Determining Material Moisture Characteristics for Pavement Drainage and Mechanistic Empirical Design

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INTRODUCTION

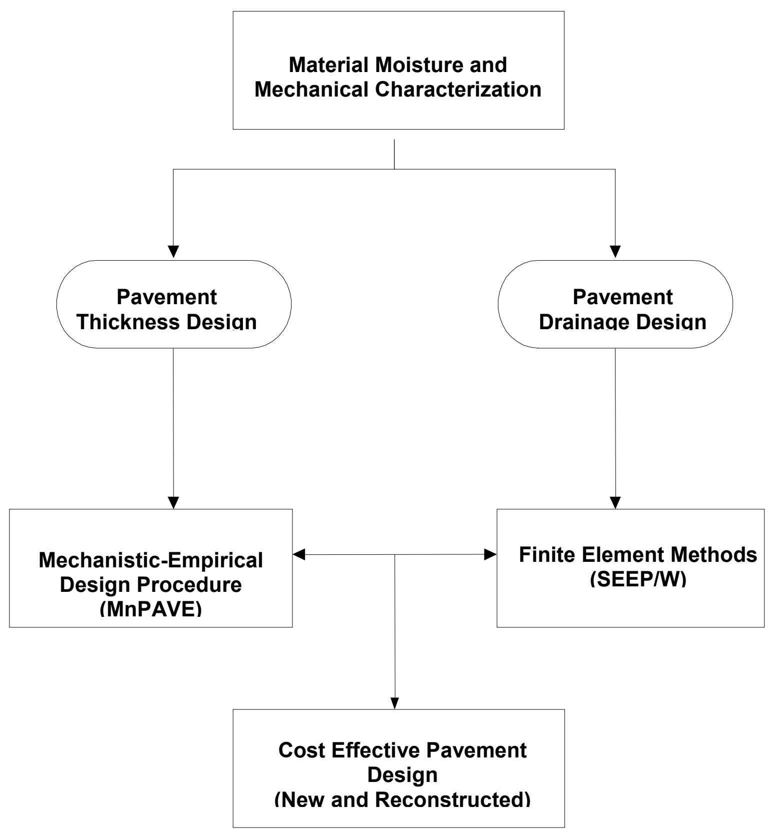
Material properties that contribute to pavement distress include modulus and shear strength, which are greatly influenced by moisture content, density, and gradation. Failures in flexible pavements resulting from poor performance of granular layers are manifested as permanent deformation (rutting), fatigue and longitudinal cracking, depressions, corrugations and frost heave. Failures in rigid pavements resulting from poor performance of granular layers include pumping, faulting, cracking, corner breaks, and fatigue cracking (Saeed *et* al, 2001). These distresses diminish the structural integrity of the pavement and reduce pavement life. In particular, moisture entering the pavement system through joints and cracks or from seasonal fluctuations in temperature and precipitation contribute to loss of load carrying capacity due to a reduction in base and subgrade strength and stiffness. If the relationships between material properties and distress are not well defined in the design process, the result can be premature pavement failure or inefficient pavement structures.

To address moisture related distresses originating in the base and subgrade, and to meet design requirements, an understanding of material moisture characteristics is critical. The material moisture study currently underway at the Office of Materials and Road Research serves a dual purpose by addressing mechanistic-empirical (ME) design requirements and also providing a means for evaluating pavement drainage design and construction practice. This Research Bulletin provides an overview of the project.

BACKGROUND

Results from research conducted at the Mn/ROAD test facility indicate that the moisture conditions in the pavement aggregate base, granular subbase, and subgrade are variable over time and space. Variably saturated conditions occur on a seasonal basis as well as in response to single precipitation events. The goal of Mn/DOT's research is to incorporate material moisture characteristics into both ME-design and pavement drainage design in order to more fully account for changing moisture conditions, and to reduce moisture related distress. Soil physics and soil mechanics theories and methods are used to define the relationships between soil moisture and permeability, and soil moisture and strength characteristics of saturated and unsaturated base, subbase, and subgrade materials. Ultimately improving our understanding of the relationships between moisture properties and critical pavement design parameters.

The objectives of the study are to characterize the moisture and mechanical properties of pavement base and subgrade materials through testing in the laboratory and field where possible. Properties such as gradation, permeability, moisture retention,



modulus, and shear strength are measured and used to expand an existing database of material properties. The database will be used to develop soil property functions that relate physical index properties to mechanistic structural design properties, and for FEM models used to simulate moisture flow within pavement systems.

SUBSURFACE MOISTURE CONDITIONS

Water content is measured in the pavement base, subbase, and subgrade using Time Domain Reflectometry (TDR) methods. From the plot of water content data (figure 1) it is clear that the moisture conditions in the pavement base vary during the year. Figure 1 is a graph of water content data collected from Mn/ROAD test section 12, 9" Jointed Portland Concrete (JPC) over 5" of drained Mn/ROAD Class 5 Special aggregate base (Mn/DOT, 2000). The TDR data shows that the base begins to thaw on day 45 (February 15, 1998), long-term (seasonal) and short-term (single-event) changes in moisture content in the Class 5 aggregate base material, and a moisture content gradient between the outer wheel path (OWP) and the centerline (CL). Moisture contents in the outer wheel path remain higher than moisture contents at the centerline seasonally and after single events.

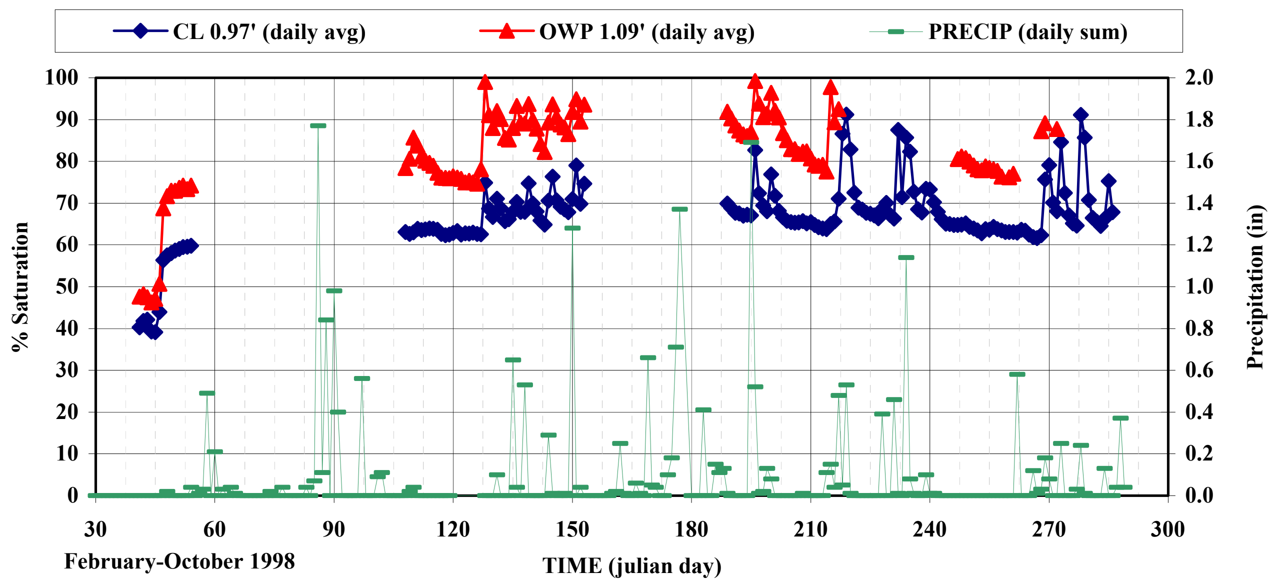


Figure 1: Mn/ROAD test section 12, automated TDR data and precipitation vs time.

The moisture content in the outer wheel path varies between 75% and 100% saturation, while centerline moisture content varies between 60% and 90% saturation. According to Fredlund *et* al. *(*1993) air entry potential (figure 3), or the suction at which the largest pores begin to drain due to gravity, is generally between 80-90% saturation. Below air entry the soil is in an unsaturated state. Tempe Cell measurements conducted at the University of Minnesota (Kjaersgaard and Gupta, 2001) verify this for Mn/ROAD Class 5 Special. Air entry for the Class 5 Special is approximately 90% saturation or 4 kPa suction (figure 5). Based on this measurement, the centerline is primarily in an unsaturated condition, while the outer wheel path hovers around saturation depending on available moisture. Since water flows from high potential (saturated) to a low potential (unsaturated) the hydraulic potential gradient is driving moisture from the outer wheel path toward the centerline.

A second example of variable moisture conditions measured in the pavement base can be seen in figure 2. Data in figure 2 were collected from a drained concrete test section. The pavement structure consisted of 9" of JPC over 4" of drained Permeable Asphalt Stabilized Base (PASB), over 3" of a Class 4 Special granular subbase separator layer. Similar to test section 12 there are variably saturated conditions with the centerline remaining dryer than the outer wheel path on both a seasonal and single event basis. Water content data from test section 10 indicates that the PASB appears to have a "dampening" affect on moisture content increases in the Class 4 Special granular subbase separator layer. The sharp response to single precipitation events seen in the Class 5 Special base layer in test section 12 (figure 1) is not evident in data collected from test section 10. This has implications for pavement drainage because it appears that water infiltrating through the lane-shoulder joint is not drawn under the pavement into the PASB layer. Although, as with test section 12 the hydraulic gradient is from the outer wheel path toward the centerline in the Class 4 Special separator layer. This suggests that water entering through the lane-shoulder joint moves from the outer wheel path toward the centerline regardless of the presence of the PASB or the edge drains. However, the presence of the PASB layer does prevent moisture from accumulating directly beneath the pavement layer. Additionally, since the lane-shoulder joint is the primary source of infiltration (Ahmed *et* al., 1997) this would explain why the outer wheel path remains at higher moisture contents than the centerline in both test sections.

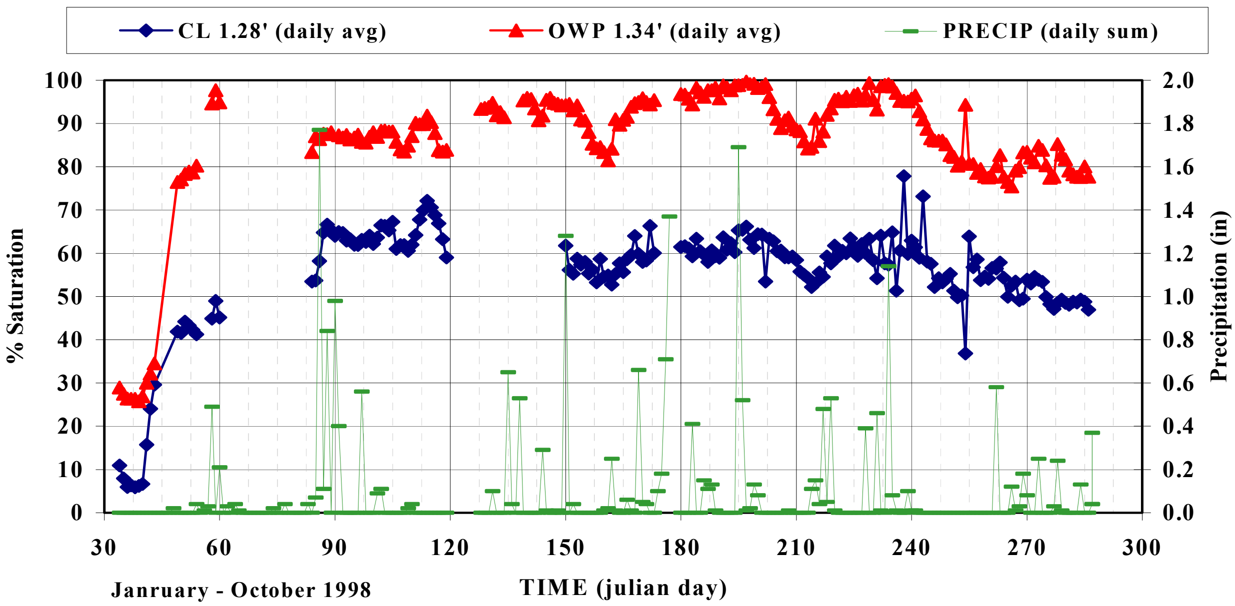


Figure 2: Mn/ROAD test section 10, automated TDR data and precipitation vs time.

Soil Water Characteristic Curve

The Soil Water Characteristic Curve (SWCC) (Figure 3) is central to understanding variably saturated soil behavior. The SWCC describes the relationship between the volume of water in the soil and the energy state of that water (Gupta and Wang, 2002). The SWCC is also referred to as the moisture characteristic or moisture release curve.

The shape of the SWCC is a function of the pore size distribution, which is determined by the soil particle size distribution (gradation), particle shape, and the packing of those particles. Figure 4 illustrates the soil structure as it desaturates. When the soil is saturated all the pores are filled with water. As the soil begins to dry the relatively large pores begin to drain under gravity. If desaturation continues the soil approaches the air-entry suction, the critical suction value representing the threshold between saturated and unsaturated conditions. Below air-entry suction the larger pores have emptied and the smaller pores hold the water via matric suction. Matric suction refers to the attraction of the water molecules for each other (cohesive forces) plus the attraction of the water molecules to the soil-particle surface (adhesive forces). Water movement occurring under unsaturated conditions is due primarily to the matric suction component of the hydraulic potential. Detailed descriptions of the SWCC are provided in many soil physics textbooks (Hillel, 1980, Jury et al, 1991, Hanks and Ashcroft, 1986). Fredlund and Rahardjo (1993) provide a look at the SWCC from an engineering perspective.

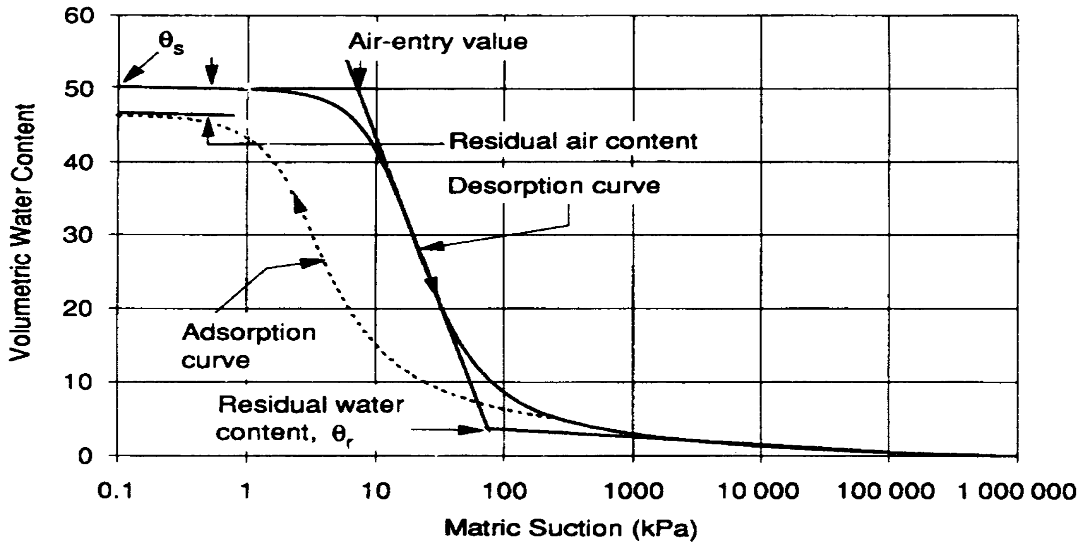


Figure 3: Soil Water Characteristic Curve (SWCC) (Fredlund *et* al. 1995)

Figure 5 is a plot of SWCCs for three different aggregate gradations. The Select Granular gradation is considered less moisture susceptible than either the Class 5 or Class 6 because the upward movement of water, or the height of rise due to capillarity, in the Select Granular is low relative to the Class 5 and Class 6. This is attributed to the dominance of large pores in the Select granular material. For example, at 80% saturation the suction values are approximately 1.7 kPa, 3 kPa, and 10 kPa for the Select Granular, Class 6 Special, and Class 5 Special respectively.

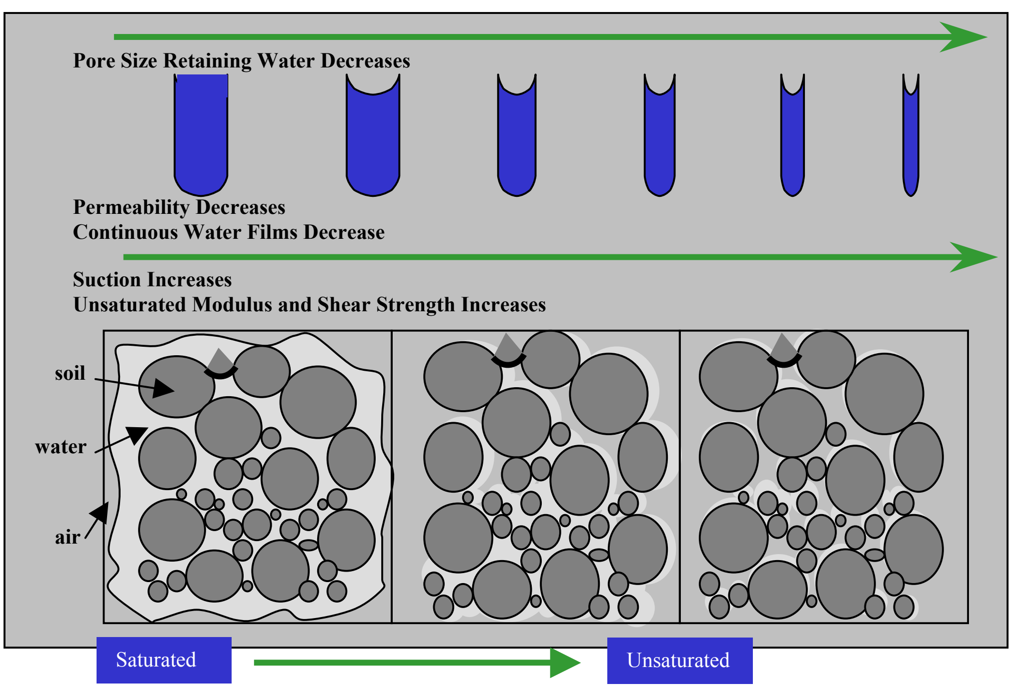


Figure 4: As the soil dries from saturated to unsaturated, permeability decreases while shear strength increases.

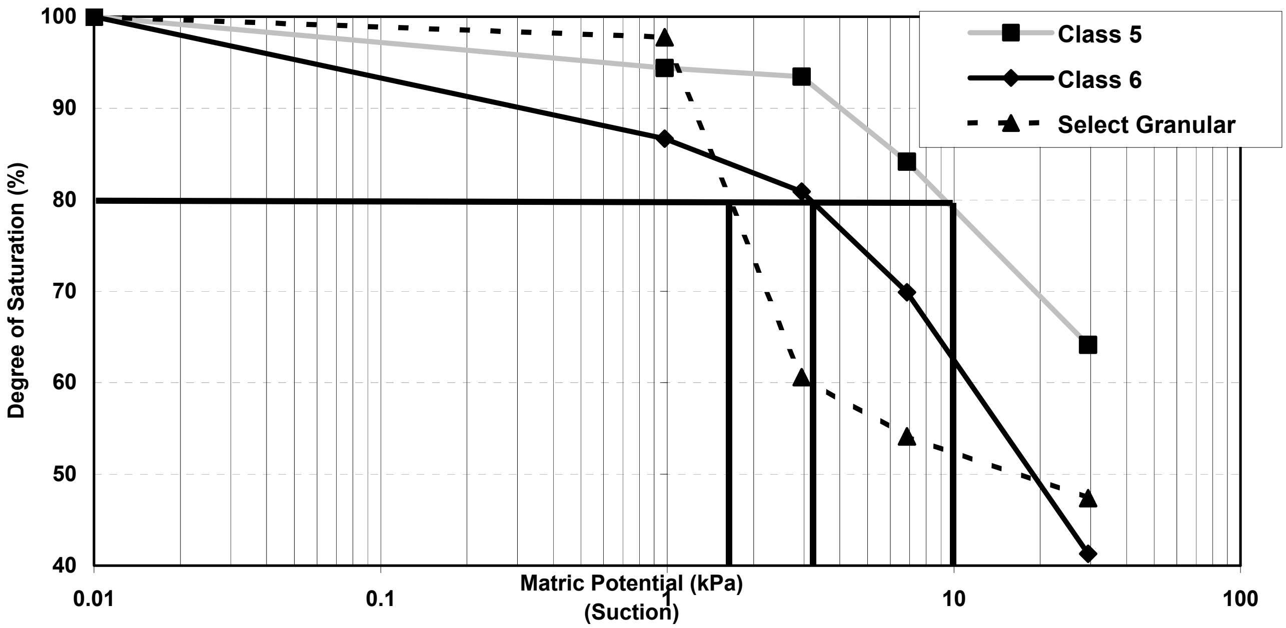


Figure 5: SWCC's for MnROAD Class 5 and 6 Special and Select Granular (Onamia, Mn TH169).

MODELING WATER MOVEMENT

Modeling flow patterns and pavement subsurface drainage requires the use of numerical methods. Finite element methods (FEM) of analysis are commonly used in geotechnical engineering to model seepage around structures such as dams and foundations. More recently FEM have been used to compare the effectiveness of pavement drainage designs, taking into account the unsaturated conditions present in the base and subbase layers (Hassan and White, 1998, Lebeau and Lafleur, 1998). SEEP/W (GEO-SLOPE, 1991) is finite element software currently used by Mn/DOT's Road Research Section to model water movement in variably saturated soils. Ariza and Birgisson (2001) provide justification for the use of SEEP/W to model moisture movement in pavement systems. Input parameters such as the soil water characteristic curve, soil hydraulic conductivity function, precipitation, and depth to water table, are used to estimate flow patterns below the pavement surface.

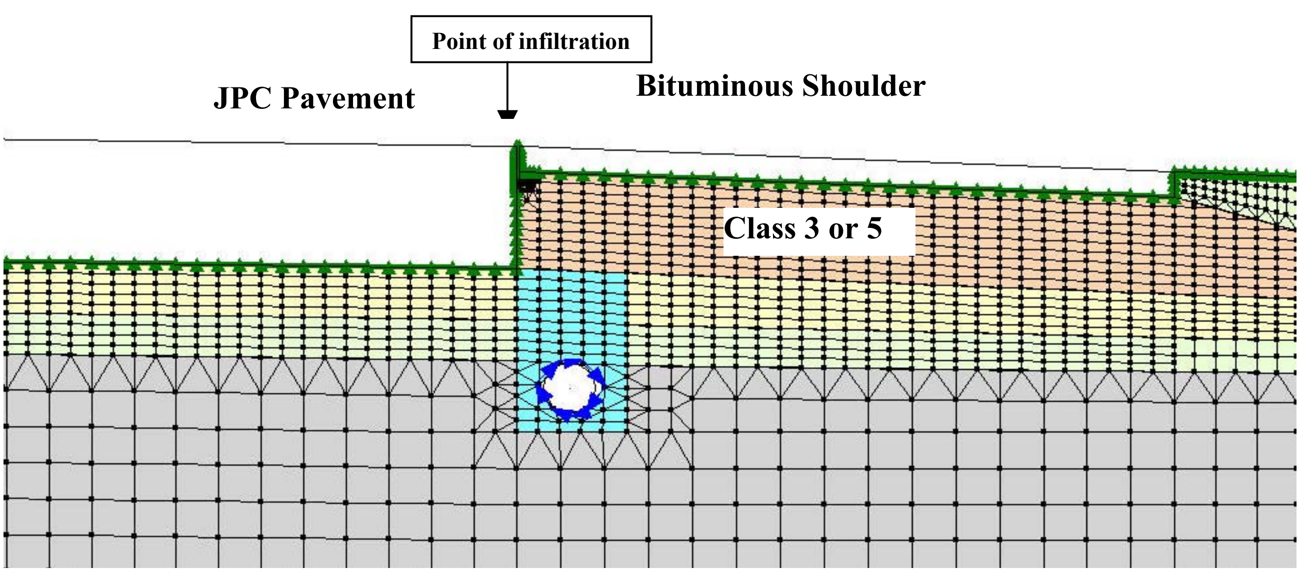


Figure 6: Mn/ROAD test section 10. Geometry and mesh used to simulate water movement in pavement base and subgrade layers (P. Ariza and B. Birgisson, 2001).

Figures 6 and 7 show the pavement geometries and FEM mesh used to evaluate two Mn/DOT pavement drainage designs. The geometry in figure 6 is used to simulate infiltration and moisture redistribution in test section 10. Model results confirm that infiltration into unsaturated material at the lane-shoulder joint will result in a hydraulic potential gradient from the outer wheel path toward the centerline. Water entering at this joint moves under the pavement in the Class 4 granular subbase toward the centerline. The geometry and mesh in figure 7 represents Mn/DOT's reduced frost design. Select Granular is used to fill a 30 inch subcut. The purpose of the subcut drain is to mitigate the "bathtub" effect.

Finite element methods provide a powerful tool for evaluating pavement drainage design. Material moisture properties are key in the modeling process, while data collected at the Mn/ROAD site provide a means for model verification.

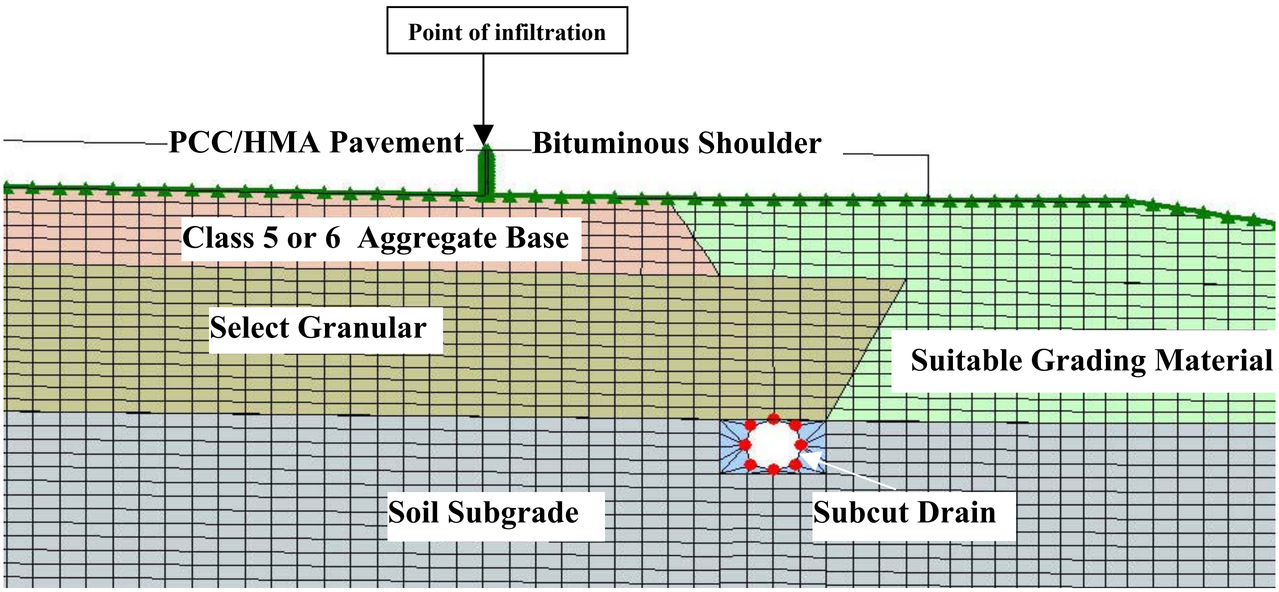


Figure 7: Mn/DOT's Reduced frost design.

SWCC and Mechanistic Empirical Design Parameters

The effect of matric suction on resilient modulus and shear strength is recognized as contributing to the behavior of unsaturated soils. Pavements are typically constructed above the ground water table and have equilibrium water contents below saturation. Therefore matric suction (i.e. SWCC) should be incorporated into material characterization and pavement structural design (Oloo and Fredlund, 1998). Understanding and quantifying this relationship for pavement aggregate base, granular subbase, and soil subgrade materials will improve estimates of the seasonal strength properties and improve design processes.

Mechanistic and Empirical Design

One of the features of MnPAVE, Mn/DOT's mechanistic-empirical pavement design software, is consideration of the affect of moisture on thickness design. Pore suction resistance factors are proposed as a means for incorporating variably saturated soil conditions into pavement thickness design. These pore suction resistance factors are based on unsaturated pore suction occurring when the ground water table is deeper than approximately 5 feet from the pavement surface. Pore suction resistance factors will account for the ability of different soils to draw water into open pore spaces (capillarity). The pore suction factors are important because they are used to modify seasonal moisture resistance factors. Current moisture resistance factors are based on Mn/ROAD test sections constructed on a clay loam subgrade.

The pore suction resistance factors are currently based on the relationship between the difference in the laboratory percent saturation near standard Proctor optimum moisture, and the in situ saturation expected for Minnesota soils (Swanberg and Hansen, 1946; Kersten, 1944). The pore suction resistance factors are under development and will be modified by research proposed by Mn/DOT at the University of Minnesota. This research is intended to define the soil moisture characteristics for a sample of Minnesota soils and aggregate base materials.

SUMMARY

Variably saturated conditions are measured in the pavement aggregate base, granular subbase and subgrade. To determine how properties such as permeability, strength, and modulus change with changing moisture conditions it is necessary to measure or estimate the SWCC for different pavement materials and soil types. The Office of Materials and Road Research is currently using finite element methods to simulate moisture movement in the pavement system for evaluating and improving drainage design practices. Researchers are also using material moisture characterization to predict seasonal changes in the stiffness and strength properties for incorporation into mechanistic-empirical structural design.

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