EVALUATION OF UNTREATED BASE COURSE MATERIAL FOR DRAINABILITY

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Disclaimer

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EXECUTIVE SUMMARY

Through a process that is commonly known as "pumping," water enters the pavement section and quickly destroys the integrity of the pavement section. Water enters the pavement section by precipitation penetrating the surface and through high capillary action of the soils beneath the base. The best method to avoid the damaging effects caused by pumping is to construct a base that will prevent the infiltrating water from collecting directly under the pavement. The base should consist of open graded material which allows the water to quickly drain away from the pavement. The open graded base can be placed under selected roads only or under all roadways, depending on the specific circumstances.

The Utah Department of Transportation (UDOT), through research and experience, realized that water was not draining away from the pavement structure and wanted to know how to improve the drainability of their base material. The research procedure involved measuring the hydraulic conductivity (k) of UDOT's current untreated base material, collecting helpful information from states who use permeable bases, establishing the k-value for various states permeable base material, and conducting a cost analysis on improving the permeability of the base material.

A permeability test was conducted for UDOT's current untreated base material and results confirmed that the material, with a permeability value of less than 0.30 m/day (1 ft/day), is low compared to results from other states. The permeability values of others states ranged from 100 to more than 1,000 m/day (300 to more than 3,000 ft/day). The main difference

between UDOT's and other states' gradations was the amount of material passing the smaller size sieves, 2.0 mm to 0.075 mm (No. 10 thru No. 200) sieve. UDOT's material has a higher percentage of fines. Results from several studies have shown that the permeability increased as the percentage of material passing the smaller sieves decreased. A cost analysis indicated it would cost an additional $1.65 per metric ton ($1.50 per ton) to improve the drainability of the desired roadways.

The costs associated with reducing the amount of material passing the smaller sieves is insignificant compared to the money saved on maintenance and increased life expectancy of the road. Permeable bases can increase the life-span of the road by as much as 50 percent. States using a permeable base are quite satisfied with the noticeable results of less maintenance costs and the longer life-span of the pavement section.

To improve the permeability of UDOT's base material it was recommended that a gradation similar to New Jersey's be used. This recommendation is based on findings from reviewing literature, current practices in other states, basic research, and findings presented in this study.

The findings of this study will be implemented by revision of the UDOT Standard Specification by the UDOT Materials Division. The implementation of the recommendations of this study will result in improved long-term performance of Utah highways.

INTRODUCTION

Origin and Nature of Problem

Through a process that is commonly known as "pumping, water enters the pavement section and quickly destroys the integrity of the pavement section. Water enters the pavement section by precipitation penetrating the surface and through high capillary action of the soils beneath the base. The best method to avoid the damaging effects caused by pumping is to construct a base that will prevent the infiltrating water from collecting directly under the pavement. The base should consist of open graded material to allow the water to quickly drain away from the pavement. Open graded material is "characterized by a relatively narrow range of particle sizes" (Hoppe, 1996, p. 1).

This premature pavement failure to Utah's highways has prompted the Utah Department of Transportation (UDOT) to investigate ways of preventing water from infiltrating through the pavement and collecting in the untreated base course material. This report will focus on one method of reducing and even eliminating the harmful effects of free water penetrating the pavement section and accumulating in the base material.

Objectives

In an effort to prevent pumping and reduce premature pavement failures due to infiltrated water, UDOT has contracted Utah State University (USU) to evaluate the hydraulic conductivity (k) of Utah's dense graded untreated base course material. The hydraulic conductivity describes the ease with which water will flow through the untreated base material

(Daniel, 1993). In addition to evaluating the *k*-value, USU also will introduce possible methods of increasing the flow rate through the base. The analysis will list the hydraulic conductivity of various gradations and their projected costs. This will allow officials at UDOT to choose the most effective untreated base course material with the least associated cost. This research involves looking at present untreated base material specifications and developing new, possible future, specifications to determine the hydraulic conductivity for each specified gradation and then analyzing the costs involved with preparing (i.e. crushing and cleaning) the material needed. It also will be necessary to evaluate if any additional construction costs are involved (i.e. having to use different construction techniques and equipment).

Four main objectives will be the focus throughout this study:

- The first objective is to measure the hydraulic conductivity of UDOT's current dense graded untreated base course and granular borrow materials.
- The second objective is to survey various states and to gather helpful information such as the gradation of their base material, the associated hydraulic conductivity, the annual precipitation, and the required base thickness.
- The third objective is to compare the information gathered from other states to Utah's. This will be accomplished by testing the various states' gradations (refer to Appendix E) and establishing the hydraulic conductivities of their gradations using the same constant head apparatus as used to establish UDOT's *k*-value. In other words, a common ground must be established because each state

selected uses different techniques, test methods, and apparatuses when determining the hydraulic conductivity for their material.

- The final objective is to perform a cost analysis of each gradation, including evaluating other potential sources of drainable material. This will be accomplished by having professional estimators submit a cost analysis for each gradation.

REVIEW OF LITERATURE

The subject of permeable bases can be so broad that UDOT and USU outlined the specific details of permeable bases that were most important and would best represent Utah's situation and needs. The specific details this report focused on included evaluating only untreated base material, the distress on PCC pavements caused by pumping, precipitation as the main source of free water, and the use of the ASTM approved constant head method. Addressing only these items throughout the report helped to focus on Utah's current needs, but many other considerations that are associated with permeable bases have been researched and published. These considerations are important under many circumstances encountered when planning and constructing permeable bases. These considerations, along with the specific details outlined by UDOT, are presented and discussed in this section.

Distresses

One of the major distresses on Portland Cement Concrete (PCC) pavements is caused by pumping. Pumping, which eventually leads to the complete break up of the pavement, occurs in both flexible and rigid pavements. In Hot Mix Asphalt (HMA) pavements the physical evidence of problems due to pumping are potholes, rutting, and cracking; whereas the problems in PCC pavements are evident by joint spalling, punchout, cracking, and faulting (National Technical Information Service, 1981). Other problems associated with both HMA and PCC pavements, due to inadequate subsurface drainage are "frost heave and slope instability" (Randolph et al., 1996, p. 1). This report will focus primarily on PCC pavements.

As explained by the U.S. Department of Transportation (1992), the pumping action begins when water infiltrates the pavement and begins to fill the voids of the base material. As shown in Figure 1, heavy wheel loads, as they approach the joint, stir up the water and soil directly below the pavement. The upstream slab deflects downward which sends water rushing up under the downstream slab. As traffic passes over the joint, the water and soil are pushed forcefully back toward the upstream slab. Because of the higher fluid pressure and volume developed under the downstream slab, erosion is greater under the downstream slab than under the upstream slab.

Figure 2 shows the churning action of the soil and water being pushed back and forth. Eventually the material under the downstream slab is eroded away and deposited under the upstream slab or pumped up through the joint. Thus the downstream slab is lower than the upstream slab adjacent to the pavement joint. The ejection of the infiltrated water and the soil is the first step in destroying the integrity of PCC pavements (U.S. Department of Transportation, 1992).

The first evidence of pumping is a small dip with soil stains around it located next to the joint. This evidence is commonly referred to as a "bird bath." Figure 3 shows a typical bird bath, notice the elevation change between slabs.

Figure 1. Churning of water and soil due to saturated base material and heavy wheel loads.

Figure 2. The pumping action.

Figure 3. First evidence of pumping. Commonly known as the “bird bath.” Notice the stains created by the ejection of soil and water.

The bird bath effect will continue to expand along the entire length of the joint. When this happens the result is a difference in elevation between slabs, known as faulting. Figure 4 shows a stretch of highway where faulting has become severe. The horizontal lines running across the pavement, in Figure 4, are due to the downstream slab dropping in elevation relative to the upstream slab.

Figure 5 shows the next phase in pavement deterioration. After faulting has occurred, the downstream slab begins cracking in the middle and then throughout the entire section. This break up, which is due to loss of support under the slab and joint, includes corner breaks (as illustrated in Figure 5) and joint deterioration. The final stage of pavement deterioration is severe cracking and the complete break up of the pavement slab (U.S. Department of Transportation, 1992).

Figure 4. Faulting due to loss of support under slab.

Figure 5. Pavement distress due to pumping includes corner breaks and joint deterioration.

The Base Function

The main function of the dense graded base was to provide uniform support for both flexible and rigid pavements. Dense graded material is characterized by its "relatively broad particle size distribution" (Hoppe, 1996, p. 1). This type of base originally was considered to retain its strength under saturated conditions and designed to be extremely stable and resist erosion, but time has shown the harsh effects that free water can impose on pavements. In conjunction with increased wheel and traffic loads, infiltrated water led to pumping in PCC pavements, erosion of material through cracks and joints, and eventually caused premature failure of the pavement section.

A new base design is being evaluated by several states that addressed the concern of free water remaining beneath the pavement. The base still provides uniform support but is composed of a more open graded material (a smaller percentage of material passing the 2.0 mm [No. 10] thru the 0.075 mm [No. 200] sieve), which will immediately drain infiltrated water away from the pavement section and into a collection system. The challenge is maintaining stability while increasing the permeability in the base. This type of base, with the open graded material, will be referred to as a permeable base in this report.

Several states have experimented with their own type of permeable base and, in doing so, two distinct types of bases have evolved. They are treated and untreated bases. The treated base came from states trying to establish the highest permeability possible with any type of material that was available (i.e. crushed rock, slag, recycled concrete or asphalt) and then treating this material with a three percent concrete or asphalt mixture. The untreated type base was developed by states removing portions of the finer material from their established dense graded base course gradation.

Treated versus Untreated Bases

A permeable base, as discussed in this study, is defined as a gradation of a particular granular material that is open enough to allow water to flow through yet stable enough to support the design traffic. As mentioned above, there are two types of permeable bases. They are referred to as treated and untreated bases.

Treated bases are more open graded and thus, in general, much more permeable. Stability is developed by the cementing action of the stabilizer material at the point of aggregate contact. The stabilizer material usually consists of approximately 3 percent Portland or asphalt cement. It also is important that the treated base is designed to be non-erodible. Untreated bases consist of aggregate gradations that contain finer-sized aggregates. These bases develop their stability by mechanical interlock of the aggregates (U.S. Department of Transportation, 1992).

Sources of Water

It would be impossible to cover all the sources of water that could enter the pavement structure, but it is important to know and understand the major contributor. As discussed by the Transportation Research Board (1982) in a synthesis titled "Pavement Subsurface Drainage Systems," the primary source of water in pavements is atmospheric precipitation. After a storm, rain or snow, there are many ways this free water can enter the pavement section and begin its destructive process. Free water can infiltrate through cracks and joints, rise up through capillary forces or saturate the base material through a high water table.

"Free water is the form of most concern to the designer because it can decrease the strength of the pavement and is the only form of water that can be significantly removed by gravity drainage." (Transportation Research Board, 1982, p. 1)

Horizontal Flow versus Vertical Flow

The main principle behind laboratory testing is to duplicate the in-situ conditions as best as possible. As to measuring the hydraulic conductivity of the soil, the question addresses why the flow is measured in the vertical direction for the lab when the flow appears to be horizontal direction in the field? What is the difference, if any, between the two permeability values?

The coefficient of permeability value is the most important factor in determining the drainability of the permeable base, yet every state has their own method for determining the k-value. Some states have developed their own apparatus for testing the coefficient of permeability using a vertical flow. Others have developed permeability apparatuses that force the flow in the horizontal direction. States that test the hydraulic conductivity of the base material using the horizontal flow theory get values several times higher than *k*-values obtained using the vertical flow theory on the same material.

Using the same type of material, John H. Vu (1992) compared the coefficient of permeability values obtained from the Iowa permeameter to the values obtained from the New Jersey Falling Head permeameter. The Iowa permeameter measures the permeability coefficient using a horizontal flow and the New Jersey permeameter measures the coefficient of permeability using a vertical flow. The results showed that there was no correlation between the two apparatuses. The *k*-values for Iowa's permeameter ranged between 100 m/day (300 ft/day) up to 4,000 m/day (12,000 ft/day) and New Jersey's testing device produced values between 3 m/day (9 ft/day) and 7 m/day (21 ft/day) (Vu, 1992, p. 12).

All testing performed for this study used the vertical flow theory for establishing the coefficient of permeability value. Which flow theory is correct? Which flow direction best describes the field conditions? Perhaps the vertical flow results are misleadingly conservative or maybe the horizontal flow results are erroneous? It is important to establish permeable base drainability criteria with an understanding of which test method will be used as the guideline.

Drainable Pavement Systems

Drainable pavements systems consists of a permeable base, a separator layer, and an edgedrain system all properly designed so there is no weak link in the drainage system.

Installing a permeable base beneath the pavement is not enough to solve the problem with premature pavement failure. Prior to laying down a permeable base, a separator layer needs to be installed. The purpose of the separator layer is to prevent fines of the subgrade from migrating into and clogging the permeable base (Southwest Concrete Pavement Association, 1993). The separator layer can be a select aggregate gradation or a geomembrane. The separator layer must be strong enough to support the construction traffic during base installation and have a low permeability to divert water towards the drains.

Drains also are an important function in drainable pavement systems. Conventional pipe for the edgedrains are the most common type used. Proper placement of the drain is important to ensure that the water will reach them before saturation occurs. The collector pipes must have adequate capacity to handle the design flows.

Load transfer devices (dowels), a competent uniform subgrade, and pavement thickness, cannot be neglected when considering permeable bases. When positive load transfer, uniform subgrade, and pavement thickness are incorporated in the design of the entire drainable pavement system, the premature failure due to pumping will be significantly reduced and the life of the pavement section will be increased.

Enhancing Drainability

To properly investigate how drainability can best be enhanced, it is necessary to look at various soil parameters. Some soil parameters will directly influence the permeability of a material, whereas other soil parameters could indirectly effect the drainability.

The coefficient of permeability is an engineering term that defines the flow relationship in a soil. It is an indicator of the ability of water to flow through the material. The coefficient of permeability can be affected, either directly or indirectly, by various soil parameters.

The percent fines (P200), defined as the percentage of material passing the 0.075 mm (No. 200) sieve, was initially thought to be the number one influence on the coefficient of permeability. Dr. Edward J. Hoppe (1996, p. 11) studied the influence of fines on the drainage of aggregate bases and concluded that there was no significant increase in the coefficient of permeability when reducing the “maximum allowable fines content from 7 percent down to 5 percent, while keeping the remaining gradation limits unchanged.” Most experts still believe that it is important to limit the amount of fines in the base course material.

The effective size (D_{10}) of a gradation is the particle size, in millimeters, in which 10 percent of the material, by weight, is smaller. The D_{10} is an indicator of a material's permeability. The greater the effective size (D_{10}), the larger the particles of the material and the more permeable (refer to Figure 6).

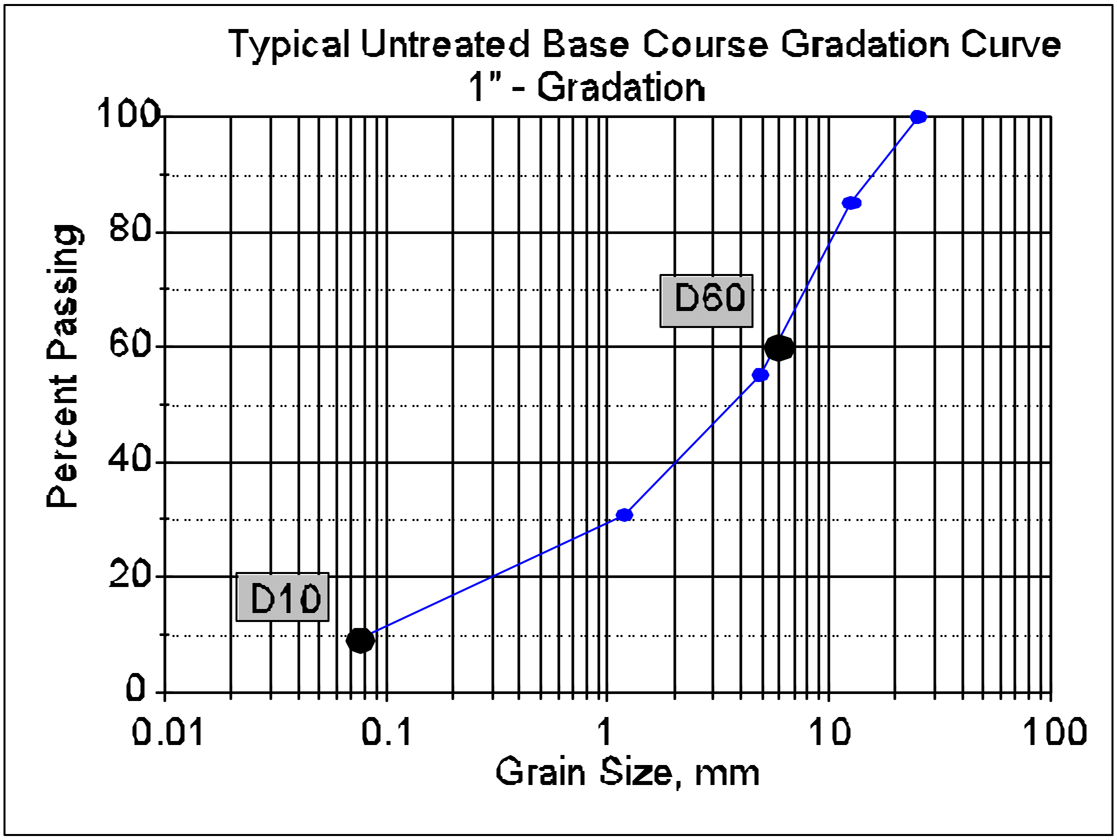

Figure 6. Gradation curve showing the coefficient of uniformity ($C_u = D_{60} / D_{10}$).

The effective size (D_{60}) of a gradation is the particle size, in millimeters, in which 60 percent of the material, by weight, is smaller. The D_{60} also is an indicator of a material's permeability. The greater the effective size (D_{60}), the larger the particles of the material and the more permeable the material (refer to Figure 6).

A sieve analysis is an important tool that aids the engineer in evaluating the coefficient of uniformity (C_u) of a material. The coefficient of uniformity is the ratio of the D_{60} particle size divided by the D_{10} particle size. The coefficient of uniformity is an indication of the variation of particle sizes (refer to Figure 6). Dr. Hoppe (1996) found in his research that the coefficient of uniformity (C_u) had the most profound influence on the hydraulic conductivity.   Dr. Hoppe (1996, p. 10) stated that "in the observed C_u range of approximately 10 to 115, improved drainage may be achieved by using a low C_u gradation, with no adverse impact on strength." The coefficient of uniformity indicates how well graded the material is. It also is an indirect indicator of the material's permeability. Open graded material will have a low coefficient of uniformity. This range is somewhere between two and six, while dense graded material has a range between 20 and 50. A value of four or greater is recommended for stability (U.S. Department of Transportation, 1992).

Porosity (n) is another parameter used to indicate an aggregate material's ability to store and give up water. The porosity of a material is the volume of voids divided by the total volume of sample, expressed as a ratio.

Unit weight is an important parameter in drainage design since it determines the porosity of the soil or aggregate. A range of dry unit weights between 15.9 kN/m^3 and 19.0 kN/m^3 (101 lb/ft^3 and 121 lb/ft^3) is likely in permeable base design.

These unit weight values produce a range of porosities from 0.28 to 0.40, respectively, based on a bulk specific gravity of 2.68 (U.S. Department of Transportation, 1992, p. 41).

PROCEDURES AND RESULTS

UDOT's Current Material

Procedure

The first step was to establish the coefficient of permeability for UDOT's current dense graded untreated base course material. ASTM's permeability of granular soils (constant head) testing procedure was selected as the best representative method because it is the most suitable test for relatively permeable soils and aggregates (Cedergren, 1967). Also, this method is the only approved method for determining the coefficient of permeability in ASTM. The evaluation involved the following process:

- The permeability was determined using the standard test method for permeability of granular soils, ASTM D 2434-68 (Reapproved 1994). The American Association of State Highway and Transportation Officials (AASHTO) recommends this specific method. Refer to Appendix A for the ASTM D 2434-68 (Reapproved 1994) test procedures. Figure 7 shows the permeability apparatus.
- Compaction was achieved by using the AASHTO T 180-93 test procedure (i.e. five layers with 56 blows per layer, using a 4.54-kg [10-lb] hammer with an 457-mm [18-in] drop). The material was compacted at optimum moisture, approximately 5 percent to 7 percent, to simulate

field conditions. See Appendix B for AASHTO T 180-93 test procedures. Figure 8 shows the compaction equipment.

- Tests were performed on previously selected specifications. They included the 38.1 mm (1-1/2 in), 25.4 mm (1 in), 19.1 mm (3/4 in), and the pit run (unprocessed) gradations for UDOT's current dense graded untreated base course material. Tests also were performed on the A-1-a, A-1-b, A-2-4, and the pit run (unprocessed) gradations for the non-plastic granular borrow material. The pit run gradation refers to testing the material in its natural state (i.e. without any alterations from original sampling). The granular borrow pit run material classifies as an A-1-b. Refer to Appendix C and Appendix D for details on the various gradations.
- The gradations for both the untreated base course and granular borrow materials were built on centerline (i.e. at mid-point of range given for each sieve size). See Appendices C and D for details.
- All samples were soaked for a minimum of 24 hours, in the permeability apparatus, before tests were performed. This process aided in evacuating the air trapped in the soil.

The constant head permeability apparatus consisted of a steel mold with a diameter of 152.4 mm (6 in) and a height of 177.8 mm (7 in), a base plate, two 12.7 mm (0.5 in) thick porous stones, three stiff springs, and a top plate. The water flowed from the bottom of the soil sample up and out the top of the mold. The head difference for UDOT's current material was 1.2 m (4 ft) and this was within the laminar flow range.

Figure 7. Constant head apparatus used to establish coefficient of permeability values.

Figure 8. Equipment used to compact the dense graded untreated base course and granular borrow material.

Results

Tests were conducted on UDOT's specified gradations for both the dense graded untreated base course and granular borrow material. The laboratory results show that the hydraulic conductivity is extremely low. The results show that the granular borrow has a slightly higher k-value than the base course material, but both materials have k-values that are less than 0.3 m/day (1 ft/day). Table 1, compares the results of the various gradations for the untreated base course and granular borrow material. These results are approximate values because of the many variables that could effect the data (i.e. air bubbles, degree of saturation, and migration of fines).

Table 1. Coefficient of Permeability Results of UDOT's Material.

	Coeff. of Permeability, k, m/day (ft/day)	Coeff. of Uniformity, Cu	Dry Unit Weight, γ, kN/m^3 (lb/ft^3)
DENSE GRADED UNTREATED BASE COURSE MATERIAL			
38.1 mm (1 ½ in)	0.002 (0.007)	82	21.7 (138)
25.4 mm (1 in)	0.0006 (0.002)	71	21.9 (139)
19.1 mm (3/4 in)	1.5 (5)	60	19.6 (125)
Pit Run	0.01 (0.04)	30	19.9 (127)
GRANULAR BORROW MATERIAL			
A-1-a	0.3 (0.9)	95	21.7 (138)
A-1-b	0.01 (0.03)	184	20.8 (132)
A-2-4	1.5 (5)	231	19.6 (125)
Pit Run	0.1(0.4)	45	20.3 (129)

As can be seen from Table 1, the coefficient of permeability is extremely low for both materials. The values for the 19.1 mm (3/4 in) and the A-2-4 gradations are slightly higher because they were loosely compacted without any moisture added. These two samples were prepared this way to demonstrate the effects that compaction and moisture can have on the *k*-value for dense graded untreated base material. Obviously the dense graded untreated base material needs good compaction effort at optimum moisture to achieve the desired stability. This is not necessarily the case for open graded materials, as will be evident later in the report. The other gradations all were compacted to approximately 95 percent of maximum dry density at optimum moisture. Notice that the unit weight ranges from 19.6 kN/m^3 to 21.9 kN/m^3 (125 lb/ft^3 to 139 lb/ft^3) and the coefficient of uniformity ranges from 30 to 231. These unit weight values classify this material, assuming a specific gravity of approximately 2.65, as a stable and well-graded material.

The time required for water to flow through 152.4 mm (6 in) of untreated base course or granular borrow, with 1.2 meters (4 ft) of head, is between one hour and 24 hours. Table 2 is a good example of how slow the water was flowing through 152.4 mm (6 in) of material during testing. Table 2 shows the time it took for each gradation to fill a regular 0.24 liter (8 ounce) drinking glass.

Table 2. Time Required to Drain 0.24 liters (8 ounces) of Water.

	Dense Graded Base Course			**Granular Borrow**		
Gradation	38.1 mm	25.4 mm	Pit Run	A-1-a	A-1-b	Pit Run
Time	19 hrs.	45 hrs.	3 hrs.	8 min.	4 hrs.	15 min.

Due to the collection of free water in the base course material, this type of material does not provide the drainage needed to avoid premature failure. The base course material could work if a few parameters were changed. The most critical property to change is the effective sizes (D_{10} and D_{60}). This can be accomplished by decreasing the amount of material passing the 2.0 mm (No. 10) sieve thru the 0.075 mm (No. 200) sieve, this is evident in Table 3. The gradations listed in Table 3 are commonly used gradations and were selected to show the comparison between the effective size and the *k*-value for each gradation.

Table 3. Comparison Between Open and Dense Graded Material.

Sieve Size	Open Graded #1	Open Graded #2	Dense Graded
38.1 mm (11/2 in)	100	100	100
25.4 mm (1 in)	95 - 100	95 - 100	----
19 mm (3/4 in)	----	----	81 - 91
12.7 mm (1/2 in)	25 - 60	60 - 80	67 - 77
4.75 mm (No. 4)	0 - 10	40 - 55	43 - 53
2.36 mm (No. 8)	0 - 5	5 - 25	----
1.18 mm (No. 16)	----	0 - 8	23 - 29
0.30 mm (No. 50)	----	0 - 5	----
0.075 mm (No. 200)	0 - 2	----	6 - 10
Eff. Size (D_{10})	4.9 mm	1.5 mm	.075 mm
C_u value	2.5	6	82
k-value, m/day (ft/day)	2,000 (6,000)	500 (1,500)	1.2 (4)

As shown in Table 3, the effective size is an indicator of a material's permeability. The greater the effective size, the larger the particles will be and the more permeable the material. The *k*-values referenced in Table 3 were obtained from the U.S. Department of Transportation (1992) on page 94.

After making these slight changes just described, the end result is an open graded permeable base material that will drain away unwanted water, while still providing the necessary support.

There are two types of permeable bases — untreated and treated — as described in the Literature Review section. The untreated base develops its stability by increasing the amount of fines, yet still maintains a permeability value of 151 m/day to 758 m/day (500 ft/day to 2,500 ft/day). The treated base achieves high permeability by eliminating the amount of finer material, between 758 m/day to 3030 m/day (2,500 ft/day and 10,000 ft/day), and gains stability through the use of stabilizers such as Portland cement or asphalt cement.

Survey of Various States

Procedure

Realizing the importance of using an open graded untreated base material, the second part of this research involved looking at and identifying other states that are using open graded material as a base. Based on their established gradations for permeable bases, six states were selected. These states were Iowa, Minnesota, New Jersey, Pennsylvania, Wisconsin, and Wyoming.

To properly gather information, the Department of Transportation for each state was contacted. The following 11 questions were asked:

1. What is the specified test method for your state (i.e. constant or falling head, etc.) and what *k*-value is expected (lab results) ?
2. What method of compaction is used in the lab?
3. Is the sample compacted at optimum moisture or dry?
4. What type of construction techniques are being used in the field?

5. What is the annual precipitation for your area?

6. What is the thickness of the base material?

7. Is the base material treated or untreated?

8. In what areas is the open graded material required?

9. Where, in the pavement cross-section, is the material located?

10. What does this material cost?

11. Are there any noticeable results from using a permeable base?

Results

Each of the states responded to the questions. Some answers were quite varied while others were identical for each state. For example, all states prefer using untreated base material over treated material because these types of bases are generally less expensive to construct. However, Wyoming is leaning towards the treated base as being less expensive overall. In the cross-section, the permeable base is always placed directly under the PCC pavement. Also, each state requires that open graded material be placed under all PCC pavements and in moist areas for flexible pavements. Each state has noticed an improvement in the life of their roads. The following is the full response from each state:

Iowa's Response:

Iowa responded by explaining that they use a special test method for finding the coefficient of permeability. This test method measures the lateral flow rather than the more common approach of measuring the vertical flow. The test is performed in a box approximately

2 meters (6 ft) long and 45.7 cm (18 in) deep. Iowa achieves approximately 300 m/day (1,000 ft/day) with the test box. Lab samples are compacted to a density of 16.5 kN/m^3 (105 lb/ft^3) using a vibrator. Construction compaction consists of three passes with a rubber tire or drum roller, with the vibrators turned off. The annual precipitation is approximately 81.3 cm (32 in). The base is installed at optimum moisture or greater at a thickness of 10.2 cm to 25.4 cm (4 in to 10 in), depending on traffic volume. The open graded material costs approximately $7.15 per metric ton ($6.50 per ton). Iowa is quite satisfied with the increased life in their pavement section (Stanley, 1996).

Minnesota's Response:

Minnesota's DOT uses a modified falling head apparatus with a head of 1.2 meters (4 ft). The expected *k*-value is approximately 300 m/day (1,000 ft/day), but the material ranges from approximately 122 m/day to 610 m/day (400 ft/day to 2,000 ft/day). Compaction for the lab sample is achieved by using a 4.54 kg (10 lb) Marshall hammer with a 22.9 cm (9 in) drop and seven blows per lift. The lab sample is compacted at optimum moisture. A steel wheel roller, not pneumatic, makes approximately three passes in the field. The annual precipitation for Minnesota is approximately 66 cm (26 in). A minimum thickness of 10.2 cm (4 in) is required at a cost of approximately $7.70 per metric ton ($7.00 per ton). Permeable bases have reduced the maintenance cost and increased the life of the pavement section for Minnesota (Gerty, 1996).

New Jersey's Response:

New Jersey has developed a falling head permeameter that is acknowledged as an accepted method for the determination of the coefficient of permeability by the Federal Highway Administration and other states. The apparatus has a 10.2 cm (4 in) diameter by 91.4 cm (36 in) tall plexiglass standpipe which rests on top of the soil sample. The standpipe is filled with water and drained. The elapsed time is recorded to measure the permeability. A 1.18 mm (No.16) screen is placed beneath the soil sample to retain the fines. The lab sample is vibrated dry and the field construction involves using vibratory rollers on 15.2 cm to 20.3 cm (6 in to 8 in) of dry base material. The annual precipitation is 114.3 cm (45 in). The cost is approximately $7.15 to $8.30 per metric ton ($6.50 to $7.50 per ton). New Jersey has seen good results with using the permeable base (Mottola, 1996).

Pennsylvania's Response:

Pennsylvania uses a modified falling head permeameter and gets values around 610 m/day (2,000 ft/day) on their open graded material. The lab sample is placed dry and loose. The material in the field, which also is dry, is rolled until no movement in the material occurs. Pennsylvania receives an average of 104 cm (41 in) of precipitation annually. A minimum of 10.2 cm (4 in) of material is required at a cost of approximately $7.15 to $8.85 per metric ton ($6.50 to $8.00 per ton). Pennsylvania feels that the permeable base has reduced the premature pavement failure and increased the life in their PCC pavements (Reidenouer, 1996).

Wisconsin's Response:

Wisconsin follows New Jersey's procedures for laboratory testing and has no established guidelines for compaction of field material. The actual roadway is designed using 22.9 cm to 30.5 cm (9 in to 12 in) of concrete pavement, a 15.2 cm (6 in) drainable base, and then 22.9 cm (9 in) of gravel beneath the base, with a french drainage system and a liner beneath. The cost for open graded material was unavailable. The average annual precipitation is 78.7 cm (31 in). Wisconsin thinks that by using permeable bases they have reduced the overall costs associated with constructing and maintaining the pavement section (Volkner, 1996).

Wyoming's Response:

Wyoming is in the middle of comparing the treated and the untreated permeable bases. They recently have constructed two stretches of highway, one with a treated base and the other with an untreated base. Although these stretches were just recently built and not all the information has been gathered, preliminary results show the treated base with the advantage.

The Wyoming DOT prefers the stabilized permeable base because the construction was easier and they thought that the overall cost was lower. Wyoming also believes that possibly the best method in preventing premature pavement failure is to combine permeable bases with load transferring devices, such as installing rebar dowels to transfer the load from one slab to the next.

Wyoming does not have a system in place for determining the coefficient of permeability for their open graded material for the field or lab. The estimated values are 1,830 m/day

(6,000 ft/day) and 305 m/day (1,000 ft/day) for their treated and untreated base, respectively. The thickness required is a minimum of 10.2 cm (4 in) and 15.2 cm (6 in) for the treated and untreated material, respectively. The material for the treated base is approximately $7.15 per metric ton ($6.50 per ton), whereas, the cost is approximately $6.90 per metric ton ($6.25 per ton) for the untreated material. Wyoming's average annual precipitation is close to Utah's at 33 cm (13 in) per year (Babbit, 1996).

Comparisons Between Various States

Procedure

After establishing the permeability values of UDOT's base material and gathering permeable base information from other states, it was necessary to establish a common ground.

The gradations from other states were tested using the same procedure as was used in testing UDOT's specified gradations except this material was compacted dry using a vibrating table. This compaction method was chosen because of the large amount of rock contained in these gradations.

The open graded base gradations were fabricated using local material according to recommendations obtained from other states. Refer to Appendix E for each state's gradation. The hydraulic conductivity was measured for each of the open graded gradations using the same constant head apparatus that was used to establish UDOT's dense graded untreated base course material. By using the same apparatus for all the tests, a direct comparison could be made. The compaction for these gradations was achieved in two lifts using a vibrating table and a surcharge weight of 6.82 kg (15 lbs).

Results

Table 4 compares the coefficient of permeability for each state's gradation.

Table 4. Established Gradations Results.

	Coeff. of Permeability, *k*, m/day (ft/day)	Coeff. of Uniformity, C_u	Dry Unit Weight, γ, kN/m^3 (lb/ft^3)
Iowa	83.8 (275)	21	20.4 (130)
Minnesota	160.0 (525)	10	18.9 (120)
New Jersey	518.1 (1700)	5	18.2 (116)
Pennsylvania	1066.7 (3500)	7	18.1 (115)
Wisconsin	853.4 (2800)	3	16.0 (102)
Wyoming	1127.7 (3700)	11	19.8 (126)

As can be seen from Table 4, the unit weight ranges from 16.0 to 20.4 kN/m^3 (102 to 126 lb/ft^3) and a coefficient of uniformity value between 3 and 21, which classifies this untreated base course material as a stable and open graded material.

The time it takes for water to permeate through 15.2 cm (6 in) of this open graded untreated base course material with a 0.64 cm (0.25 in) of head, takes between one and five minutes.

It's important to emphasize that the results listed in Table 4 are approximate values that were determined by following the ASTM D 2434-68 guidelines and using the same constant head apparatus used to establish UDOT's dense graded untreated base material. The *k*-values for other states' gradation, listed in the Survey of Various States section, were calculated using their local material and their established methods and apparatuses. The local material of the various states alone could effect the coefficient of permeability value to some extent by being composed of different particle shapes and containing different minerals. Therefore, the coefficient of permeability values listed by each state in the Survey of Various States section and those values found in Table 4 can not be directly compared. The information found in Table 4 will help to determine which *k*-value and the associated gradation would best serve UDOT's purposes.

Cost Analysis

Procedure

Preventing premature pavement failure is essential, but at what cost is it still essential? How much stability would be sacrificed for drainability and vise-versa? Knowing the cost associated with improving the PCC pavement is another major factor in this process. A cost estimate was performed for Utah's and the other states' gradation. Also, in an effort to explore the possibility of using other types of material for permeable bases, a cost estimate was performed for a slag material located from Geneva Rock.

Mr. Randy Anderson (1996) of Jack B. Parsons, agreed to analyze and present a cost estimate for each of the gradations previously specified (Wyoming gradation not included). He received and evaluated gradations for UDOT's 38.1 mm (1-1/2 in), 25.4 mm (1 in), and 19.1 mm (3/4 in) specifications; along with Pennsylvania's, Minnesota's, Wisconsin's, Iowa's, and New Jersey's gradations (Refer to Appendices C and D for details).

Results

Mr. Anderson (1996) concluded that UDOT's current gradations would cost between $3.70 and $3.85 per metric ton ($3.35 and $3.50 per ton) and that any deviation from that would initially cost an additional $1.50 to $1.65 per metric ton ($1.35 to $1.50 per ton).

Also noted in Mr. Anderson's (1996) cost estimate, was the fact that by producing more open graded material rejects approximately 17 percent to 43 percent of the pit material. The increase in price mentioned above was only a bid price based on limited use of the material (a one time offer). The cost of preparing but not using the rejected material still must be accounted for. Therefore, if a specific open graded gradation became part of UDOT's specification, it is possible that that gradation could end up costing more in the long run.

According to Geneva Rock, the slag material would cost between $3.30 and $4.40 per metric ton ($3 to $4 per ton) (Fryer, 1996). The slag has a density of 11.8 kN/m^3 (75 lb/ft^3) and has good stability due to the angularity of the material (Fryer, 1996). Geneva can sieve the material to meet specifications for gradations, permeability, and stability. The stability would be controlled by the coefficient of uniformity value or by the percentage of fines contained in the gradation.

There are other considerations that must be considered when using a more open graded mix. Besides the additional crushing (processing) fees, there may be more costs associated with construction techniques. Open graded material is not as stable as the dense graded material and generally will not support truck loads on top of the base course material as well. In addition to less stability of the open graded material during the construction phase, the potential for contaminating and clogging the open graded material is greatly increased. If the open graded material becomes contaminated and clogged, the entire purpose of constructing an open graded permeable base with untreated base course material has been defeated. Therefore, all construction must be performed from the side of the road.

CONCLUSION

The first objective of this study was to measure the hydraulic conductivity of UDOT's current dense graded untreated base course material. The results of this objective revealed that the hydraulic conductivity of UDOT's material is extremely low compared to the *k*-values of various other states. UDOT's *k*-value was less than 0.3 m/day (1 ft/day) compared to the *k*-values of various other states which ranged between 83.8 m/day (275 ft/day) and 1127.7 m/day (3700 ft/day). The chances of experiencing premature pavement failure due to slow drainage of the pavement section is significantly increased when UDOT's current dense graded untreated base course material is used. Premature pavement failure due to pumping could reduce the life expectancy of the road by up to 50 percent and maintenance costs would skyrocket.

The second objective was to survey various states and to gather helpful information about their permable bases. Six states were surveyed and all six states use open graded untreated base course material for their permeable bases. The permeable bases of these states are always placed under interstates and primary roadways. Occasionally, permeable bases are placed under secondary roadways when swampy conditions exist. The survey also revealed that all six states saw a significant increase in the life expectancy and a decrease in maintenance costs for roadway sections with permeable bases in the pavement section. All states surveyed expressed complete satisfaction with using permeable bases.

The results of the final two objectives conclude that a permeable base is a viable solution for quickly removing water from the pavement section. These bases are definitely worth installing as a means of preventing premature failures in Portland and HMA cement concrete pavements. Harry R. Cedergren (1974) addressed the issue of how cost effective and important permeable bases are in preventing premature pavement failures versus other approaches used in the past. These approaches included increasing the pavement thickness and using load transfer dowels while ignoring the drainability of the base material. Cedergren (1974, p. 43) states that "on the whole, efforts to change details without improving drainability are having only little effect on the amount of deterioration and failure in relation to cost." While increasing the pavement thickness and using load transfer devices are important, they are basically insignificant unless used in conjunction with a drainable base. There are important recommendations to consider when constructing a permeable base.

The first important recommendation is the type of aggregate used when constructing a permeable base. The aggregate used in the untreated open graded permeable base must have at least two sides with fractured faces. To get good interlocking of the aggregate, it is necessary to use material that is angular, hard, and durable. The state of Washington found that open graded material with 100 percent fractured faces had a large impact on the coefficient of permeability value. “For the same type of gradation, the aggregate with 100 percent fractured faces is more permeable than the aggregate with 88 percent fractured faces.” This study also noticed that fractured faces for dense graded material did not make a significant difference in the hydraulic *k*-value (Southwest Concrete Pavement Association, 1993, p. 67). Although fractured faces do not effect the hydraulic conductivity of dense graded material, the percentage of fractured faces is extremely important in the constructability and stability of the base.

Previous studies indicate that the hydraulic conductivity of the in-situ material decreases by approximately half when comparing the same material tested in the lab. This decrease in the permeability value of the in-situ material is attributed to increased contamination and segregation of the base material. Therefore, another recommendation to consider is the minimum hydraulic conductivity value needed to quickly drain away free water. Since field results vary from lab results, a minimum hydraulic conductivity value of 320 m/day (1,000 ft/day) is suggested. Using an open graded material that will produce a higher *k*-value, approximately 1,000 m/day (3,000 ft/day), is highly recommended.

A minimum base thickness of 101.6 mm (4 in) is recommended. The base thickness should be increased for interstates and primary roads and where heavy traffic loads are expected, where swampy conditions exist, and where annual precipitation is high.

An untreated open graded material with a gradation similar to New Jersey's is the overall best choice. Table 5 shows the specified sieve sizes for the recommended gradation. New Jersey's gradation has a permeability coefficient of approximately 550 m/day (1700 ft/day), using the constant head apparatus and a uniformity coefficient of five which indicates good stability. According to the cost analysis, this gradation only rejects approximately 20 percent of the material that will help keep the cost down. The selling point for this type of gradation is the fact that of the six states selected, New Jersey has the highest amount of precipitation annually (45 inches compared to Utah's 12 inches) and they are completely satisfied with the results of their permeable base material.

Table 5. Recommended Gradation

New Jersey's Gradation (Recommended)		
Sieve Size	Percent Passing	Centerline
38.1 mm (1 ½ in)	100	100
25.4 mm (1 in)	95 - 100	97.5
12.7 mm (1/2 in)	60 - 80	70
4.75 mm (No. 4)	40 - 55	47.5
2.36 mm (No. 8)	5 - 25	15
1.18 mm (No. 16)	0 - 8	4
0.30 mm (No. 50)	0 - 5	2.5

In addition to the previously mentioned recommendations and the selected gradation, the following suggestions are strongly recommended.

Enforcing minimal construction traffic on the unstabilized base during construction is important. This will significantly reduce the potential for contamination of the base. Compaction requirements must be established. The U.S. Department of Transportation (1992) suggests three to five passes with a steel roller or until the material is properly seated. A positive slope must be maintained at all times. A minimum slope of 0.02 ft/ft is recommended. The length of the drainage path should be kept to a minimum.

The recommendations discussed so far deal with the permeable base. The permeable base is not complete without constructing the entire drainable pavement system. The drainable base system consists of the permeable base, the separator layer, and the longitudinal edge drains. Figure 9 shows the recommended cross-section for the drainable base system. Further research is suggested on the type of material that should be used for the separator layer and which edge drains would best serve UDOT's interests.

Further research also is recommended for each of the topics addressed in the Literature Review section. These topics include distresses, treated verses untreated base material, sources of water, horizontal versus vertical flow, type of permeability apparatus, and PCC versus asphalt pavements. Researching these topics will help to improve the overall quality of the pavement section.

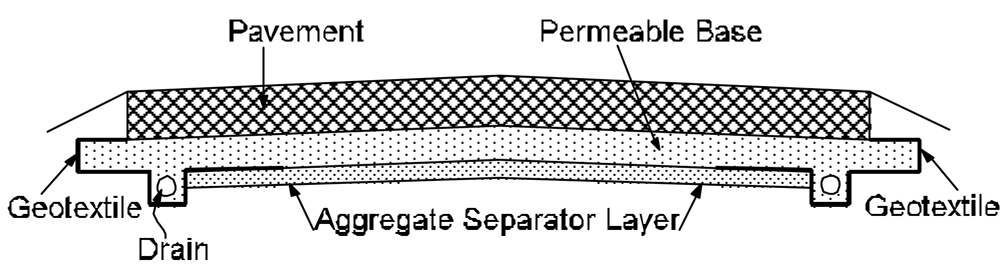

Figure 9. Recommended cross-section for the drainable base system.

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Appendix A

Standard Test Method for Permeability of Granular Soils (Constant Head)

Procedures for Determining
the Coefficient of Permeability of Granular Soils
(taken from ASTM D 2434 - 68)

1. The permeameter chamber shall have a minimum diameter of approximately eight or 12 times the maximum particle size.

2. The permeameter shall contain a porous stone or a screen at the bottom with a permeability greater than that of the soil specimen.

3. Take a representative sample of dry granular soil, containing less than 10 percent of the material passing the 0.075 mm (No. 200) sieve and approximately twice the amount required for filling the permeameter chamber.

4. Prepare the sample, if desired, with the appropriate amount of water to bring the sample up to the optimum moisture content. The sample also can be tested dry.

5. Carefully place the prepared sample in equal lifts and compact each lift to the desired relative density by any appropriate method until chamber is filled to approximately 12.7 mm (0.5 in) below the top rim. See Appendix B for compaction method used on UDOT's dense graded untreated base course and granular borrow material. The sample must be carefully placed to avoid segregation of the material.

6. Gently level the upper surface of the soil and place the top porous stone or screen in position.

7. Measurements must be made and recorded on a data sheet. These measurements include the average length (L) of the soil, the inside chamber diameter (D), the weight (W) of the soil, and the head (H) difference between the free water surface where the water enters the apparatus and the free water surface where the water exits the apparatus.

8. Calculate the cross-sectional area (A) of the permeameter chamber. The dry unit weight, void ratio, and relative density of the test specimen can be computed and recorded.

9. Place three springs on top of the porous stone or screen and clamp down the top plate against the springs. This will help hold the soil in place so the volume will remain constant throughout the test.

10. Using a vacuum pump to remove the air adhering to the soil particles, evacuate the specimen under a pressure of 50 cm (20 in) Hg minimum for 15 minutes.

11. After the specimen has been allowed to saturate, the test is ready to be conducted. Slowly open both the inlet and outlet valves and allow to flow until a stable head is established.

12. Measure and record the time (t), the head (H), the quantity of flow (Q), and the water temperature (T).

13. Run the test several times, varying only the head (H), to establish the range of laminar flow. For open graded materials the head may be less than 25.4 mm (1 in) and for dense graded material the head may be as large as 1.5 m (5 ft).

14. At the completion of the permeability test, inspect the soil sample for any evidence of segregation of fines. Also, look for channels that may have developed between the soil sample and the sides of the permeameter mold.

15. Calculate the coefficient of permeability using the following equation:

$$k = QL / AtH$$

where:

k = coefficient of permeability
Q = quantity of water discharged
L = length of soil sample
A = cross-sectional area of cylinder
t = total time of discharge
H = difference in head

Appendix B

Standard Method of Test for Moisture-Density Relations of Soils

Procedure for determining the"Moisture-Density Relations of Soils
Using a 4.54-Kg [10-lb] Rammer and a 457 mm [18-in] Drop"
(adapted from AASHTO T 180-93)

This test procedure, if fully developed, would determine the moisture-density relationship of the given soil sample. This method was used only to properly compact UDOT's dense graded untreated base course and granular borrow soil samples used in determining the coefficient of permeability. The following procedure (method D) was used to properly compact the soil sample.

1. If a collar is added, the same mold used to determine the coefficient of permeability can be used to compact the soil specimen. Using the same mold helps to prevent any disturbance to the sample while setting up the permeability test.
2. Obtain a representative sample of dry material with a mass of at least 5 kg (12 lb).
3. Thoroughly mix the selected representative sample with the appropriate amount of water to achieve optimum moisture.
4. Carefully place the material in the mold in five equal lifts and uniformly compact each successive lift with 56 blows using the 4.54 kg (10 lb) rammer. The rammer should be allowed to freely drop from a height of 457 mm (18 in) above the soil.
5. The mold should rest firmly on a dense, uniform, and stable foundation, while compacting the soil sample.
6. The fifth lift should be compacted to approximately 12.7 mm (0.5 in) below the top of the base mold.

7. Record the weight of the soil, and the specimen is ready to perform the permeability test. Refer to Appendix A for permeability test procedures.

Appendix C

UDOT's Specifications for Dense Graded Untreated Base Course Material

Table C. 1994 Green Book Specifications Manual Dense Graded Untreated Base Course Material					
38.1 mm (1 ½ in) - Gradation*			**25.4 mm (1 in) - Gradation***		
Sieve Size	% Passing (Range)	% Passing (Center-line)	Sieve Size	% Passing (Range)	% Passing (Center-line)
38.1 mm (1 ½ in)	100	100	25.4 mm (1 in)	100	100
19 mm (3/4 in)	81 - 91	86	12.7 mm (1/2 in)	79 - 91	85
12.7 mm (1/2 in)	67 - 77	72	4.75 mm (No. 4)	49 - 61	55
4.75 mm (No. 4)	43 - 53	48	1.18 mm (No. 16)	27 - 35	31
1.18 mm (No. 16)	23 - 29	26	0.075 mm (No. 200)	7 - 11	9
0.075 mm (No. 200)	6 - 10	8			
19.1 mm (3/4 in) - Gradation*			**Pit Run - Gradation***		
19 mm (3/4 in)	100	100	19 mm (3/4 in)	100	100
9.5 mm (3/8 in)	78 - 92	85	9.5 mm (3/8 in)	78 - 92	82
4.75 mm (No. 4)	55 - 67	61	4.75 mm (No. 4)	55 - 67	64
1.18 mm (No. 16)	28 - 38	33	1.18 mm (No. 16)	28 - 38	40
0.075 mm (No. 200)	7 - 11	9	0.075 mm (No. 200)	7 - 11	4

Note * : indicates gradations used in cost analysis.

Appendix D

UDOT's Specification for Granular Borrow

Table D. 1994 Green Book Specifications Manual Granular Borrow Material					
A-1-a Gradation*			**A-1-b Gradation***		
Sieve Size	% Passing (Range)	% Passing (Center-line)	Sieve Size	% Passing (Range)	% Passing (Center-line)
76.2 mm (3 in)	100	100	76.2 mm (3 in)	100	100
38.1 mm (1 ½ in)	85 - 95	90	38.1 mm (1 ½ in)	85 - 95	90
19 mm (3/4 in)	65 - 85	75	19 mm (3/4 in)	65 - 85	75
4.75 mm (No. 4)	35 - 75	55	4.75 mm (No. 4)	35 - 75	55
2.0 mm (No. 10)	50 max	45	2.0 mm (No. 10)	25 - 55	40
0.425 mm (No. 40)	30 max	25	0.425 mm (No. 40)	50 max	35
0.075 mm (No. 200)	15 max	10	0.075 mm (No. 200)	25 max	20
P.I.	6 max	--	P.I.	6 max	--
L.L	--	--	L.L	--	--
A-2-4 Gradation*			**Pit run Gradation***		
76.2 mm (3 in)	100	100	76.2 mm (3 in)	100	100
38.1 mm (1 ½ in)	85 - 95	90	38.1 mm (1 ½ in)	85 - 95	100
19 mm (3/4 in)	65 - 85	75	19 mm (3/4 in)	65 - 85	98
4.75 mm (No. 4)	35 - 75	55	4.75 mm (No. 4)	35 - 75	81
2.0 mm (No. 10)	25 - 55	40	2.0 mm (No. 10)	25 - 55	61
0.425 mm (No. 40)	15 - 55	35	0.425 mm (No. 40)	10 - 20	34
0.075 mm (No. 200)	35 max	30	0.075 mm (No. 200)	35 max	4
P.I.	10 max	--	P.I.	--	--
L.L	40 max	--	L.L	--	--

Note * : indicates gradations used in cost analysis.

Appendix E

Various States' Open Graded Untreated Base Course Gradations

Table E. Established Untreated Base Course Gradations					
Iowa* (*k*-value = 83.8 m/day [275 ft/day])			**Minnesota*** (*k*-value = 160.0 m/day [525 ft/day])		
Sieve Size	% Passing (Range)	% Passing (Center-line)	Sieve Size	% Passing (Range)	% Passing (Center-line)
25.4 mm (1 in)	100	100	25.4 mm (1 in)	100	100
2.36 mm (No. 8)	10 - 35	22.5	19 mm (3/4 in)	65 - 100	82.5
0.30 mm (No. 50)	0 - 15	7.5	9.5 mm (3/8 in)	35 - 70	52.5
0.075 mm (No. 200)	0 - 6	3	4.75 mm (No. 4)	20 - 45	32.5
			2.0 mm (No. 10)	8 - 25	16.5
			0.425 mm (No. 40)	2 - 10	6
			0.075 mm (No. 200)	0 - 3	1.5
New Jersey* (*k*-value = 518.1 m/day [1700 ft/day])			**Pennsylvania*** (*k*-value = 1066.7 m/day [3500 ft/day])		
38.1 mm (1 ½ in)	100	100	50.8 mm (2 in)	100	100
25.4 mm (1 in)	95 - 100	97.5	19 mm (3/4 in)	52 - 100	76
12.7 mm (1/2 in)	60 - 80	70	9.5 mm (3/8 in)	33 - 65	49
4.75 mm (No. 4)	40 - 55	47.5	4.75 mm (No. 4)	8 - 40	24
2.36 mm (No. 8)	5 - 25	15	1.18 mm (No. 16)	0 - 12	6
1.18 mm (No. 16)	0 - 8	4	0.075 mm (No. 200)	0 - 5	2.5
0.30 mm (No. 50)	0 - 5	2.5			
Wisconsin* (*k*-value = 853.4 m/day [2800 ft/day])			**Wyoming** (*k*-value = 1127.7 m/day [3700 ft/day])		
25.4 mm (1 in)	100	100	38.1 mm (1 ½ in)	100	100
19 mm (3/4 in)	90 - 100	95	25.4 mm (1 in)	90 - 100	95
9.5 mm (3/8 in)	20 - 55	37.5	12.7 mm (1/2 in) mm	50 - 70	60
4.75 mm (No. 4)	0- -10	5	4.75 mm (No. 4)	20 - 50	35
2.36 mm (No. 8)	0 - 5	2.5	2.36 mm (No. 8)	10 - 30	20
			0.075 mm (No. 200)	0 - 4	2

Note * : indicates gradations used in cost analysis.