Low)
Swell (High)

Wet of Optimum
Strength (Lower)
Compressibility (Higher)
Permeability (Lower)
Volume Change (Lower)
Shrink (Lower)
M & D for Different Soils

- **Sandy silt**
- **Silty clay**
- **Highly plastic clay**
- **Poorly graded sand**

Dry unit weight, $\gamma_d$ (lb/ft$^3$) vs. Moisture content, $w$ (%)
Subgrade Testing – Compaction with M & D

- Compact to 95% of maximum Standard Proctor Density
- Ensure moisture content is within range of optimum moisture to 4% above optimum (SUDAS)

Test soil strength with CBR Test
- Compares soil bearing capacity vs. well graded crushed stone
- High quality crushed stone CBR = 100%
- Typically 3-4 in Iowa

Source: ELE International
Dynamic Cone Penetrometer (DCP)
Subgrade Testing – Proof Roll

Proof Roll
  • loaded single axel (20,000 pounds)
  • loaded tandem axle (34,000 pounds)
  • 10 mph

Unstable if:
  • soil wave in front of load
  • rutting >2 inches

Source; Geomax Soil Stabilization
Working Platform Problems

• High Plasticity = High Plasticity Index = Instability

• Expansive clays = Volume change

• Weak soils = Poor bearing capacity

• Wet/soft subgrade = Poor support
Soil Improvement Options

1. Scarify and drying
2. Blending soil
3. Add geogrid and subbase
4. Add chemical stabilization
5. Remove unsuitable and replace with select material in at least upper 2’
Subgrades – Proper Compaction and Consolidation to Prevent Settlement

12” Subgrade Preparation

Blend non-uniform soil in 8” lifts and provide M&D at 95% standard proctor density
Geogrids

Geogrid + aggregate subbase:
- Creates stronger composite structure
- Minimizes subbase fill
- Serves as construction platform
- Extends service life

SUDAS Specification 2010 or Iowa DOT 4196.01B
- Rectangular or Triangular
- Max. Aperture size 2”
- Min. Aperture size 0.5”
- Min. Tensile strength @2% strain 250 lbs/ft
- Min. Ultimate junction strength 800 lbs/ft
Chemical Soil Stabilization Options

Soil Stabilization:
To amend the undesirable properties of poor native soils to make suitable for construction

Fly Ash
• Class C 15-18%

Quick lime
• High quality 3-4%
• Dolomite quicklime 6-8%

Cement Modified Soils (CMS)
• Cement 2-3%
Fly Ash & Lime

Fly Ash
- Some concern for weakening in spring thaw
- May tend to group clay particles together and make more frost susceptible
- Recommend compaction within 2 hours

Quicklime
- Has slower reaction than Fly Ash
- If applied to dry soil, it can expand later

Both create a working platform

Source: Boone County Expo Research Study
Cement Modified Soils (CMS)

Use 2 - 3% Cement
1. Provides Uniformity
2. Provides Working Platform
3. Provides bonding of particles
4. Reduces Shrink-Swell Potential of Clay Soils
5. Wet cohesive soils may require disking to cut in cement
6. All operations in one day
7. May be applied in dry or slurry form

Source: PCA
Chemical Soil Stabilization Construction

- Recommend placement in temperatures above 40ºF otherwise it sits dormant

- Blend in soil with rotary mixer

- Use sheepfoot roller for initial roll, then smooth drum roller

- Shape with motor grader to final crown and grade
Effect of 3% Cement on Cohesive Soils

Before CMS

7 days after adding 3% cement

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Effect of Cement on Cohesive Soils

AASHTO Criteria

Plastic Index

Low

Medium

High

A-6 (Clay)

A-2-6 (Granular with A-6)

A-7-6 (High Plasticity Clay)

A-7-5 (Moderate plastic clay)

A-2-7 (Granular with A-7)

A-4, A-2-4

A-5, A-2-5

Liquid Limit

PI=LL-30

Before

After CMS
SUBBASES (UNSTABILIZED)
Subbases

- Used when soil is reasonably stable & not excessively wet.
- Provides a working platform during construction
- Provides uniformity as a support layer
- Serves as a drainage system to help drain surface water away from the pavement
- Provides a cutoff layer from subsurface moisture (and risk for pumping)
- Reduces shrink and swell of high volume change soils
- A subdrain and outlet system needs to be provided
Granular Subbases Stability versus Permeability

Dense stable (Class “A”)
- High fines/High Stability
- Low Permeability

Moderately Permeable (Modified Subbase)
- Medium Fines/Medium Stability

Highly Permeable (Granular Subbase)
- Few if any Fines/Low stability
NEW RESEARCH FINDINGS ON PAVEMENT SUPPORT LAYERS
IHRB TR–640 Optimizing Pavement Base, Subbase and Subgrade Layers for Cost and Performance on Local Roads

Field Investigation

David J. White, Ph.D., P.E.
Associate Professor
Director, CEER

Pavana KR. Vennapusa, Ph.D.
Research Assistant Professor
Asst. Director, CEER

Guidance for Improving Foundation Layers to Increase Pavement Performance on Local Roads

IOWA STATE UNIVERSITY
Institute for Transportation
Project Objectives

- Determine the level of increased performance when Portland Cement Concrete (PCC) is placed on granular subbase
- Quantify the performance and cost effectiveness
- Develop a user guide for various traffic, soils and pavement factors
- Performance measured by PCI
• PCC Pavement (16 Sites) were tested to capture range of conditions statewide
  – Pavement Age: 30 days to 42 years
  – Surface Distress Conditions: Poor to Excellent (PCI = 35 to 92)
  – Support Conditions:
    ▪ Natural Subgrade
    ▪ Fly Ash Stabilized Subgrade
    ▪ 6 in. to 12 in. Granular Subbase
  – Pavement Thickness: 6 to 11 in.
  – Traffic (AADT): 110 to 8900
TR-640 Findings

- Low & variable support values (due to low CBR)
- Poor drainage (Cd)
- Loss of support
- The more uniform subgrade and higher coefficient of drainage (Cd), the higher the PCI
- Increase in drainage has the largest effect on the PCI
TR-640 Performance Prediction Model

Factors:
- Age
- Drainage Coefficient ($C_d$)
- Coefficient of variation for $k$ & CBR
- Weak subgrade layer (CBR)
- Traffic
- Pavement thickness
- Subbase (if or if not)

PCI Prediction Model

Best Fit

Prediction Model Equation (multiple linear regression trend)

TR640 Data: 
PCI = 5.553 - 1.615 (Age) - 2.009 (CBR$_{SG, Weak}$) 
- 1.055 (COV of CBR$_{SG, Weak}$) + 205.907 (C$_d$) + 0.004 (AADT) 

Adj. $R^2 = 0.959$, RMSE = 4.430 
($a = +6.891$ if subbase is present, and $-6.891$ if subbase is not present)
Guidance for Improving PCC Pavement Performance

Pavements with aggregate subbase are performing better than those without
PCI Prediction Calculation

PCI vs Age
500 AADT, 7" PCC, Prediction Model

Prediction Model

\[ PCI = 5.553 - 1.615 \, (\text{Age}) - 2.009 \, (\text{CBR}_{SG-Weak}) - 0.2245 \, (\text{COV of } \text{CBR}_{SG-Weak}) + 205.907 \, (C_d) + 0.004 \, (\text{AADT}) - 1.055 \, (\text{COV of } k_{FWD-corr}) - 2.395 \, (\text{PCC Thickness}) + a \]

\[ a = +6.891 \text{ if subbase is present and } -6.891 \text{ if subbase is not present} \]
PCI Prediction Calculation

**Prediction Model**

\[
PCI = 5.553 - 1.615 \cdot \text{(Age)} - 2.009 \cdot \text{(CBR}_{SG\text{-Weak}}) - 0.2245 \cdot \text{(COV of } \text{CBR}_{SG\text{-Weak}}) + 205.907 \cdot \text{(C}_d) + 0.004 \cdot \text{(AADT)} - 1.055 \cdot \text{(COV of } \text{k}_{FWD\text{-corr}}) - 2.395 \cdot \text{(PCC Thickness)} + a
\]

\[a = +6.891 \text{ if subbase is present and } -6.891 \text{ if subbase is not present}\]
What was Learned from the IHRB-TR640 Study

Aggregate Subbase Loss

Pavement thickness design software programs do not reflect actual pavement foundation conditions except immediately after construction.
Geotextiles

Woven
• High strength support
• Less permeable
• Used to increase support & stabilization (and filtration and separation)

Nonwoven
• Felt-like
• More permeable
• Used for filtration and separation

Made of Polypropylene fibers
Benefits of Geotextiles

Southwest Westlawn Drive (Poor Subgrade)

Woven Geosynthetic Fabric
Aggregate Subbase Thickness Limitations (IRI)

MEPDG Failure mode: IRI (in./mi)

Subbase thickness over 5” does not benefit PCC
Aggregate Subbase Thickness Limitations

MEPDG Failure mode: % Cracked Slabs

Subbase thickness over 5” does not benefit PCC
### Cost Example for Improved PCC Pavement Performance

<table>
<thead>
<tr>
<th>Subgrade Conditions</th>
<th>Approach &amp; Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet &amp; Unstable</td>
<td>Chemically treated soils</td>
</tr>
<tr>
<td></td>
<td>6” Cement Modified Soils = $4.50/ Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>5” aggregate subbase = $6.00/ Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>$10.50/ Sq.Yd.</td>
</tr>
<tr>
<td>After compaction, slightly wet &amp; somewhat stable but will not pass proof rolling</td>
<td>Dry out soil, place woven geotextile with 5” aggregate subbase.</td>
</tr>
<tr>
<td></td>
<td>Geotextile (woven) = $2.50/Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>5” aggregate subbase = $6.00/Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>$8.50/Sq.Yd.</td>
</tr>
<tr>
<td>Meets moisture &amp; density control and passes proof rolling</td>
<td>Non woven geotextile</td>
</tr>
<tr>
<td></td>
<td>5” aggregate subbase = $1.75/Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>= $6.00/Sq.Yd.</td>
</tr>
<tr>
<td></td>
<td>$7.75/Sq.Yd.</td>
</tr>
</tbody>
</table>

CMS or Fly Ash $0.75/Sq.Yd/in; Aggregate $1.20 /Sq. Yd/in.
Thank you!

National CP Tech Center
www.cptechcenter.org/