STUDY OF PERMEABILITY OF PAVEMENT BASE MATERIALS

A Thesis Presented to
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Rawee Tangpithakkul
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CHAPTER 1

INTRODUCTION

1.1 Scope

In recent years, numerous studies have indicated that a large percentage of highway pavements in the United States are distressed due to excessive moisture in the pavement structure and increasing loads and traffic volumes. The excessive moisture occurs in the pavement structure because of inadequate base and subbase drainage. In the 1993 AASHTO Guide for Design of Pavement Structures, drainage was finally considered as one of the design factors for highway pavement. Currently, the design process considers the drainage property of materials as well as strength and load distribution.

According to the AASHTO Guide (1993), most existing design methods have relied on the practice of building pavements strong enough to resist the combined effects of loads and moisture. However, they do not account for the potential destructive effects of water within the pavement structure. As a result, those pavements have a shorter than intended service life.

Moisture enters the pavement structure either as infiltrations through cracks, joints, pavement surfaces, and shoulders, or as groundwater from interrupted acquifers,
high water table, or localized springs. When water is trapped in the pavement structure, it causes many negative effects as described in the following:

(1) reduced strength of unbound granular materials,
(2) reduced strength of roadbed soils,
(3) pumping of concrete pavements with subsequent faulting, cracking, and general shoulder deterioration, and
(4) pumping of fines in the aggregate base under flexible pavements with resulting loss of support.

The effects of subsurface moisture can be minimized if an adequate subsurface drainage system is installed properly. It should be included as a portion of the pavement structure in both new and rehabilitated pavements. A subsurface drainage system usually drains water by gravity. In other words, only free water from saturated soils present in the pavement structure can be removed by the energy gradient supplied by elevation (gravity). For the conditions that exist within the pavement structure, the assumption of laminar flow of Darcy’s law is satisfactory. The application of Darcy’s law requires a determination of the coefficient of permeability, $k$, which is a measurement that represents the drainage property of materials. Laboratory determination of the coefficient of permeability of materials utilized as base and subbase is essential for highway pavement design, especially for subsurface drainage systems.
Generally, the coefficient of permeability of soils can be determined in the laboratory by two different methods: constant head and falling head methods. The constant head method is suitable for granular materials whereas the falling head method is appropriate for fine-grained soils.

Base and subbase courses usually consist of graded granular materials or materials stabilized with suitable admixtures. Graded granular materials include crushed stone, crushed slag, crushed gravel and sand, or combinations of these materials. Many admixtures are used for treated aggregates such as portland cement, asphalt, lime, cement-flyash, and lime-flyash.

Typically, a determination of the coefficient of permeability of pavement base materials performed in laboratories uses water as a permeating liquid. However, the coefficient of permeability of pavement base materials could change through time with infiltration of different liquids, e.g., flows containing sodium chloride, suspended solids, or other constituents in the liquid. In this study the laboratory test is setup to determine the coefficient of permeability of base materials with liquids containing sodium chloride and suspended solids.
1.2 Objectives

In order to study the drainage properties of pavement base materials, an experimental study was conducted to determine the coefficient of permeability of three types of pavement base materials: (1) dense graded aggregate base (DGAB), (2) permeable cement treated base (PCTB), and (3) the composite materials of PCTB/DGAB. The specimens were infiltrated by (1) tap water, (2) a sodium chloride solution, (3) a suspended solids solution. The following objectives were established for this research:

(1) Compare permeability characteristics of these types of highway base materials.

(2) Determine variation in the permeability of these base materials as a function of suspended solids and chloride concentrations.

(3) Evaluate the liquid characteristics after flows have passed through the materials.

(4) Evaluate the effect of granular soils with different compactive efforts on permeability.

(5) Evaluate the effect of cement-aggregate ratio of PCTB on permeability.
1.3 Outline

An outline of this thesis is provided as follows, including a brief description of the contents and main ideas in each chapter:

Chapter 1: Introduction

A brief discussion of pavement distress due to excessive subsurface water is provided. The need of the subsurface drainage system in the pavement structure is discussed. A short discussion on laboratory determinations of the coefficient of permeability is presented.

Chapter 2: Literature Review

The effects, types, and sources of subsurface water are discussed. An explanation of Darcy's law and the coefficient of permeability is provided. Nomographs and charts used to estimate the coefficient permeability are presented. The applications of permeable cement treated materials as a drainage layer in highway construction are discussed. The advantages and disadvantages of road salt are also discussed.

Chapter 3: Experimental Setup and Procedures

The background of laboratory permeability tests with the constant head method is provided. The equations utilized to calculate the coefficient of permeability are also presented. The methodology utilized in the test and
system operation are presented. The physical properties of aggregates are explored.

Chapter 4: Experimental Results

The permeability results of the three types of pavement base materials are presented in figures and tables. Summary and analysis of permeability results and concentrations of liquid effluents are also provided.

Chapter 5: Conclusions and Recommendations

Summary and conclusions based on data results of this research and recommendations for further investigation are provided.
CHAPTER 2

LITERATURE REVIEW

2.1 Adverse Effects of Excessive Subsurface Water

Excessive moisture in the pavement structure (surface, base, and subbase) and subgrade can cause a wide variety of problems, leading to early pavement distress and ultimately to complete destruction of the pavement if remedial measures are not undertaken.

According to Moulton (1980), the effects of excessive subsurface water can be placed in two general categories: (1) slope instability, including the sloughing and sliding of cut slopes and sidehill fills, and (2) unsatisfactory pavement performance as manifested in premature rutting, cracking, faulting, increasing roughness, and a relatively rapid decrease in the level of serviceability.

Slope instability results when the applied shear stresses exceed the strength of the soil or rock mass along a potential sliding surface. Subsurface water can contribute to this instability by increasing the stress level and decreasing the shear strength (Moulton, 1980).

Unsatisfactory pavement performances from excessive subsurface water can be found in both asphaltic concrete (AC) and portland cement concrete (PCC) pavements. If
pavement structure and subgrade become saturated, by groundwater and/or infiltration, its ability to transmit the dynamic loading imposed by traffic can be greatly impaired (Cedergren, 1987). In asphaltic concrete pavement (AC), this impairment is primarily the result of the temporary development of very high pore water pressures and consequent loss of strength in unbound base, subbase, and subgrade under dynamic loading. This action is illustrated schematically in Figure 2.1. In portland cement pavement (PCC), ejection of water and fines, called pumping, occurs at the joints between slabs and/or edges between slabs and shoulders. Concrete slabs may crack because of the lack of adequate support (Cedergren et al., 1973). Figure 2.2 shows the pumping phenomena under PCC pavement.

Another adverse effect of excessive moisture results from freeze-thaw cycles (Moulton, 1980). If water is present in the base, subbase, and subgrade, moisture will migrate through the capillary fringe toward the freezing front to increase ice lenses, as illustrated in Figure 2.3. During the freezing period, the growth of ice lenses can result in substantial heave of the overlying pavement structure. This is called frost-heave phenomena. During spring thaw period, the thawing ice lenses cause the subgrade soil to become saturated. Since the thawing generally takes place from the top down, the excess moisture from subgrade will flow into voids that exist in the pavement structure, as shown in Figure 2.4. Then, the subsequently destructive mechanisms will take effect as discussed in Figure 2.1 and 2.2.
Figure 2.1  Action of free water in AC pavement structural sections under dynamic loading (Cedergren et al., 1973)

Figure 2.2  Pumping phenomena under PCC pavement (Cedergren et al., 1973)
Figure 2.3 Capillary moisture migrating toward freezing front to feed the growth of ice lenses (Moulton, 1980)
Figure 2.4  Seepage of meltwater from ice lenses into pavement structure (Moulton, 1980)
Most studies conclude that if water is removed rapidly from pavement structures, it can extend the life of pavement. Moreover, subsurface drainage systems should be installed as part of pavement structure for drainage purposes.

2.2 Sources of Subsurface Water

Water in a pavement structure can exist in many forms such as free water, capillary water, bound water, and water vapor. However, only free water can be considered in subsurface drainage design because of two reasons: (1) it can decrease the strength of granular materials and (2) it is the only form of moisture that can be removed by a subsurface drainage system (Ridgeway, 1982).

Sources of free water that enter pavement structure are considered as groundwater and infiltration (Moulton, 1980). The melting of ice water from a frost area during a thawing cycle is considered as groundwater, as shown in Figure 2.4. Infiltration water reaches the pavement structure in several ways, which is illustrated in Figure 2.5. For PCC pavement, water enters the structural section through longitudinal and transverse joints, the joints between concrete slabs and shoulders, and cracks in concrete slabs and shoulders. For AC pavement, water enters structural pavement through longitudinal joints between shoulders and the surface course, longitudinal and transverse cracking joints, and voids in the surface course.
2.3 Subsurface Drainage System

Free water that exists in a highway pavement structure must be removed before it causes any damage. It can be removed either vertically through the subgrade or laterally through the drainage layer into a system of pipe collectors (AASHTO Guide, 1993). In most areas, vertical drainage is not adequate because the coefficient of permeability of subgrade materials is usually very low. Therefore, lateral drainage is needed to carry free water away from pavement structure.
A system of lateral drains uses a drainage layer to carry the infiltrated water to a collector system, which consists of longitudinal or transverse drains. A drainage layer generally consists of highly permeable materials. Figure 2.6 shows the location of the drainage layer in a pavement structure. In (a), the base course is used as a drainage layer and satisfies both the requirements of strength for a base course and coefficient of permeability for a drainage layer. In (b), the drainage layer is placed on top of the subgrade, either as an extra layer or as a part of the subbase. Longitudinal drains are usually made of slotted pipes and are installed parallel to the centerline. Transverse drains are occasionally installed at critical locations, as shown in Figure 2.7.

The design of removal flow in a pavement structure uses the concept of saturated flow with the energy gradient supplied by changes in the elevation heads. Darcy’s law is satisfied by this condition, and it is also adequate for subsurface drainage design. Two types of pavement subsurface drainage design criteria have been proposed as follows (Ridgeway, 1982):

(1) The time for a certain percentage of drainage of base or subbase beginning with the completely flooded condition should be less than a certain value.

(2) An inflow-outflow criterion, by which drainage occurs at a rate greater than or equal to the inflow rate.
A. Base is used as the drainage layer.

B. Drainage layer is part of or below the subbase.

Note: Filter fabrics may be used in lieu of filter material, soil, or aggregate, depending on economic considerations.

Figure 2.6 Location of drainage layer and filter (Ridgeway, 1982)
Figure 2.7 Transverse drains on superelevated curve (Cedergren et al., 1973)
Ridgeway (1976) recommends an inflow rate estimated by the water-carrying capacity of a pavement crack or joint, and by an estimated joint or crack length. The recommended inflow rate is $0.1 \text{ ft}^3/\text{hr.}$ of crack ($0.01 \text{ m}^3/\text{hr.}/\text{m.}$), and the equations used to calculate the total inflow for lateral drainage are as follows:

(a) For rigid pavement

$$Q = q (N + 1 + \frac{W}{S})$$

(b) For flexible pavement

$$Q = q (N + 1 + \frac{W}{40})$$

where

- $Q$ = total inflow, $\text{ft}^3/\text{hr.}/\text{linear ft.}$ of pavement,
- $q$ = inflow rate, $0.1 \text{ ft}^3/\text{hr.}/\text{ft.}$ of crack,
- $N$ = number of lanes,
- $W$ = lane width (ft.),
- $S$ = transverse joints spacing (ft.), and
- $40$ = estimated mean spacing of transverse cracks in flexible pavements (ft.).

Once an inflow rate has been calculated, the required thickness and coefficient of permeability of the drainage layer can be determined. In addition, all materials surrounding the drainage layer and collector drains must meet the filter criteria. Filter materials are used to prevent the clogging of the drainage layer and collector drains.
2.4 Darcy’s Law

Darcy’s law is the empirical flow equation utilized to explain the water flow in saturated soils, in terms of the discharge velocity and the rate of flow. Darcy’s law implies a linear relationship between the rate of flow, \( q \), or flow velocity, \( \nu \), and the hydraulic gradient, \( i \). For valid laminar flow conditions, which is the flow of water through void spaces between soil particles, Darcy’s law is generally expressed as:

\[
\nu = k \cdot i
\]

\[
...............(2.3)
\]

or

\[
q = k \cdot i \cdot A
\]

\[
...............(2.4)
\]

where

- \( \nu \) = the flow discharge velocity \([\text{L/T}]\),
- \( i \) = the hydraulic gradient \([\text{L/L}]\),
- \( q \) = the volume of flow per unit of time \([\text{L}^3/\text{T}]\),
- \( A \) = the cross-sectional area to the direction of flow \([\text{L}^2]\), and
- \( k \) = the constant of proportionality, commonly termed the coefficient of permeability which has the same units as velocity \([\text{L/T}]\).
2.5 The Coefficient of Permeability

The coefficient of permeability, $k$, also called the hydraulic conductivity by hydrogeologists, is an important value for expressing the drainage capability of soils. The coefficient of permeability, $k$, which is a unit of velocity, is a measure of the ease with which fluids can travel through a porous medium. The coefficient permeability of saturated soils can be measured in the laboratory with either a rigid or flexible wall permeameter. Rigid wall cells are preferred for granular materials, and either rigid or flexible wall cells are preferred for low coefficient of permeability materials, depending on the types of test specimen and conditions being simulated (Daniel, 1994). Either constant or falling head test can be performed in both types of permeameters.

The coefficient of permeability depends largely on the properties of both the porous medium and the permeating liquid (Olson and Daniel, 1981). The property of the porous medium is the size of the pores or the voids within the soil particles. The details of soil property that affect the coefficient of permeability will be discussed in section 2.6. The permeating liquid properties are influenced by the viscosity and specific weight. Shear resistance is controlled by the viscosity, while the driving force is controlled by the specific weight. The following Kozeny-Carman equation expresses the relationship between these terms (Gordon and Forrest, 1981):

$$k = \frac{k_i \gamma}{\mu} \quad \cdots \cdots \cdots \cdots \cdots (2.5)$$
where

\[ k \quad = \quad \text{coefficient of permeability [L/T]}, \]
\[ k_i \quad = \quad \text{intrinsic permeability [L}^2\text{]}, \]
\[ \gamma \quad = \quad \text{specific weight of the fluid [M/L}^3\text{]}, \]
\[ \mu \quad = \quad \text{dynamic viscosity of fluid [M} \cdot \text{T/L}^2\text{]}. \]

From the equation above, the intrinsic permeability, \( k_i \), has a unit of square length, and it is a function only of the properties of the porous material, not the permeating liquid. However, the coefficient of permeability is preferred by civil engineers and groundwater specialists because the density and viscosity of water are relatively constant (Daniel, 1994).

### 2.6 Factors Affecting the Coefficient of Permeability

The range of the coefficient of permeability of soils can vary greatly. For example, clean gravels may have a high coefficient of permeability value of around 35 cm/sec, whereas fine clays may have a low of about \( 1 \times 10^{-9} \) cm/sec. There are many factors that influence the coefficient of permeability such as: mineralogical composition, particle size and distribution, void ratio, degree of saturation, and nature of fluid (Head, 1982). However, factors affecting the coefficient of permeability in granular soil are different from those affecting fine-grained soils. The factors that affect the coefficient of permeability of fine-grained soils reported by Kim (1996) are: particle orientation and clod size, compaction method, hydraulic gradient, and permeameter type. The factors that
influence granular soils are particle size, particle size distribution, density, and particle shape and texture.

2.6.1 Particle Size

The particle size of soil is the main factor affecting the coefficient of permeability, especially finer particles. The smaller the particles, the smaller the voids between them; therefore, the coefficient of permeability decreases with decreasing particle size.

The effects of finer particles has been studied widely. Barber and Sawyer's study (1952) shows that the finer the particles, the lower the coefficient of permeability. The findings from this study are shown in Table 2.1. Another study on particle size is reported by Moulton (1980). He developed a chart used to estimate the coefficient of permeability of granular drainage and filter materials. This chart is illustrated in Figure 2.8. Three parameters: effective grain size ($D_{10}$), dry density ($\gamma_d$), and the percentage of soils passing No. 200 sieve ($P_{200}$) are used in this chart. Moulton also points out that a small increase in the amount of fines (particles passing through No. 200 sieve) can cause a large decrease in the coefficient of permeability.

2.6.2 Particle Size Distribution

The coefficient of permeability of a granular soil is influenced by its particle size distribution. Consequently, well-graded soils can be expected to be less permeable than
more uniform soils. Cedergren et al. (1973) illustrated the chart showing the permeability for soils of varying gradations and densities, which is presented in Figure 2.9.

Table 2.1 Permeability of Graded Aggregates (Barber and Sawyer, 1952)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample</th>
<th>Sample</th>
<th>Sample</th>
<th>Sample</th>
<th>Sample</th>
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<tr>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Percentage passing ——</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4 in. sieve</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1/2 in. sieve</td>
<td>85</td>
<td>84</td>
<td>83</td>
<td>81.5</td>
<td>79.5</td>
<td>75</td>
</tr>
<tr>
<td>3/8 in sieve</td>
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<td>76</td>
<td>74</td>
<td>72.5</td>
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<tr>
<td>No.4 sieve</td>
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<td>52.5</td>
<td>49</td>
<td>43.5</td>
<td>32</td>
</tr>
<tr>
<td>No.8 sieve</td>
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<td>34</td>
<td>29.5</td>
<td>22</td>
<td>5.8</td>
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<td>No.10 sieve</td>
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<td>39</td>
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<td>No.20 sieve</td>
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<td>No.40 sieve</td>
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<td>0</td>
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<tr>
<td>No.60 sieve</td>
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<td>7.5</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No.140 sieve</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>No.200 sieve</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dry density, lb/ft(^3)</td>
<td>121</td>
<td>117</td>
<td>115</td>
<td>111</td>
<td>104</td>
<td>101</td>
</tr>
<tr>
<td>Coefficient of permeability, ft/d</td>
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<td>110</td>
<td>320</td>
<td>1,000</td>
<td>2,600</td>
<td>3,000</td>
</tr>
</tbody>
</table>

Note: 1 ft/d = 0.00035 cm/sec.
\[
k = \frac{6.214 \times 10^5 (D_{10})}{(\frac{p_{200}}{200})^{0.597}} \, (\text{ft./day})
\]

\[
n = \text{Porosity} = (1 - \frac{\gamma_d}{62.4G})
\]

G = Specific Gravity
(assumed = 2.70)

**Example:**
\[
p_{200} = 2\%
\]
\[
D_{10} = 0.6 \text{ mm}
\]
\[
\gamma_d = 117 \text{ lb./cu.ft.}
\]
Read:
\[
k = 65 \text{ ft./day}
\]

**Figure 2.8** Nomograph for estimating coefficient of permeability of granular drainage and filter materials (Moulton, 1980)
Note: 1 ft/day = 0.00035 cm/sec.

**Figure 2.9** Typical gradations and permeabilities of open-graded bases and filter materials (Cedergren et al., 1973)
2.6.3 Density

Density, also void ratio or porosity, of soil is another factor that impacts its coefficient of permeability. The denser a soil and the smaller the pores, the lower its coefficient of permeability. Figure 2.10 shows the relationship between dry density and coefficient of permeability in many types of soils. A study by Strohm et. al (1967) indicated that when well-graded mixtures of sand and gravel contained as little as 5 % of fines (sizes smaller than No. 200 sieve), high compactive efforts reduced the coefficient of permeabilities to less than 0.01 % of those at moderate densities.

![Figure 2.10 Relationship between coefficient of permeability and density of soil types](Cedergren, 1989)
2.6.4 Particle Shape and Texture

The shape and texture of grains also influences the coefficient of permeability. Elongated or irregular particles create flow paths which are more tortuous than those around nearly spherical particles. Particles with a rough surface texture provide more frictional resistance to flow than do smooth-textured particles. Both effects tend to reduce the rate of flow of water through the soils, i.e., to reduce its permeability. The effects of particle shape and texture are noted in the thesis conclusion of Mohammed (1994).

2.7 Permeable Cement-Treated Base

Permeable cement-treated base (PCTB) is a base course constructed with coarse aggregates held together by a paste of hydraulic cement and water. Actually, permeable cement-treated material is used as a drainage layer, which is placed either as a base or subbase; as illustrated in Figure 2.6. However, a drainage layer as a base is more preferable (Huang, 1993). In addition to a base course, permeable cement-treated materials can be used as a surface course. It has been widely used as a surface course in such states as Florida, New Mexico, and Utah (Ghafoori and Dutta, 1995).

The application of a permeable cement-treated base (PCTB) has been reported in several states, i.e., California, Illinois, New Mexico, Oklahoma, and Wisconsin. These states have their own specifications. Illinois and Oklahoma use No. 57 stone while California and Wisconsin developed their own gradation requirements. The mix
proportion contains 282 lb/yd$^3$ (167.5 kg/m$^3$) of cement in California, Illinois, and Oklahoma while Wisconsin uses 200 lb/yd$^3$ (118.8 kg/m$^3$) of cement. California, Illinois, and Wisconsin keep the water-cement ratio at 0.37 whereas Oklahoma uses a water-cement ratio of 0.45. It should be noted that PCTB was also used in the research project *Ohio SHRP Test Pavement DEL-23-17.48*, which is located on US 23 in Delaware County, Ohio. Several universities are involved in this project, including Ohio University. The cement content 250 lb/yd$^3$ (148.5 kg/m$^3$) and water-cement ratio 0.34 are used in this project.

The mixing and installing procedures of PCTB are similar to that of conventional concrete. A PCTB can be mixed in a ready mix truck, then placed on the roadway over a filter layer, as shown in Figure 2.11. It is generally placed 1 to 3 feet outside each pavement edge to support the tracks of pavers. After placing the base material, spread it with a paving machine or, for small areas such as driveways, with hand tools. This base is spread at a loose thickness of 8 inches, then compacted to 6-inch thickness. Compaction, by a nonvibratory roller weighing 6 to 10 tons, should begin within a half hour after spreading. The surface course materials can be placed over the base about 32 hours after the base has been spread (Kozeliski, 1992).

The physical properties of PCTB have been investigated in laboratory studies. The compressive strength of PCTB in 4 × 8 in. cylinders was measured at 7 and 14 days and varied from 500-1000 psi. Moreover, the coefficient of permeability of PCTB has been
studied and reported in some states: 20,000 ft/day (6,096 m/day) in Illinois and Oklahoma, 18,000 ft/day (5,486 m/day) in Wisconsin, and 4,000 ft/day (1,219 m/day) in California (Ghafoori and Dutta, 1995).

A wide array of research has been conducted to study pavement performance, most of which indicates that pavements constructed with a permeable base are in good condition after 10-15 years of service. A permeable base eliminates pumping, faulting, and cracking of portland cement concrete pavements. With permeable bases, most pavements are anticipated to have a 50% increase in service life (Kozeliski, 1992).

![Typical permeable base pavement section](image)

**Figure 2.11** Typical permeable base pavement section (Kozeliski, 1992)
2.8 The Use of Road Salt on Highway

Sodium chloride, or road salt, has been widely used for controlling ice and snow on highways during the winter. Sodium chloride melts ice or prevents its formation on pavement to provide more driveable and less hazardous road conditions. Sodium chloride is the most popular chemical deicer because it is inexpensive, reliable, and easy to handle, store, and apply (Highway Deicing, 1991).

However, intensive applications of chloride deicing salts have caused various problems, including damage to motor vehicles, infrastructure, and environment. The most common effects on motor vehicles and infrastructure result in corrosion of steel on automobile bodies and bridges. One example of environmental problems is a high concentration of sodium and chloride in drinking water (Zenewitz, 1977).

Calcium Magnesium Acetate (CMA) has been introduced as an alternative to sodium chloride. However, the drawback of CMA is that its cost is 20 times more than that of sodium chloride, and its effects on the environment require further study. Therefore, in spite of its drawbacks, sodium chloride will remain the predominant highway deicer for many years (Highway Deicing, 1991). Highway agencies and private industry continue to seek and develop new ways to prevent and treat salt’s adverse effects, for example, by improving corrosion protection and developing new corrosion repair methods, relocating storage facilities, and improving salt application techniques.
This last method of treatment, improving application techniques, has been researched by the US army Corps of Engineers (1982). In a study designed to determine the relationship between the optimum salt application rate for the most effective ice control and safe stopping distance, the Corps concluded that there was "... No reduction in stopping distance if chloride concentration is higher than 1,000 mg/L per lane for driving speed 30 mph or less." This minimum chloride concentration rate of 1,000 mg/L was the standard measure utilized in the laboratory tests performed in this study.

2.9 Summary

The excessive moisture in pavement structure causes highway in shorten service life. To solve this problem, water has to be removed through a proper subsurface drainage system. Darcy's law is sufficient for subsurface drainage system design. The application of Darcy's law requires the determination of the coefficient of permeability. The coefficient of permeability is a measure of the ease with which a fluid will flow through a porous medium. The coefficient of permeability has units of velocity, i.e., cm/sec., ft/day, etc. It can be determined in the laboratory by two methods: constant and falling head method. The constant head method is suitable for granular soils. The coefficient of permeability depends largely on (a) the viscosity of the flowing fluid and (b) the size and continuity of the pore spaces or joints through which the fluid flows, which, in soils, depend on the size and shape of the soil particles and the density of the soil mass.
CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURES

3.1 Background

The coefficient of permeability, or permeability, is determined by a constant-head method in accordance with the specifications of the *Standard Test Method for Permeability of Granular Soils (Constant Head)*, ASTM D 2434-68. The constant-head method is best suited for granular soils which have high permeability. According to ASTM D 2434-68 specifications, the test procedure is limited to disturbed granular soils containing not more than 10% soils passing the 75 μm (No. 200) sieve.

According to the constant-head test, the laminar flow of water is made through granular soils under a constant head. The coefficient of permeability at a test temperature is calculated by using the equation (3.1).

\[
k_T = \frac{QL}{Ath} \quad \ldots \ldots (3.1)
\]

\[
k_{20} = \frac{\eta_T}{\eta_{20}} k_T \quad \ldots \ldots (3.2)
\]

where
\( k_T \) = coefficient of permeability at the test temperature, cm/sec.

\( k_{20} \) = coefficient of permeability at 20 °C, cm/sec

\( Q \) = quantity of water discharged, cm³

\( L \) = distance between manometers, cm.

\( A \) = cross-sectional area of specimen, cm²

\( t \) = time of discharge, sec.

\( h \) = difference in head on manometers, cm.

\( \eta_T \) = viscosity of fluid at the test temperature,

\( \eta_{20} \) = viscosity of fluid at 20 °C.

Then, the permeability is corrected to the value at 20 °C (68 °F) by multiplying \( k_T \) with the ratio of viscosity of water at the test temperature to the viscosity of water at 20 °C, as shown in the equation (3.2). The values of water viscosity corrections are shown in Appendix A. However, some fundamental conditions are required for ASTM D 2434-68 specifications, which are described in the following:

(1) Continuity of flow with no soil volume change during a test,

(2) Flow with the soil voids saturated with water and no air bubbles in soil voids,

(3) Flow in the steady state with no change in hydraulic gradient, and

(4) Direct proportionality of velocity of flow with hydraulic gradients below certain values, at which turbulent flow starts.
3.2 Test Description

In this study the permeability of pavement base materials was determined by a constant head method in accordance with ASTM D 2434-68 specifications. A constant head method was chosen for this study due to the relatively high permeability of test materials, simple test setup, and high reliability and accuracy of the test. A low hydraulic gradient of 2 % was used for testing. The validity of laminar flow, which is the requirement of Darcy's law, was checked by using a Reynolds number. Darcy's law is valid as long as the Reynolds number based on average grain diameter does not exceed value between 1 - 10 (Freeze and Cherry, 1979). The Reynolds number is calculated by using the equation (3.3).

\[
Re = \frac{q \rho \delta}{\mu}
\]

where

\[
Re = \text{Reynolds number},
\]

\[
q = \text{flow velocity},
\]

\[
\rho = \text{fluid density},
\]

\[
\delta = \text{average size of pore space},
\]

\[
\mu = \text{fluid viscosity}.
\]

It should be noted that the diameter corresponding to 50 % finer in particle size distribution curve, \( D_{50} \), was used for the average size of pore space, \( \delta \), for the equation above.
Three types of base materials, Dense Graded Aggregate Base (DGAB), Permeable Cement Treated Base (PCTB), and a combination materials of DGAB and PCTB (PCTB/DGAB), were subjected to different liquids: tap water, a chloride solution (Cl\textsuperscript{−}), a 50 mg/L suspended solids solution (SS\textsubscript{1}), and a 100 mg/L suspended solids solution (SS\textsubscript{2}), respectively. All tests were continuously run until they reached steady state of flow, which were usually about 30 to 40 hours. However, each liquid flow was continued for 49 hours to assure the steady state of flow. In addition, the concentrations of the effluent liquids that passed through the permeameters were also tested. The specifications outlined in the Standard Methods for Examination of Water and Wastewater (1992) were followed for all effluent tests. A total of 5 tests were performed in this study. The description of the specimens in each test is shown in Table 3.1.
Table 3.1 Test description

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Specimen</th>
<th>Depth in.</th>
<th>Density, lb/ft³</th>
<th>Fluids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>DGAB</td>
<td>PCTB</td>
</tr>
<tr>
<td>1</td>
<td>DGAB(1)</td>
<td>12</td>
<td>92.44</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DGAB(2)</td>
<td>12</td>
<td>103.30</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DGAB(3)</td>
<td>12</td>
<td>116.71</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>PCTB(1)</td>
<td>12</td>
<td>-</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>PCTB(2)</td>
<td>12</td>
<td>-</td>
<td>101</td>
</tr>
<tr>
<td>3</td>
<td>DGAB(4)</td>
<td>8</td>
<td>119.62</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DGAB(5)</td>
<td>12</td>
<td>119.11</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>PCTB(3)/DGAB(6)</td>
<td>4/6</td>
<td>120.21</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>PCTB(4)/DGAB(7)</td>
<td>6/6</td>
<td>120.21</td>
<td>101</td>
</tr>
<tr>
<td>5</td>
<td>PCTB(5)/DGAB(8)</td>
<td>4/6</td>
<td>94.87</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>PCTB(6)/DGAB(9)</td>
<td>6/6</td>
<td>94.87</td>
<td>101</td>
</tr>
</tbody>
</table>
3.3 Material Preparation

Two different sizes of aggregates were used in this study, one for DGAB and the other for PCTB. The aggregates were brought from the site used for the project OHIO SHRP Test Pavement DEL-23-17.48, which is located on US 23 in Delaware County, Ohio. The aggregates were stored in Room 032, Stocker Center, Ohio University.

3.3.1 Dense Graded Aggregate Base (DGAB) Material

The aggregate used for DGAB is crushed limestone. The particle size ranges from 2 inches to No. 200. As the requirement of ASTM D 2434-68, particles bigger than 3/4 inch cannot be used for a 5-inch diameter permeameter. Therefore, particles bigger than 3/4 inch were discarded. Figure 3.1 shows the particle size distribution curve of DGAB after such particles were discarded, including the ODOT grain size specifications for DGAB. The ODOT grain size specification was placed for the upper and lower limit of % passing sieve. A specific gravity of 2.65 was used for DGAB throughout this study.

The amount of material blended at one time was that weight needed to provide a single specimen at desired depth and density. Water was added to dry materials to provide a water content near optimum. Then, it was covered with a plastic sheet for 24 hours for curing. Prior to being spooned into the permeameter for compaction, the moist material was placed in a large pan and thoroughly remixed. Material was compacted into the permeameter by a 5.5-lb. hammer with a 12-inch drop. This hammer is the same as used for the Standard Proctor Test. Material was compacted into layers according to ASTM D
2434-68 specifications. A small portion of materials was taken for water content determination. Once the water content was determined, the dry density of soil, $\gamma_d$, and void ratio, $e$, can be calculated by the following equations:

$$\gamma_d = \frac{\gamma}{100 + w} \times 100$$

$$e = \frac{G_s \gamma_w}{\gamma_d} - 1$$

where

$\gamma_d$ = dry density of soil [M/V],

$\gamma$ = moist density of soil [M/V],

$\gamma_w$ = unit weight of water = 62.4 lb/ft$^3$,

$w$ = moisture content [%],

$e$ = void ratio,

$G_s$ = specific gravity of soil.

### 3.3.2 Permeable Cement Treated Base (PCTB) Material

Permeable cement treated base material (PCTB) consists of ASTM Type 1 portland cement, crushed limestone coarse aggregate, and water. The crushed limestone coarse aggregate was compiled according to the grading requirements of AASHTO No. 57 ranging from 3/4 inch to No. 4 sieve. Figure 3.2 shows the particle size distribution curve of AASHTO No. 57. It indicates a uniformly graded coarse aggregate.
Several basic soil laboratory tests were performed to determine the physical properties of the aggregate. All testing procedures followed the standard tests appearing in the 1993 *Annual Book of ASTM Standards*. The physical properties of the coarse aggregate were as follows: saturated-surface dry (SSD) specific gravity = 2.60, absorption = 4.1%, SSD density = 91.8 lb/ft³, voids = 43%.

Two different cement-aggregate ratios (by weight), c/g, 1 : 10 and 1 : 12, were mixed to make the specimens for test 2. Only the cement-aggregate ratio (c/g) 1 : 12 was used for tests 4 and 5. Concrete batches were mixed at their optimum water-cement ratio. An optimum water content produces a mixture which has a wet metallic appearance. Compared to conventional concrete, PCTB is very rocky. Table 3.2 represents the mixture proportion details of PCTB. Mixed-concrete was placed and compacted in the permeameter in accordance with ASTM C 192-90. Then, the specimens were cured for 24 hours before testing. ASTM C 138-92 was followed to calculate the cement content and water-cement ratio.

**Table 3.2** Mixed-proportion of PCTB

<table>
<thead>
<tr>
<th>Cement-aggregate Ratio</th>
<th>Cement Content, (lb/yd³)</th>
<th>Added water, (lb/yd³)</th>
<th>Water-cement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 : 10</td>
<td>251</td>
<td>90.5</td>
<td>0.36</td>
</tr>
<tr>
<td>1 : 12</td>
<td>214</td>
<td>79.2</td>
<td>0.37</td>
</tr>
</tbody>
</table>
3.3.3 The Composite Materials of PCTB/DGAB

The composite materials combination of PCTB and DGAB was used for tests 4 and 5. The specimens were prepared as followed: First, DGAB was mixed and placed in the permeameter at the required depth and density. Compaction of DGAB was performed according to requirements of the permeability test. Then, the PCTB was mixed and placed on top of the DGAB. The depth of PCTB was placed as required. Like the PCTB alone, the specimens were cured for 24 hours before testing.
Figure 3.1 The particle size distribution curve of DGAB

Figure 3.2 The particle size distribution curve of coarse aggregate (AASHTO No. 57)
3.4 Permeameter Design

Two identical permeameters were employed for the permeability tests. The permeameters are made of clear acrylic cylindrical stock. Figure 3.3 shows the dimension of the permeameters used in this study. Flanges are installed at both ends to provide a bolting surface for the end caps. There are two ports in the inlet side, one for liquid entering and the other for air bleeding. Only one port is installed in the outlet cap. This port allows water to exit the permeameter. Both ends are tightened by hex head bolts. In addition, an O-ring is placed inside the cap to prevent liquid leaking. Porous plastic plates, faced with 200 by 200 stainless steel mesh, are placed inside both ends of the permeameter to prevent movement of media. On the top side of the permeameter, the porous plastic mesh has a larger hole opening than that of the bottom.

An extra manometer tube was installed at the middle of the permeameters. For tests 1, 2, and 3, it was taken out for ease of compaction. For tests 4 and 5, it was also taken out during DGAB compaction, and reconnected to the permeameter before the PCTB was placed. An extra manometer tube was used to measured the head pressure between the two layers of specimens so that the upper and lower permeabilities could be determined.
Note: All dimensions are in inches

Figure 3.3 Permeameter Dimensions (Eisenhart, 1992)
Figure 3.4 System Overview (CGER Report, 1992)
3.5 System Overview

The test system was installed in Room 032B, Stocker Center. Figure 3.4 shows the schematic system for the permeability test. The test system consists of:

1. a liquid storage tank; 55 gallon capacity,
2. an electric pump; 1/3 hp,
3. an upper reservoir; 7.5 gallon capacity,
4. upper and lower head tanks connected to permeameter,
5. a bubbler system model 7600 for measuring pressure head and flow rate,
6. a permeameter,
7. a thermometer,
8. an effluent storage tank; 55 gallon capacity,
9. a recorder; YOKOGAWA HR 1300.

The fluid was stored in the 55-gallon polypropylene storage tank; then it was transferred to the upper reservoir by the 1/3-hp pump. An automatic on-off switch was installed in the upper reservoir to control the amount of fluid. The fluid flows to the upper head tank by gravity. The volume of liquid was controlled by a valve installed under the reservoir. There are three ports in the upper head tank: inlet, outlet, overflow. Extra fluid was sent back to the storage tank through the overflow port. The fluid was passed through the permeameter through the outlet port. The flow was maintained through the permeameter during the experiment. The flow from the permeameter goes to a lower head tank. The lower head tank is the same as the upper head tank but it has only two
ports: inlet and overflow ports. The overflow from the lower head tank goes to the effluent storage tank or to a graduated cylinder to measure the flow rate.

In order to determine the permeability, the head differences and flow rate were measured by the bubbler system. Since data has to be recorded very often, an automatic recorder is needed for convenient readings. Therefore, the bubbler system was connected to the HR 1300 YOKOGAWA recorder for automatic reading. Readings from the bubbler systems were recorded by the recorder every two hours.

3.6 Model 7600 Bubbler System

The model 7600 bubbler system was used for measurements of liquid levels in the permeability tests. It is a bubbler style sensor that measures the hydrostatic back pressure generated by the slow purge of air through a dip tube sense element submerged in the media. Also, it is an ideal instrument for the situation in which the liquid is very viscous or contains more suspended solids. As the dip tube is the only wetted part, extremely aggressive media can be measured.

Figure 3.5 illustrates the principle of operation of the model 7600 bubbler system. The bubbler forces gas through the dip tube into the liquid. The pressure in the line is equal to the hydrostatic pressure at the exit point. The pressure sensor is connected to the feed line and measures the pressure signal from the exit of the dip tube. This pressure is a
direct indication of the liquid level. The output signal from the bubbler system is DC 4-20 mA. (Computer Instruments Corporation, 1992).

![Diagram of Bubbler Operation](image)

**Figure 3.5** Principle of Bubbler Operation (Computer Instruments Corporation, 1992)

Figure 3.6 shows the bubbler system installed in the permeability testing system. There are two sets of bubbler systems installed in the Room 032B laboratory, one system for each permeameter. Each system measures upper, medium, and lower heads and flow rates of the testing system. For head measurements, the bubbler system measures the fluid height in reading cylinders, which are constructed of 1-1/2 inch I.D. acrylic cylindrical stock. The bubbler system is connected to the reading cylinders by purge lines, made of...
1/8- inch Tygon tubing. These cylinders are connected by 1/4-inch Tygon tubing to the inlet, outlet, and middle manometers of the permeameter. The level in the head tanks can be measured because it is the same height as in the reading cylinders. To measure the flow rate, overflow from the lower head tank flowing to the 200 mL graduated cylinder was measured. The height of fluid in the graduated cylinder was measured for a certain period of time and converted to volume of liquid by the recorder. A constant air supply, provided by the central air compressor of the building, maintains a pressure of 5 psi. in the bubbler system. The data readings from the bubbler system were recorded by the recorder.

3.7 Data Acquisition

A Model HR 1300 YOKOGAWA recorder was used for data acquisition from the output signal of the bubbler system. The recorder has a capacity of up to 20 channels. Six channels were programmed to receive head pressure readings, and two channels were programmed for flow rate readings.

The recorder receives inputs in many ways such as through DC voltage, thermocouple, etc. To meet the input requirement, a shunt resistor, 11Ω, was connected to the bubbler system output to provide DC voltage, and then the recorder converts DC voltage to the fluid height in inches. Output options include digital readout, hard copy, computer memory card or direct loading on to computer software.
The hydraulic head measurement was read directly from the bubbler system. In case of the flow rate, the height readings of liquids in the graduated cylinder were converted to produce volume readings of liquid. The data was recorded on the data sheet and then input to a computer spreadsheet for a formatted output.

3.8 Liquid Preparation and Loading

3.8.1 Liquid Preparation

Two main different types of liquids were applied in this study — a chloride solution and a suspended solids solution. The amount of liquids utilized in each specimen depended on the flow rate of each specimen. Liquids were mixed and added to the testing system for continuous tests.

The salt, ZERO ICE®, manufactured by Howard Johnson's, was used to form the chloride solution. 300 g. of salt was mixed with about 50 gallons of tap water. The solution was mixed and stored in the storage tank. The chloride concentration of influent samples was determined to be approximately 1000 mg/L.

Two concentrations of suspended solids solutions were applied for the permeability test — 50 mg/L and 100 mg/L suspended solids solutions. For the 50 mg/L suspended solids solution, 25 g. of clay passing through a No. 200 sieve was mixed with about 50 gallons of tap water. A double amount of clay was used for the 100 mg/L suspended solids solution. Again, the solutions were mixed and stored in the storage tank.
3.8.2 Liquid Loading

After the specimens were connected to the testing system, they were saturated by a flow of tap water from the bottom upward as required by ASTM D 2434-68 specifications. The saturation continued until the permeameters were full of water (no air). Then, the tests started with the downward flow. The upper and lower head tanks were readjusted to maintain a 2% gradient. Flow rates were recorded after heads were in a stable condition. The tests were continued until they reached a steady state of flow. After the water test was completed, valves installed at the inlet and outlet ports of the permeameter were closed. Water was taken out of the system while the specimens were still full of water. Consequently, the prepared chloride solution was connected and pumped to the testing system. The valves were opened to start the flow of the chloride solution. Again, the test was continued until it reached a steady state of flow. The 50 mg/L and 100 mg/L suspended solids solutions were subsequently applied to the testing system after the chloride test was completed. The loading procedures of these solutions were the same as in the chloride solution. When each test was completely finished, the system was shut down and the materials were taken out of the permeameters.

It should be noted that the initial readings for chloride and suspended solids solutions began after the theoretical detention time. The theoretical detention time is defined as the period of time that in which fluids wash away the previous liquid in specimens. It can be calculated by the following equation:
\[ \theta = \frac{V_v}{Q} \]  

where

\[ \begin{align*}
\theta &= \text{theoretical detention time, [T]} \\
V_v &= \text{volume of voids in the permeameter, [L}^3] \\
Q &= \text{Flow rate of liquid, [L}^3/T].
\end{align*} \]

### 3.9 Effluent Analysis

One hundred milliliters of effluents were collected every 6 hours to determine the concentrations of chloride and suspended solids. The chloride concentration was determined by the method 4500-CI B (Argentometric Method) described in the *Standard Methods for Examination of Water and Wastewater* (1992). The suspended solids concentration was determined by the method 2540 D in the *Standard Methods for Examination of Water and Wastewater* (1992). A 0.45 micrometer (\(\mu\)m) pore opening size and 25 mm. diameter filter was used to determine the suspended solids. The effluent analysis was performed in Room 203, Stocker Center.
Figure 3.6 Photograph of permeability system and bubbler installation
3.10 Summary

A permeability test, constant-head method, was set up for this study in accordance with ASTM D 2434-68 specifications. A total of 5 tests were conducted to determine the permeability of three types of pavement base materials, DGAB, PCTB, and the composite materials of PCTB/DGAB. The specimens were subjected to four different liquids: (1) tap water, (2) chloride solution (approximate 1000 mg/L), (3) 50 mg/L suspended solids solution, and (4) 100 mg/L suspended solids solution. A bubbler system was installed for head and flow rate measurements, and a recorder was connected to the bubbler systems for automatic readings. In addition, sample effluents of chloride and suspended solids solutions that passed through the specimens were collected to determine the concentrations of chloride and suspended solids, respectively. The testing procedures specified in the Standard Methods for Examination of Water and Wastewater (1992) were followed for the determination of effluent concentrations.
CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Permeability Results

A total of 5 laboratory tests were conducted for this study. Three types of materials, DGAB, PCTB, and PCTB/DGAB were subjected to 4 different liquids (1) tap water, (2) chloride solution, (3) 50 mg/L suspended solids solution, and (4) 100 mg/L suspended solids solution, respectively. Each fluid flow was continued for 49 hours. The initial readings of permeability for chloride and suspended solids solutions were recorded after each flow was continued for 30 minutes, which is longer than the theoretical detention time of about 20 minutes. The coefficient of permeability was calculated by using the equations (3.1) and (3.2), and the theoretical detention time was calculated by using the equation (3.6). Moreover, the validity of laminar flow was checked by using the Reynolds number, which is calculated by using the equation (3.3). These equations are represented in Chapter 3.

4.1.1 Test 1

In test 1, the permeability of Dense Graded Aggregate Base (DGAB) material was measured. Three specimens of DGAB — dry density 92, 103 and 117 lb/ft$^3$ — were applied in this test. The properties of each specimen are shown in Table 4.1. The specimens were subjected to different liquids. First, all three specimens were run with tap
water as a base. Then, the remaining two specimens, dry density 92.44 and 116.71 lb/ft^3, were run with a chloride solution (Cl^-), a 50 mg/L suspended solids solution (SS[1]), and a 100 mg/L suspended solids solution (SS[2]), respectively.

Table 4.1 Properties of DGAB for test 1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Air-dried Unit Wt. (lb/ft^3)</th>
<th>Moisture Content (%)</th>
<th>Oven-dried Unit Wt. (lb/ft^3)</th>
<th>Specific Gravity</th>
<th>Void Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGAB(1)</td>
<td>99</td>
<td>7.10</td>
<td>92.44</td>
<td>2.65</td>
<td>0.79</td>
</tr>
<tr>
<td>DGAB(2)</td>
<td>111</td>
<td>7.45</td>
<td>103.30</td>
<td>2.65</td>
<td>0.60</td>
</tr>
<tr>
<td>DGAB(3)</td>
<td>125</td>
<td>7.10</td>
<td>116.71</td>
<td>2.65</td>
<td>0.42</td>
</tr>
</tbody>
</table>

4.1.1.1 Baseline Permeability of DGAB

The baseline permeability was determined by using tap water. As expected, the permeability of DGAB decreased as the density increased. Figure 4.1.1 represents the baseline permeability of DGAB for test 1. The initial permeabilities were 0.0133, 0.0092, and 0.0039 cm/sec. for DGAB(1), DGAB(2), and DGAB(3), respectively. The permeabilities increased slightly before an apparent steady state of flows was reached. It took about 20-30 hours to reach a steady state of flow. The final permeabilities were 0.0143, 0.0097, 0.0042 cm/sec. for DGAB(1), DGAB(2), and DGAB(3), respectively.
4.1.1.2 With Chloride Solution

Two specimens, DGAB(1) and DGAB(3), were used to determine the permeability of the chloride solution. Figure 4.1.2 shows the permeability curve of DGAB with the chloride solution. The chloride permeability dropped very minimally compared to the baseline permeability. The decrease of chloride permeability is negligible because it is too minimal.

4.1.1.3 With 50 mg/L Suspended Solids Solution, SS[1]

Figure 4.1.3 shows the permeability curve of DGAB with the 50 mg/L suspended solids solution. The initial permeabilities were 0.0138 and 0.0039 cm/sec. for DGAB(1) and DGAB(3) respectively. The permeability dropped gradually in the first 20 hours. The final permeabilities were 0.0126 and 0.0030 cm/sec. for DGAB(1) and DGAB(3), respectively.

4.1.1.4 With 100 mg/L Suspended Solids Solution, SS[2]

Following the study with the 50 mg/L, the 100 mg/L suspended solids solution was used to determine its permeability. The permeability curve is shown in Figure 4.1.4. The initial permeabilities were 0.0126 and 0.0030 cm/sec. for DGAB(1) and DGAB(3), respectively. The permeability change was higher compared to that of SS[1]. The final permeabilities were 0.0106 and 0.0020 cm/sec. for DGAB(1) and DGAB(3), respectively.
4.1.1.5 Overall Permeability for Test 1

Test 1 was completed after finishing with the 100 mg/L suspended solids solution. The overall permeability dropped from 0.0143 to 0.0106 and 0.0042 to 0.0020 cm/sec. for DGAB(1) and DGAB(3), respectively. The permeability of all fluids can be put together as overall permeability curve, which is shown in Figure 4.1.5.
Figure 4.1.1 Test 1: The baseline permeability curve of DGAB

Figure 4.1.2 Test 1: The permeability curve of DGAB with chloride solution
Figure 4.1.3 Test 1: The permeability curve of DGAB with SS[1]

Figure 4.1.4 Test 1: The permeability curve of DGAB with SS[2]
Figure 4.1.5 Test 1: The overall permeability curve of DGAB
4.1.2 Test 2

The permeable cement treated base (PCTB) material was applied for test 2. Two specimens of PCTB were mixed with a cement-aggregate ratio of 1: 10 and 1: 12 by weight. The properties of the two specimens are shown in Table 4.2. As in test 1, the specimens were subjected to 4 different liquids, (1) tap water, (2) a chloride solution, (3) a 50 mg/L suspended solids solution, and (4) a 100 mg/L suspended solids solution, respectively.

Table 4.2 The properties of PCTB for test 2

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cement-aggregate Ratio (1)</th>
<th>Cement Content (lb/yd³)</th>
<th>Water-cement Ratio (2); (%)</th>
<th>Unit Weight (lb/ft³)</th>
<th>Air Content (3) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCTB(1)</td>
<td>1: 10</td>
<td>251</td>
<td>0.36</td>
<td>103</td>
<td>30.95</td>
</tr>
<tr>
<td>PCTB(2)</td>
<td>1: 12</td>
<td>214</td>
<td>0.37</td>
<td>101</td>
<td>32.15</td>
</tr>
</tbody>
</table>

Note: (1) wt. of air-dried aggregate ÷ wt. of cement

(2) wt. of water ÷ wt. of cement

(3) by gravimetric method ASTM C 138-92
4.1.2.1 Baseline Permeability of PCTB

The baseline permeability of PCTB is shown in Figure 4.1.6. The initial permeabilities were 0.8467 and 0.9173 cm/sec. for PCTB(1) and PCTB(2), respectively. The permeabilities of both specimens were fluctuated in the first 10 hours because of hydraulic adjustment. Then, the permeabilities became stable and reached an apparent steady state at 0.8857 and 0.9754 cm/sec. for PCTB(1) and PCTB(2), respectively.

4.1.2.2 With Chloride Solution

The chloride solution was started after the baseline permeability was completed. Figure 4.1.7 shows the permeability of PCTB with the chloride solution. The permeabilities started at 0.8658 and 0.9754 cm/sec. for PCTB(1) and PCTB(2), respectively. The permeabilities of the both specimens fluctuated in the first 20 hours, then they became stable. The final permeabilities were 0.8562 and 0.9632 cm/sec. for PCTB(1) and PCTB(2), respectively.

4.1.2.3 With 50 mg/L Suspended Solids Solution, SS[1]

Figure 4.1.8 shows the permeability curve of PCTB with the 50 mg/L suspended solids solution. The initial permeabilities were 0.8467 and 0.9632 cm/sec. for PCTB(1) and PCTB(2). The permeabilities did not change significantly. The final permeabilities were 0.8375 and 0.9513 cm/sec. for PCTB(1) and PCTB(2), respectively.
4.1.2.4 With 100 mg/L Suspended Solids Solution, SS[2]

Figure 4.1.9 represents the permeability of PCTB with the 100 mg/L suspended solids solution. The initial permeabilities were 0.8375 and 0.9513 cm/sec. for PCTB(1) and PCTB(2), respectively. The permeability of PCTB(1) was very stable while it fluctuated slightly in the first 20 hours for PCTB(2). The final permeabilities were 0.8285 and 0.9397 cm/sec. for PCTB(1) and PCTB(2), respectively. The changes in permeability of SS[2] were approximately the same as in SS[1].

4.1.2.5 Overall Permeability for Test 2

Test 2 was completed after finishing with the 100 mg/L suspended solids solution. The data was collected for 196 hours. Figure 4.1.10 shows the overall permeability of PCTB which, according to the permeability curve, is very stable.
Figure 4.1.6 Test 2: The baseline permeability curve of PCTB

Figure 4.1.7 Test 2: The permeability curve of PCTB with the chloride solution
Figure 4.1.8 Test 2: The permeability curve of PCTB with SS[1]

Figure 4.1.9 Test 2: The permeability curve of PCTB with SS[2]
Figure 4.1.10 Test 2: The overall permeability curve of PCTB
4.1.3 Test 3

In test 3, two specimens were made with different depths of DGAB: DGAB(4), 8-inch depth and DGAB(5), 12-inch depth. The properties of each specimen are shown in Table 4.3. From the table, the dry unit weights of both specimens are close. Figure 4.1.11 shows the permeability curve for test 3. The initial permeabilities were 0.0024 and 0.0025 cm/sec. for DGAB(4) and DGAB(5), respectively. As in test 1, the permeabilities of both specimens increased slightly as time passed. The final permeabilities were 0.0028 and 0.0030 cm/sec. for DGAB(4) and DGAB(5). It should be noted that the permeabilities of both specimens were very close.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Depth (in.)</th>
<th>Air-dried Unit Wt. (lb/ft³)</th>
<th>Moisture Content (%)</th>
<th>Oven-dried Unit Wt. (lb/ft³)</th>
<th>Specific Gravity</th>
<th>Void Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGAB(4)</td>
<td>8</td>
<td>130</td>
<td>8.90</td>
<td>119.62</td>
<td>2.65</td>
<td>0.38</td>
</tr>
<tr>
<td>DGAB(5)</td>
<td>12</td>
<td>128</td>
<td>7.46</td>
<td>119.11</td>
<td>2.65</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Figure 4.1.11 Test 3: The permeability curve of DGAB with different depth
4.1.4 Test 4

In test 4, the specimens were made from a combination of PCTB and DGAB. The PCTB was placed over the DGAB. One 4-inch layer and another 6-inch layer of PCTB were placed above a 6-inch layer of DGAB. For both specimens, the densities of DGAB and PCTB were 120.21 and 101 lb/ft^3 respectively. The physical properties of DGAB in test 4 are shown in Table 4.4. The permeability was measured in the upper and lower parts and overall of the permeameter. This test was run using two liquids: tap water and a 100 mg/L suspended solids solution.

Table 4.4 The properties of DGAB in test 4 and test 5

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Air-dried Unit Wt., (lb/ft^3)</th>
<th>Moisture Content, (%)</th>
<th>Oven-dried Unit wt., (lb/ft^3)</th>
<th>Specific Gravity</th>
<th>Void Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>129</td>
<td>7.31</td>
<td>120.21</td>
<td>2.65</td>
<td>0.38</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>7.52</td>
<td>94.87</td>
<td>2.65</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Note: The two specimens in each test have the same properties

4.1.4.1 Baseline Permeability of PCTB/DGAB

Figures 4.1.12 and 4.1.13 show the baseline permeability curve of PCTB/DGAB 4"/6" and 6"/6" respectively. The upper, lower, and overall permeabilities are presented in each figure. In general, the overall permeability of the specimens in test 4 was higher than that of DGAB but lower than that of PCTB. The overall permeability was similar to
the permeability of the lower part (DGAB). The permeability details of each part are shown in Table 4.5.

4.1.4.2 With 100 mg/L Suspended Solids Solution, SS[2]

After the baseline permeability test was completed, the flow of the 100 mg/L suspended solids solution passed through the specimens in test 4. Figures 4.1.14 and 4.1.15 show the permeability curve with the 100 mg/L suspended solids solution. The upper and lower parts and overall permeabilities dropped slightly compared to the baseline permeabilities. Details of permeability in test 4 are shown in Table 4.5.

4.1.4.3 Overall Permeability for Test 4

Test 4 was completed after finishing with the 100 mg/L suspended solids solution. The data was collected for 98 hours. Figures 4.1.16 and 4.1.17 shows the overall permeability of PCTB/DGAB 4”/6” and 6”/6”, respectively.
Table 4.5 The permeability results for tests 4 and 5

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Specimen</th>
<th>Depth (in.)</th>
<th>Permeability, (cm/sec.)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper</td>
<td>Lower</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>4</td>
<td>With water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>4/6</td>
<td>0.8271</td>
<td>1.0189</td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>6/6</td>
<td>0.8497</td>
<td>0.9725</td>
</tr>
<tr>
<td>4</td>
<td>With SS[2]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>4/6</td>
<td>1.0189</td>
<td>0.7989</td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>6/6</td>
<td>0.9614</td>
<td>0.8412</td>
</tr>
<tr>
<td>5</td>
<td>With water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>4/6</td>
<td>0.8460</td>
<td>1.0575</td>
</tr>
<tr>
<td></td>
<td>PCTB/DGAB</td>
<td>6/6</td>
<td>0.8053</td>
<td>1.0067</td>
</tr>
</tbody>
</table>

Note: Test 4 was run with two liquids: tap water and the 100 mg/L suspended solids solution (SS[2])
Figure 4.1.12 Test 4: The baseline permeability curve of PCTB/DGAB 4”/6”

Figure 4.1.13 Test 4: The baseline permeability curve of PCTB/DGAB 6”/6”
Figure 4.1.14 Test 4: The permeability curve of PCTB/DGAB 4''/6'' with SS[2]

Figure 4.1.15 Test 4: The permeability curve of PCTB/DGAB 6''/6'' with SS[2]
Figure 4.1.16 Test 4: The overall permeability curve of PCTB/DGAB 4”/6”

Figure 4.1.17 Test 4: The overall permeability curve of PCTB/DGAB 6”/6”
4.1.5 Test 5

This test followed the same procedures as test 4, except for the density of DGAB. For test 5, the density of DGAB was 94.87 lb/ft$^3$ (120.21 lb. ft$^3$ for test 4). The property details of DGAB for test 5 are shown in Table 4.4.

Figures 4.1.18 and 4.1.19 show the permeability curve of the two specimens for test 5. Details of the permeability are also shown in Table 4.5. The overall permeability in test 5 was higher than that in test 4 — approximately 0.012 and 0.035 cm/sec. for test 4 and test 5 respectively. It can be explained that the density of DGAB in test 5 was lower than that in test 4. The properties of DGAB controlled the permeability of each specimen.
Figure 4.1.18 Test 5: The permeability curve of PCTB/DGAB 4"/6"

Figure 4.1.19 Test 5: The permeability curve of PCTB/DGAB 6"/6"
4.2 Permeability Analysis

4.2.1 Comparison of Permeability and Types of Materials

From the data results, the comparison of permeability and types of materials at 12-inch depth can be placed into two categories:

(1) DGAB(1), PCTB(2), and PCTB(6)/DGAB(9) and
(2) DGAB(5), PCTB(2), and PCTB(4)/DGAB(7).

The density and permeability of each material are shown in Table 4.6. The permeabilities of materials in category (1) were 0.0143, 0.9754, and 0.0301 cm/sec. for DGAB(1), PCTB(2), and PCTB(6)/DGAB(9), respectively, and those of materials in category (2) were 0.0030, and 0.9754, and 0.0111 cm/sec. for DGAB(5), PCTB(2), and PCTB(4)/DGAB(7), respectively. Figures 4.2.1 and 4.2.2 show the permeability versus time of materials in category (1) and (2), respectively. The PCTB is the best material with respect to drainage property.
Table 4.6 Comparison between Permeability and Material Types

<table>
<thead>
<tr>
<th>Category</th>
<th>Specimen</th>
<th>Density (lb/ft³)</th>
<th>Final Water Permeability (cm/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DGAB(1)</td>
<td>92.44</td>
<td>0.0143</td>
</tr>
<tr>
<td>1</td>
<td>PCTB(2)</td>
<td>101</td>
<td>0.9754</td>
</tr>
<tr>
<td>1</td>
<td>PCTB(6)/DGAB(9)</td>
<td>101/94.87</td>
<td>0.0301</td>
</tr>
<tr>
<td>2</td>
<td>DGAB(5)</td>
<td>119.11</td>
<td>0.0030</td>
</tr>
<tr>
<td>2</td>
<td>PCTB(2)</td>
<td>101</td>
<td>0.9754</td>
</tr>
<tr>
<td>2</td>
<td>PCTB(4)/DGAB(7)</td>
<td>101/120.21</td>
<td>0.0111</td>
</tr>
</tbody>
</table>

4.2.2 Relationship between Permeability and Density of DGAB

For 12-inch depth of DGAB, a relationship between permeability and density can be established. Figure 4.2.3 shows the permeability as a function of density of DGAB. As expected, the permeability decreased as density increased. The permeability and density of each material are presented in Table 4.7.
**Figure 4.2.1** Permeability vs. Time

**Figure 4.2.2** Permeability vs. Time
Table 4.7 Relationship between Permeability and Density of DGAB

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Depth (in.)</th>
<th>Density (lb/ft³)</th>
<th>Permeability (cm/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGAB(1)</td>
<td>12</td>
<td>92.44</td>
<td>0.0143</td>
</tr>
<tr>
<td>DGAB(2)</td>
<td>12</td>
<td>103.30</td>
<td>0.0097</td>
</tr>
<tr>
<td>DGAB(3)</td>
<td>12</td>
<td>116.71</td>
<td>0.0042</td>
</tr>
<tr>
<td>DGAB(5)</td>
<td>12</td>
<td>119.11</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

Figure 4.2.3 Permeability vs. Density of DGAB
4.2.3 Comparison of Permeability between Estimated Values Obtained from Figure 2.8 and Test Results

For DGAB, a comparison of permeability between estimated values and test results can be made. The estimated permeability can be achieved by using Figure 2.8. Variables required for estimating permeability: (1) percent passing No. 200 sieve ($P_{200}$), (2) effective grain size ($D_{10}$), and (3) dry density ($\gamma_d$). $P_{200}$ and $D_{10}$ are obtained from the particle size distribution curve shown in Figure 3.1, and $\gamma_d$ is obtained from the Table that shows the property of each specimen. The permeability from test results is an average permeability of specimens with similar densities. The comparison can be placed into three different dry densities — 92, 103, and 120 lb/ft$^3$. Table 4.8 shows the permeability of these two sources. In general, the estimated permeability is not significantly different from the test results.

Table 4.8 Comparison of Permeability between Estimated Values Obtained from Figure 2.8 and Test Results

<table>
<thead>
<tr>
<th>Category</th>
<th>Variables</th>
<th>Permeability, (cm/sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{200}$ (%)</td>
<td>$D_{10}$ (mm.)</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.2</td>
</tr>
</tbody>
</table>
4.3 Effluent Analysis

The effluents from the permeameters in tests 1 and 2 were analyzed for chloride and suspended solids concentration. About 100 mL samples of each effluent were collected and stored in plastic beakers every 6 hours until each test was completed. Then, the effluent samples were analyzed in Stocker Center, Room 203. Results of effluent analysis are represented by graphs of concentration (mg/L) and time (hours), which are shown in Figures 4.3.1 to 4.3.6.

4.3.1 Chloride Solution

Figures 4.3.1 and 4.3.2 represent the concentration curve vs. time of the chloride effluent samples in test 1 and test 2, respectively. The chloride concentrations ranged from 620 to 975 mg/L. The average concentrations of chloride in PCTB were higher than those of DGAB. In addition, the reductions of chloride concentration in DGAB were greater than those of PCTB. The detailed concentrations of the chloride effluent solutions are shown in Table 4.9. It should be noted that the reduction of effluent chloride had a negligible affect on the permeability of either PCTB or DGAB.
Table 4.9 The concentrations of chloride effluents

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density (lb/ft^3)</th>
<th>Chloride, (mg/L)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>DGAB(1)</td>
<td>92.44</td>
<td>620</td>
<td>869</td>
</tr>
<tr>
<td>DGAB(3)</td>
<td>116.71</td>
<td>567</td>
<td>869</td>
</tr>
<tr>
<td>PCTB(1)</td>
<td>103</td>
<td>869</td>
<td>975</td>
</tr>
<tr>
<td>PCTB(2)</td>
<td>101</td>
<td>904</td>
<td>975</td>
</tr>
</tbody>
</table>

4.3.2 Suspended Solids Solution

Generally, the effluent suspended solids concentrations from the DGAB specimen were lower than those of PCTB. Figures 4.3.3 and 4.3.4 represent the effluent concentration curve versus time of the 50 mg/L suspended solids solution (SS[1]) for DGAB and PCTB, respectively. The suspended solids ranged from 32 to 48 mg/L and 40 to 48 mg/L for DGAB and PCTB, respectively. Figures 4.3.5 and 4.3.6 represent the effluent concentration curve of the 100 mg/L suspended solids solution (SS[2]), for DGAB and PCTB respectively. The suspended solids ranged from 70 to 88 mg/L and 85 to 95 mg/L for DGAB and PCTB, respectively.

The reduction of effluent suspended solids of DGAB were greater than those of PCTB. The suspended solids reductions of DGAB(1) (density 92.44 lb/ft^3) were 14 and 18 percent for SS[1] and SS[2], respectively, and they were 20 and 24 percent for SS[1] and SS[2], respectively, for DGAB(3) (density 116.71 lb/ft^3). However, the reduction of
suspended solids were almost the same in both specimens of PCTB. The suspended solids reduction of SS[1] and SS[2] were 10 and 9 percent, respectively for PCTB(1), and they were 8 and 10 percent of SS[1] and SS[2], respectively for PCTB(2). The details of effluent suspended solids concentrations are shown in Tables 4.10 and 4.11 for SS[1] and SS[2], respectively.

This decrease of effluent suspended solids of DGAB was higher than that of PCTB since more of suspended solids was retained in the specimens, as a result of the smaller pore size between particles. The smaller the pore size between particles, the more suspended solids are retained. The accumulation of suspended solids in the specimens affected the permeability. The higher the accumulation of suspended solids, the lower the permeability of materials. In addition, the accumulation of suspended solids was higher in the specimen that had higher density for DGAB. From the permeability results of test 1 with suspended solids solutions, DGAB(3) (higher density) had a higher decrease of permeability than that of DGAB(1) (lower density).
Table 4.10  The concentrations of the effluent samples of the 50 mg/L suspended solids solution, SS[1]

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density (lb/ft³)</th>
<th>Suspended Solids, (mg/L)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>DGAB(1)</td>
<td>92.44</td>
<td>34</td>
<td>48</td>
</tr>
<tr>
<td>DGAB(3)</td>
<td>116.71</td>
<td>32</td>
<td>45</td>
</tr>
<tr>
<td>PCTB(1)</td>
<td>103</td>
<td>40</td>
<td>47</td>
</tr>
<tr>
<td>PCTB(2)</td>
<td>101</td>
<td>41</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 4.11  The concentrations of the effluent samples of the 100 mg/L suspended solids solution, SS[2]

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density (lb/ft³)</th>
<th>Suspended Solids, (mg/L)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>DGAB(1)</td>
<td>92.44</td>
<td>72</td>
<td>88</td>
</tr>
<tr>
<td>DGAB(3)</td>
<td>116.71</td>
<td>70</td>
<td>84</td>
</tr>
<tr>
<td>PCTB(1)</td>
<td>103</td>
<td>86</td>
<td>95</td>
</tr>
<tr>
<td>PCTB(2)</td>
<td>101</td>
<td>85</td>
<td>94</td>
</tr>
</tbody>
</table>
Figure 4.3.1 Test 1: The Effluent Concentration vs. Time of Cl

Figure 4.3.2 Test 2: The Effluent Concentration vs. Time of Cl
Figure 4.3.3 Test 1: The Effluent Concentration vs. Time of SS[1]

Figure 4.3.4 Test 2: The Effluent Concentration vs. Time of SS[1]
Figure 4.3.5 Test 1: The Effluent Concentration vs. Time of SS[2]

Figure 4.3.6 Test 2: The Effluent Concentration vs. Time of SS[2]
4.4 Summary of Permeability Results

The summary of permeability results is shown in Table 4.12. A total of 5 tests were performed in this study. The permeating liquid was passed through the media for 49 hours. For tests 1 and 2 the total time for all liquids was 196 hours, 49 hours for tests 3 and 5, and 98 hours for test 4.

The permeability of DGAB ranged from 0.0030 to 0.0143 cm/sec, depending on the density of the specimen and the type of fluid. The higher density specimen had lower permeability. The affect of the chloride solution on the permeability of DGAB was negligible. Compared to baseline permeabilities, the permeabilities decreased by 12 to 29 percent and 26 to 52 percent for SS[1] and SS[2], respectively.

The permeability of PCTB ranged from 0.8285 to 1.0451 cm/sec. The chloride solution did not influence the permeability while the suspended solids solution tended to slightly lower the permeability.

The overall permeabilities of PCTB/DGAB ranged from 0.0097 to 0.0401 cm/sec. The overall permeability was influenced predominantly by DGAB.
Table 4.12 Summary of permeability results

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<th>Density ($\text{lb/ft}^3$)</th>
<th>Depth (in.)</th>
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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

The objectives set forth in Chapter 1 were fulfilled through experimentation and analysis of test data. A constant head permeability setup was designed to study the permeability of three types of pavement base materials: (1) dense-graded aggregate base (DGAB), (1) permeable cement-treated base (PCTB), and (3) the composite materials of PCTB/DGAB. Tap water was passed through the specimens in order to determine baseline permeabilities, then the sodium chloride solution (Cl'), the 50 mg/L suspended solids solution (SS[1]), and the 100 mg/L suspended solids solution (SS[2]), respectively, were passed through the specimens. A hydraulic gradient of 2% was applied to all tests in this study.

Five tests were conducted in the laboratory for this study. Each test had two specimens, excluding 3 specimens for test 1. Materials were prepared and compacted into a cylindrical permeameter made of clear acrylic. All specimen dimensions were 5 inches in diameter with varying depths. For tests 1 and 2, all 4 liquids were passed through the specimens. In the remaining tests, only tap water was used, except in test 4, which used a flow of the 100 mg/L suspended solids solution (SS[2]) after the water flow was stopped.
The liquid flows were continued until they reached a steady state of flow. The discharge and head differences were measured every two hours to determine the permeability.

In test 1, three specimens, dry density 92, 103, and 117 lb/ft³, were made of DGAB with a 12-inch depth. The physical properties of each specimen are presented in Table 4.1. Three specimens were subjected to tap water in order to determine baseline permeabilities while two other specimens, dry density 92 and 117 lb/ft³, were subjected to flows of Cl⁻, SS[1], and SS[2], respectively.

As expected, the lower permeabilities occurred in the specimens with higher densities. The baseline permeabilities were 0.0143, 0.0092, and 0.0039 cm/sec. for dry density 92, 103, and 117 lb/ft³, respectively. The decrease of permeability of the DGAB with Cl⁻ was negligible. The permeability with SS[1] and SS[2] tended to be lower. The permeabilities decreased from baseline permeabilities by 12 to 29 % and 26 to 52% for SS[1] and SS[2], respectively.

In test 2, two specimens of PCTB were made with different cement-aggregate ratios (c/g) 1 : 10 and 1 : 12. The procedure for mixing, placing, and compacting of these specimens was the same as for conventional concrete. The specimens were cured for 24 hours before testing.
The permeabilities of PCTB were higher than DGAB in test 1. The baseline permeabilities were 0.8467 and 0.9173 cm/sec. for c/g 1:10 and 1:12, respectively. Compared to baseline permeabilities, the permeability of PCTB subjected to Cl, SS[1], and SS[2] did not change significantly -- approximately 2 to 6%.

In test 3, two specimens were made of DGAB as in test 1, but the depths were different -- one 8 inches and one 12 inches. The properties of the specimens are presented in Table 4.3. Only water flow was passed through the specimens. The permeabilities were 0.0028 and 0.0030 cm/sec. for 8-inch and 12-inch depth specimens, respectively.

In tests 4 and 5, two specimens were made with the composite materials of PCTB and DGAB. Two different depths of PCTB -- one 4 inches and one 6 inches -- were placed over 6 inches of DGAB. The density of PCTB was the same in all specimens while the density of DGAB in test 4 was close to that of test 3 and the density of DGAB in test 5 was close to that of test 1.

The upper and lower parts and overall permeabilities of specimens were determined. The permeability of the lower part was nearly equal to that of DGAB alone, and the permeability of the upper part resembled that of PCTB alone. In addition, the PCTB/DGAB showed increases in permeability ranging from 2 to 4 times higher than the
DGAB permeability itself. The overall permeabilities were influenced predominantly by the lower part of the specimens (DGAB).

The following conclusions can be drawn from the data results:

(1) The permeability of DGAB was relatively low, ranging from 0.0028 to 0.0143 cm/sec. depending on the density of specimen and the type of fluid. The permeability of DGAB decreased with flows containing suspended solids. In addition, the decrease of permeability was higher for the specimens that had higher density.

(2) The permeability of PCTB was high because fine-grained soils were not included, resulting in larger void spaces within particles. The flows containing sodium chloride did not impact the permeability while flows containing suspended solids tended to slightly lower the permeability.

(3) The data results in test 2 could not indicate a significant effect of cement-aggregate ratios (1 : 10 and 1 : 12) on permeability because the specimens were prepared manually in small portions. In addition, mixing and placing procedures have more influence on permeability. Therefore, the effect of cement-aggregate ratio on permeability requires further study.
(4) The permeability of PCTB/DGAB was higher than DGAB but lower than PCTB itself. The PCTB/DGAB showed increases in permeability ranging from 2 to 4 times higher than the DGAB permeability itself. The overall permeabilities were influenced predominantly by the lower part of the specimens (DGAB).

(5) There have been a number of charts and nomographs developed for estimating permeability of granular base materials. Two of the most recent are a chart by Cedergren (Figure 2.9) and a nomograph by Moulton (Figure 2.8).

5.2 Recommendations for Further Research

To obtain reliable laboratory test results that will reflect actual field conditions, the permeability test specimens of base course materials should be prepared and compacted to simulate field conditions as closely as possible. Two important conditions that should be considered are the hydraulic gradient and density of materials.

For the hydraulic gradient, laminar flow cannot be anticipated in permeability tests on many base course materials; thus, expected field conditions should be approximated in the laboratory test. Where field conditions are not known, a series of tests should be performed to stay within the range of estimated field conditions. Where a series of tests is to be performed, testing should begin at the lowest hydraulic gradient to minimize effects of particle rearrangement on test results.
For the density of materials, it is difficult to compact the specimens to identical densities as in the field. Therefore, again, a series of tests should be performed on the materials that are compacted to the anticipated moisture and density conditions. Furthermore, the particle size distribution test should be performed after the permeability test to check whether the particle size distribution of specimens is changed from compaction.

In order to study more about the effect of flows containing constituents like sodium chloride, suspended solids, and so on, the permeability tests should be performed with the actual runoff taken from the field. In addition, time may be the factor that influences permeability. Thus, it is a good idea to test the specimens over a longer period of time.

Finally, a larger permeameter should be used so that larger sized materials can be tested. Moreover, the permeability test should be performed with other materials commonly used in pavement base courses such as asphalt-treated materials.
REFERENCES


## APPENDIX A

Viscosity Corrections for $\eta_T/\eta_{20}$ (Liu and Evett, 1990)

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