# FREE DRAINING BASE MATERIALS PROPERTIES

**FINAL REPORT**

**HPR Project No. 5283**

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16. Abstract

The importance of providing a positive drainage system and removing free water from pavement structures has long been recognized. Inadequate drainage of the pavement structures has been identified as one of the primary causes of pavement distress.

In the last few years, Oregon has started designing and constructing permeable bases in both flexible and rigid pavements. Two types of permeable bases have been used: one is asphalt treated permeable material (ATPM) base and the other is open-graded aggregate base. The desirable characteristics (permeability and resilient modulus) of both materials have not been determined. In addition, construction with the existing open-graded aggregate gradation revealed that the material was less stable and would ravel easily under construction traffic. Because of this ravelling, compaction was poor, the grade was difficult to control, and the open graded aggregate materials did not provide a suitable surface for paving.

This project established the desirable materials properties (permeability and resilient modulus) for the two types of free-draining base materials and establishes a more stable gradation for the open-graded aggregate base. Appropriate layer and drainage coefficients for use in the AASHTO design of permeable base sections are also determined. For comparison, a dense-graded aggregate material is also investigated.

This project consisted primarily of a laboratory investigation. Pavement cores of the asphalt treated permeable base and samples of aggregate materials were tested in the laboratory for permeability and resilient modulus. The permeability was determined using both constant and falling head test procedures.

The laboratory study indicated that the current Oregon ATPM has a sufficient drainage capability and the resilient modulus of this material is typical of other states' findings. A modified open-graded aggregate gradation is proposed. The proposed aggregate gradation has a higher permeability and a higher resilient modulus than the existing gradation.

Recommendations for implementation include selection of layer and drainage coefficients for pavement structural design and use of the proposed open-graded aggregate gradation in pavement construction.

17. Key Words

Drainage, Asphalt Treated Permeable Bases, Open-graded Aggregate, Resilient Modulus, Layer Coefficient

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## DISCLAIMER

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# 1.0 INTRODUCTION

## 1.1 Background

The importance of providing a positive drainage system and removing free water from pavement structures has long been recognized. Inadequate drainage of the pavement structures has been identified as one of the primary causes of pavement distress (Cedergren, 1988; Cook and Dykins, 1991; Mathis, 1990). For many years, researchers have theorized that improving pavement drainage might combat many pavement problems associated with water-related distresses and consequently extending the pavement service life (Flynn, 1991).

In the last few years, Oregon has started designing and constructing permeable bases in both flexible and rigid pavements. Two types of permeable bases have been used: one is asphalt treated permeable base and the other is open graded aggregate base. The desirable characteristics (permeability and resilient modulus) of both materials have not been determined. During pavement structural design using the AASHTO Guide (AASHTO, 1986), layer and drainage coefficients had to be assumed to establish pavement thickness designs. In addition, construction with the existing open graded aggregate gradation revealed that the material was less stable and would ravel easily under construction traffic. Because of this ravelling, compaction was poor, the grade was difficult to control, and the open graded aggregate materials did not provide a suitable surface for paving.

This project was initiated to obtain a better understanding of the characteristics of these permeable base materials, to develop appropriate layer and drainage coefficients for use in pavement thickness design, and to improve stability and constructability of the existing open graded aggregate material.

## 1.2 Objectives

The objectives of this project are to: 1) determine materials properties for two types of free-draining base materials and 2) establish a more stable gradation for open graded aggregate base. Appropriate layer and drainage coefficients for use in the design of permeable base sections are also to be determined. The base types to be investigated are an open-graded aggregate and asphalt-treated permeable materials (ATPM). For comparison, a dense-graded aggregate material is also investigated.

## 1.3 Scope

The scope of this project includes the following:

1. Obtain pavement cores of the ATPM and several gradations of both open-

and dense-graded aggregate base materials for testing permeability and resilient modulus in the laboratory. For aggregate materials, the effect of fractured faces will also be examined.

2. Based on the laboratory test results, recommend appropriate layer and drainage coefficients for use in pavement thickness design and modify the existing open graded aggregate gradation for improving its stability and constructability.

Chapter Two of this report provides the literature review on subjects relevant to this research effort. Chapter Three describes the laboratory study on two types of base materials that have been identified for this research. Chapter Four discusses the use of the research results. Chapter Five presents the conclusions and recommendations for this study. Appendices contain information on a questionnaire survey results, laboratory permeability test procedures, laboratory permeability test results for untreated aggregate materials, and laboratory resilient modulus test results for untreated aggregate materials.

# 2.0 LITERATURE REVIEW

A literature review has been performed on subjects relevant to the research objectives. This chapter describes the outcome of the literature review. In addition to the literature review, a questionnaire survey regarding the use of open grade aggregate in Oregon, as a base layer, is also briefly described.

## 2.1 Background

The pavement structure is the most costly element of the highway system, and its premature failure is of major concern. Among the reasons cited for failure, inadequate drainage has been identified as a primary cause (TAI, 1984; Mathis, 1990). To minimize water-related pavement distress, positive drainage should be provided to remove free water from the pavement. There are, in general, two types of drainage that are commonly seen in pavement construction: surface drainage and subsurface drainage. The surface drainage includes the disposal of all water on the surface of the pavement and the right of way (TAI, 1984).

The subsurface drainage is provided to drain water that has entered the pavement structure, therefore, a positive drainage layer in a pavement structure is critical for subsurface drainage. Inadequate subsurface drainage is a major cause of unsatisfactory pavement performance and premature pavement failures. Excessive subsurface water in a pavement and the underlying subgrade can cause a wide variety of problems as manifested in premature rutting, cracking, faulting, and frost heave, increasing roughness and accelerating the decrease in the level of serviceability.

Sources of water that enter the pavement structure are depicted in Figure 2.1 and may be described in three forms (TAI, 1984; Cook and Dykins, 1991).

1. Free water entering the structure through cracks or joints.
2. Capillary water which moves upward through the underlying soil strata as a result of capillary action.
3. Water vapor moving upward through the subgrade soil strata as a result of thermal gradients.

If a good subsurface drainage system is provided, this water is intercepted and drained away from the pavement, thus reducing the pavement structure failures due to the water. This subsurface drainage system can be designed by providing a drainage layer along with transverse and longitudinal drainage pipes to remove the water from the pavement structure.

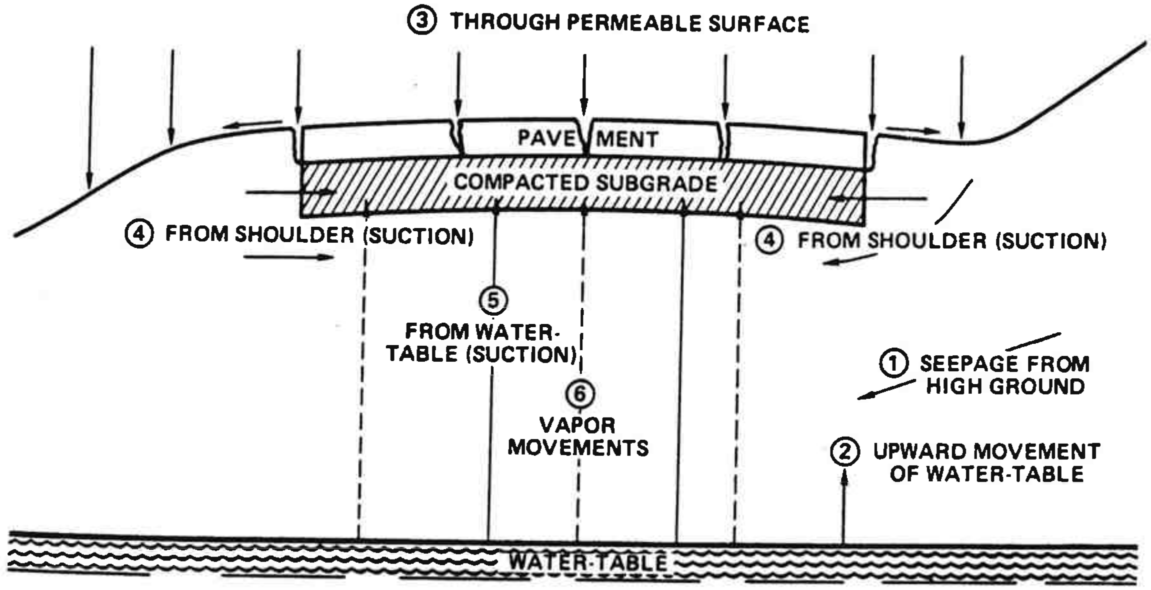



Figure 2.1: Ways in which Moisture can Enter Road Subgrades (TAI, 1984)

## 2.2 Types of Permeable Base

Permeable bases can generally be grouped into two categories: those that use a treated permeable base and those that use an untreated permeable base. With the treated permeable base, aggregate material is typically mixed with 2-4% asphalt or a certain percentage of portland cement. The asphalt treatment is more commonly used. In the untreated permeable base, open graded aggregate material is used directly in pavement base construction.

## 2.3 Treated Permeable Base

The treated permeable base, especially the asphalt treated permeable material (ATPM) base, has been widely used in the United States. In 1990, the National Asphalt Pavement Association (NAPA) distributed a questionnaire to the 50 state transportation departments. Forsyth (1991) summarized the questionnaire results. Figure 2.2 shows the number of states that responded to the questionnaire and reported construction of pavements with an ATPM layer. Of the 30 states indicating use or planned use of ATPM, as shown in Figure 2.3, 25 states place the ATPM directly below the surfacing for interception of infiltrated surface runoff and 11 states place the ATPM above the subgrade.

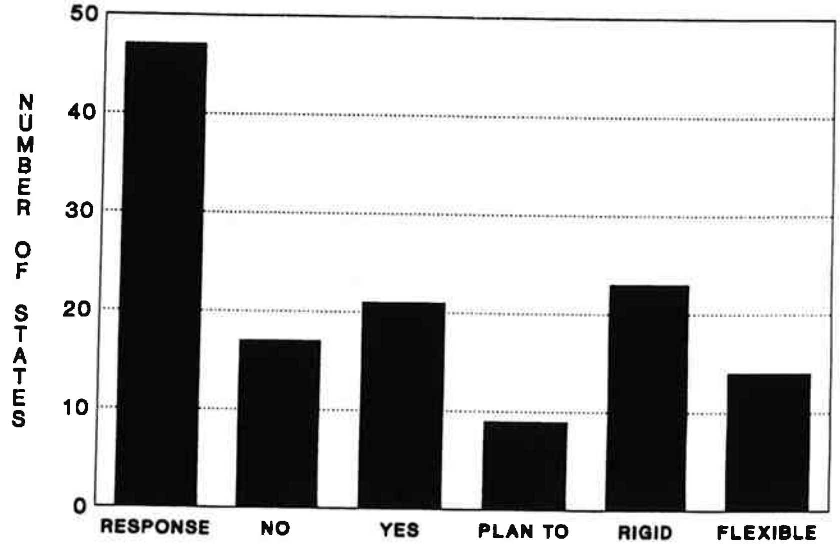



Figure 2.2: State ATPM Usage (Forsyth, 1991)

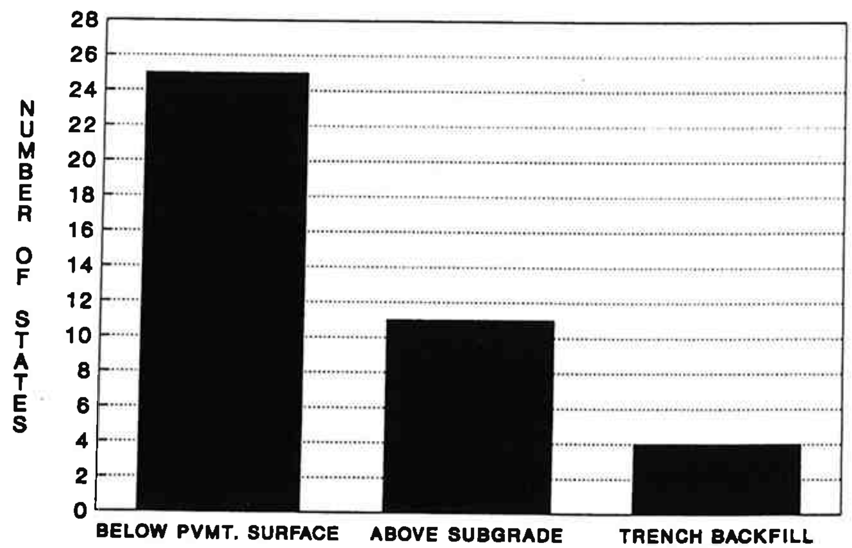



Figure 2.3: Location of ATPM (Forsyth, 1991)

### 2.3.1 ATPM Layer Thickness

The thickness required for drainage can be calculated using Darcy's Law (TAI, 1984; Wells, 1986). Mathis (1989) indicates four inches of ATPM would provide sufficient capacity, be easily constructed, and provide for construction variability. California specifies three inches of ATPM for its asphalt cement treated permeable base. Forsyth's report (1991) indicated the ATPM thickness ranged from two to six inches, with four inches being the most common. Oregon has used three to four inches of ATPM base layer on several designs (Gower, 1989; Zhou, 1990).

### 2.3.2 Coefficient of Permeability

The coefficient of permeability (k) of the ATPM can be affected by a number of factors such as aggregate gradation and asphalt content used in the mixture. Lovering and Cedergren (1962) pointed out that permeability of the ATPM would not be reduced significantly with the addition of two to three percent asphalt cement. The effect of gradations on the permeability appears to be substantial as shown in Table 2.1. Gradations used by some states are summarized by Forsyth (1991) and presented in Table 2.2 as well. Gradations were found to be relatively uniform, ranging between one inch maximum and zero to four percent passing the #200 sieve.

Table 2.1: Treated Permeable Gradations (Mathis, 1989)

| Percent Passing | | |
|---|---|---|
| Sieve Size | California | North Carolina/West Virginia |
| 1 1/2-inch | - | 100 |
| 1-inch | 100 | 95-100 |
| 3/4-inch | 90-100 | - |
| 1/2-inch | 35-65 | 25-60 |
| 3/8-inch | 20-45 | - |
| No. 4 | 0-10 | 0-10 |
| No. 8 | 0-5 | 0-5 |
| No. 200 | 0-2 | 0-2 |
| Estimated Coefficient of Permeability (feet/day) | 15,000 | >3,000/>5,000 |

## Table 2.2: ATPM Gradations used by States (Forsyth, 1991)

Percent Passing Sieve Size

| State | 1–1/2 in | 1 in. | 3/4 in. | 3/8 in. | No. #4 | No. #8 | No. #16 | No. #200 |
|---|---|---|---|---|---|---|---|---|
| Arizona | 100 | 100 | 90–100 | 20–45 | 0–10 | 0–5 | — | 0–2 |
| California | 100 | 100 | 90–100 | 20–45 | 0–10 | | | 0–2 |
| Florida | | 100 | 90–100 | 20–45 | 0–10 | 0–5 | | 0–2 |
| Georgia | 100 | 100 | 95–100 | 20–65 | | 0–10 | | 0–3 |
| Illinois | 100 | 90–100 | 84–100 | 40–60 | 0–12 | | 0–6 | |
| Indiana (1) | 100 | 70–98 | 50–85 | 15–50 | 10–20 | 3–20 | 2–15 | 0–4 |
| Kansas | 100 | 100 | 90–100 | 20–45 | 0–10 | 0–5 | | 0–2 |
| Kentucky | 100 | | 85–100 | | 0–20 | 0–10 | | 0–2 |
| Louisiana | 100 | 100 | 90–100 | 50–80 | 10–35 | 0–20 | | 0–5 |
| Maryland | 100 | 100 | 95–100 | 60–90 | 15–25 | 0–10 | 0–5 | (2) |
| Michigan | 100 | | | | 0–8 | | | (3) |
| Minnesota | 100 | 25–100 | 85–98 | 30–55 | 25–50 | | | 0–3 |
| Mississippi | 100 | 80–100 | | | 0–10 | 0–5 | | |
| Missouri | | 100 | | | | 0–15(4) | | 0–4 |
| Nevada | | 100 | 90–100 | 20–45 | 0–10 | | | 0–2 |
| New Jersey | | 100 | 95–100 | 60–90 | 15–25 | 2–10 | 2–5 | (5) |
| New Mexico | | 100 | 50–100 | 15–85 | 0–5 | | | 0–1 |
| North Carolina | 100 | 95–100 | 60–80 | 25–39 | 20–30 | 16–24 | | 0–3 |
| Oregon | | 90–100 | 85–95 | 35–68 | 0–20 | 0–5 | | 0–2 |
| Ohio | | 100 | 95–100(6) | | 25–60 | 0–10 | | |
| Oklahoma | | 100 | 95–100 | | 25–60(6) | 0–10 | | 0–1.5 |
| Pennsylvania | | 100 | 90–100 | 10–100 | 20–55 | 0–5 | 0–2 | |
| South Carolina | 100 | 95–100 | | 25–60(6) | 0–10 | | | |
| Tennessee | 90–100 | | 50–85 | | 3–15 | | | 0–6 |
| Texas | | 100 | 95–100 | 20–45 | 0–15 | 0–5 | | 2–4 |
| Virginia | | | 100 | 52–68 | 20 max. | | 5 min. | |
| Washington | 100(7) | 85–100 | | 45–70(8) | 0–15(9) | | | |
| West Virginia | 100 | 95–100 | | 25–60(6) | 0–10 | 0–5 | | |
| Wisconsin | 100 | 95–100 | 80–95 | 50–25 | 35–60 | 20–45 | | 3–10 |
| Wyoming | 100 | 90–100 | 50–20(6) | | 20–50 | 10–30 | | 0–4 |

Notes:

(1) HMA Base 5C; (2) two percent mineral filler; (3) three percent max. loss by washing; (4) No. 10; (5) two percent mineral filler added; (6) 1/2 in.; (7) 1–1/4 in.; (8) 5/8 in.

The coefficients of permeability for these gradations were not known. Many states have not performed permeability tests as indicated in Table 2.3. Percent asphalt cement and asphalt grade for the ATPM are also listed in the table.

### 2.3.3 Resilient Modulus - ATPM

Hicks, et al (1979) reported ATPM resilient modulus averaging 155,000 to 270,000 psi at 75°F depending on confining pressure. Monismith, et al (1982) reported an average resilient modulus of 159,000 psi on samples consisting of partially crushed gravel. Caltrans' experience (Forsyth, 1991) indicated that the ATPM resilient modulus ranged from 113,000 to 201,000 psi, averaging 141,800 psi.

### 2.3.4 Layer Coefficients - ATPM

Layer coefficients are used in the AASHTO Guide for Design of Pavement Structures (AASHTO, 1986). The value of layer coefficients used in design varied among the states that used ATPM. Forsyth (1991), as shown in Figure 2.4, reported that of the 30 states that have or plan to use ATPM, 11 give it no structural value while 10 assign a layer coefficient corresponding to aggregate base (AASHTO layer coefficient of 0.10 - 0.14). Six states assign layer coefficients between 0.20 - 0.30. Caltrans conducted a research project in 1981 with the objective of establishing a gravel factor for ATPM based upon deflection attenuation resulting from the placement of a three inch ATPM layer. The results suggested a gravel factor corresponding to an AASHTO layer coefficient of approximately 0.20.

Moore (1989), based on resilient modulus described in Section 2.3.3 of this report, recommended that Caltrans use a gravel factor equivalent to that of dense-graded hot mix asphalt for ATPM thicknesses up to three inches. Assuming a resilient modulus of 140,000 psi for ATPM, the procedure suggested by Rada et al (1988) results in an AASHTO layer equivalence of 0.23 (Forsyth, 1991).

Table 2.3: Asphalt Cement and Permeability Test (Forsyth, 1991)

| State | % Asphalt Cement | Asphalt Cement Grade | Permeability Test |
|---|---|---|---|
| Arizona | 2.5–3 | AC–20–40 | no |
| California | 2.5 | AR8000 | no |
| Florida | 2.5 | AC–30 | no |
| Georgia | 3–3.5 | AC–30 | Constant Head |
| Illinois | 2–3 | AC–20 | no |
| Indiana | 3–4.5 | AC–20 | AASHTO T–215 |
| Kansas | 2 | AC–10 | Constant Head |
| Kentucky | 1.5–2.5 | AC–20 | no |
| Louisiana | 2.5–4 | AC–30 | no |
| Maryland | 2.5–3.5 | AC–20 | AASHTO T–167 |
| Michigan | 2–3 | AC–10<br>85–100Pen. | no |
| Minnesota | 1.5–3 | AC–20<br>AC–60/70 | yes |
| Mississippi | 2–3 | AC–30 | no |
| Missouri | 3 | 60–70Pen | no |
| Nevada | 2.5 | AC–20 | no |
| New Jersey | 2.5–3.5 | AC–20 | N.J. Falling Head |
| New Mexico | 2 | AC–10,20<br>HFE 100,300 | no |
| North Carolina | 3 | AC–20 | Falling Head |
| Oregon | 2.5–3.5 | AC–30 | no |
| Ohio | 2 | AC–20 | no |
| Oklahoma | 2.5 | AC–20 | no |
| Pennsylvania | 1.5–3.5 | AC–20 | no |
| South Carolina | 1.5–3 | AC–20,30 | no |
| Tennessee | 2.5–7 | AC–20,30 | no |
| Texas | 2–4 | AC–10,20 | no |
| Virginia | 2.5–3.5 | AC–30 | Constant Head |
| Washington | 1.5–2.5 | AR–4000w | no |
| West Virginia | 1.5–2.5 | AC–10,20 | no |
| Wisconsin | 1.5–2.5 | 60/70–<br>200/300 Pen. | Falling Head |
| Wyoming | — | AC–20 | yes |

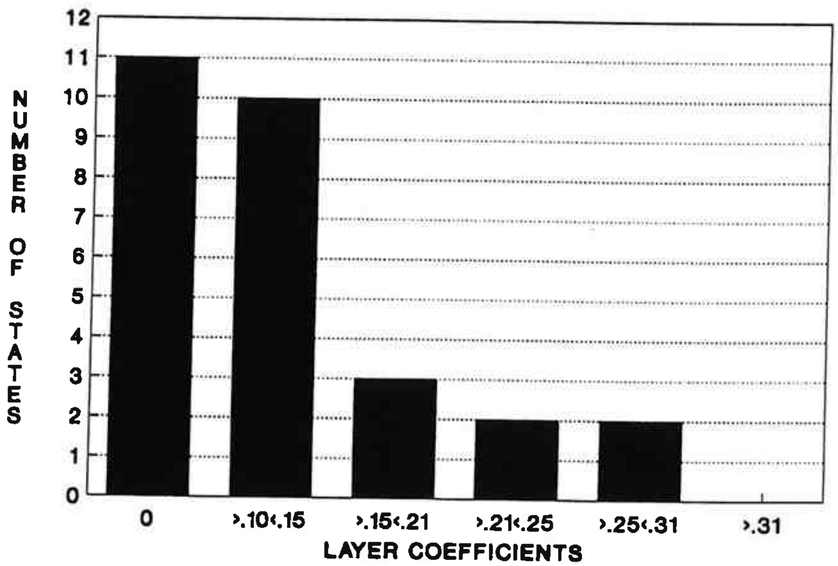



Figure 2.4: ATPM Layer Coefficients (AASHTO) Used by States (Forsyth, 1991)

## 2.4 Untreated Permeable Base

Untreated permeable bases have also been used in a number of states. In Oregon, this type of base is often referred to as free draining aggregate base (FDAB).

### 2.4.1 FDAB Layer Thickness

The FDAB layer thickness required for drainage can be determined using Darcy's Law (TAI, 1984; Well, 1986; Cedergren, 1972). There is not much information indicating typical thickness used by other states. Oregon has been using 6 - 15 inches of FDAB in pavement construction. A minimum six-inch FDAB appears to be necessary to have a proper compaction and a minimum drainage requirement. Layer thickness greater than 12 inches may be difficult to compact. In 1991, OSHD conducted a survey concerning the use of the FDAB with the current gradation. One question was specifically related to the compaction of the FDAB. The respondents to the question indicated that good compaction was difficult to achieve and the FDAB material was unstable. Therefore, modifications to the current FDAB gradation should be made to produce a more workable and stable base material. A summary and detailed description of the questionnaire survey are presented later in this charter and in Appendix A, respectively.

### 2.4.2 Coefficient of Permeability

Gradation is the primary factor affecting the permeability of the FDAB. Table 2.4 shows the FDAB gradation that Oregon is currently using. The coefficient of permeability for this gradation is not known and is to be determined in this research effort. Gradations used by other states are summarized by Mathis (1989) and presented in Table 2.5. The estimated/measured coefficient of permeability for each gradation is also shown in the table. Mathis (1989) also indicated that the untreated permeable base materials generally had a lower coefficient of permeability than the treated permeable base materials. The permeability for the untreated base materials is in the range of 200 - 3,000 feet per day.

Table 2.4: Current Aggregate Gradation for Oregon's FDAB

| Sieve Passing | Percent by Weight |
| --- | --- |
| 1-1/2" | 100 |
| 1" | 95-100 |
| 3/4" | 55-80 |
| 1/4" | 25-50 |
| No. 10 | 0-15 |
| No. 100 | 0-3 (Dry Sieve) |

Table 2.5: Untreated Permeable Base Gradations
Used by Selected States (Mathis, 1989)

| | Percent Passing | | | | | | |
|---|---|---|---|---|---|---|---|
| Sieve Size | IA | KY | MI | MN | NJ | PA | WI |
| 2" | - | - | - | - | - | 100 | - |
| 1-1/2" | - | 100 | 100 | - | 100 | - | - |
| 1" | 100 | 95-100 | - | 100 | 95-100 | - | 100 |
| 3/4" | - | - | - | 65-100 | - | 52-100 | 90-100 |
| 1/2" | - | 25-60 | 0-90 | - | 60-80 | - | - |
| 3/8" | - | - | - | 35-70 | - | 35-65 | 20-55 |
| #4 | - | - | 0-8 | 20-45 | 40-55 | 8-40 | 0-10 |
| #8 | 10-35 | 0-5 | - | - | 5-25 | - | 0-5 |
| #10 | - | - | - | 8-25 | - | - | - |
| #16 | - | 0-5 | - | - | 0-8 | 0-12 | - |
| #30 | - | - | - | - | - | 0-8 | - |
| #40 | - | - | - | 2-10 | - | - | - |
| #50 | 0-15 | - | - | - | 0-5 | - | - |
| #200 | 0-6 | 0-2 | - | 0-3 | - | 0-5 | - |
| Permeability (ft/day) | 500[a] | 20000[a] | 1000[a] | 200[a] | 2000[b] | 1000[b] | 18000[a] |

[a] Estimated.
[b] Measured using falling head test procedure.

### 2.4.3 Resilient Modulus

Resilient modulus for Oregon's FDAB materials has not yet been determined. However, a slightly lower modulus than typical dense graded aggregate is expected because of large air voids, consequently a lower density in the FDAB materials.

Many studies show that the resilient modulus of untreated aggregate materials is a function of material types and stress state occurring in the material. Table 2.6 provides some laboratory test results conducted by other researchers.

Table 2.6: Resilient Characteristics for Untreated Granular Materials

| Investigator(s) | Material(s) | $k_1$ | $k_2$ |
|---|---|---|---|
| Hicks, 1970 | Partially crushed gravel; crushed rock | 1,600 - 5,000 | 0.57 - 0.73 |
| Hicks, et al, 1970 | Untreated base - San Diego Test Road | 2,100 - 5,400 | 0.61 |
| Allen, 1973 | Gravel, crushed stone | 1,800 - 8,000 | 0.32 - 0.70 |
| Kalcheff & Hicks, 1973 | Crushed Stone | 4,000 - 9,000 | 0.46 - 0.64 |
| Boyce, Brown, & Pell, 1976 | Well graded crushed | 8,000 | 0.67 |
| Monismith, et al, 1972 | In service base and subbase materials | 2,900 - 7,750 | 0.46 - 0.65 |
| Albright, 1986 | Crushed aggregate (Saturated) | 1,300 - 2,000 | 0.69 - 0.78 |
| | Crushed aggregate (Optimum water content) | 2,000 - 2,600 | 0.70 - 0.73 |

$MR = k_1\theta^{k_2}$, where MR and $\theta$ are in psi. $\theta = \sigma_1 + 2\sigma_3$ in a triaxial test.

### 2.4.4 Layer Coefficients

Mathis (1989) reported that test results from New Jersey and Pennsylvania indicated the untreated permeable material had similar bearing capacities to dense-graded aggregate base. This implies a same layer coefficient can be assigned for both permeable and dense-graded aggregate base in pavement design.

### 2.4.5 Questionnaire Survey

In 1991, OSHD conducted a survey concerning the use of the FDAB with the current aggregate gradation shown in Table 2.4. The purpose of the survey was to obtain feedback on the use the FDAB, to investigate possible changes to the material gradation, and consequently to improve the workability of the material while still maintaining the permeability. The questionnaire was sent to three project managers' office and all responded.

The questionnaire consisted of nine questions and could be categorized into six groups as follows:

1) FDAB layer and life thicknesses
2) Gradations
3) Compaction
4) Placement and segregation
5) Price of FDAB material
6) Suggestions for improvement

The following summarizes the questionnaire results. Details of the survey results are provided in Appendix A.

FDAB layer and lift thickness

A total of five projects were constructed with the FDAB in the last two years. The FDAB layer thickness ranged from seven to 15 inches. The lift thickness varied from 3.5 to seven inches.

Gradation

Two gradations, which were slightly different from the one shown in Table 2.4, were used in the construction of the five projects. The intention of making these slight changes was to make the product easier to produce by increasing the band limit for material passing 1" and 3/4" sieves and to provide a more workable material. On one project, this product was still difficult to produce despite the changes in gradation.

Compaction

Responses from four projects indicated that the surface of the FDAB was unstable and would ravel easily under construction traffic. Because of this ravelling, compaction was poor, the grade was difficult to control, and the FDAB materials did not provide a suitable surface for paving. Compaction level was not specified and was only visually inspected.

Placement and segregation

The project managers from four construction projects reported that the segregation of the FDAB material appeared to be unavoidable. One project manager believes that plant mix aggregate would work well because the moisture added in plant mixing tend to minimizing segregation during placement by holding the particles together. The project manager also suggests that segregation of the FDAB material can be minimized by limiting the material to only the amount required for placement in a uniform thickness.

Price of FDAB

The price of the FDAB material varied from $7.00/ton to $11.50/ton. It is expected that the price would vary depending upon the quantity to be used in construction. In general, the FDAB material price appears to be comparable to dense-graded aggregate base material.

Suggestions for improvement

Suggestions for improving the workability and constructability of the FDAB materials were provided. The following presents a summary of these suggestions:

1) Specify plant mix where using FDAB. Moisture mixed in at pug tends to help hold material together and prevent segregation.
2) Change the percentage passing gradation on the #100 sieve from 0-3 (dry) to 0-5 (dry). The 0-3 (dry) is difficult to obtain during crushing.
3) Specify track mounted paver instead of rubber tire paver to reduce damage caused to base material.
4) Spray a small amount of water on dried material before compaction and then compact the material. This is to be done prior to paving and may help prevent ravelling.
5) Use seal coat on top of the FDAB material. This may help stabilize the FDAB material.
6) Run material through a pug with CSS-1 diluted emulsion approximately 3:1 to assist in keeping fines properly mixed to prevent segregation.

# 3.0 LABORATORY STUDY

To accomplish the research objectives, a laboratory study program was developed to test free draining base materials. This chapter describes the laboratory study for two types of base materials: asphalt treated and untreated aggregates.

## 3.1 Design of Laboratory Test Program

The laboratory study approach is shown in Figure 3.1. The study included permeability and resilient modulus tests on both asphalt treated and untreated aggregate materials. For permeability tests, both constant and falling head testing procedures were used. The effect of untreated aggregate fractured faces on permeability and resilient modulus was also investigated.

### 3.1.1 Permeability Tests

Two test procedures were used in this study: constant head and falling head permeability tests. The purpose of the test was to determine the coefficient of permeability (k) for the materials to be used. The apparatus for the permeability test were developed by the Oregon State Highway Pavements Unit. The equipment for constant head and falling head permeability tests are shown in Figures 3.2 and 3.3, respectively. Detailed laboratory test procedures are presented in Appendix B.

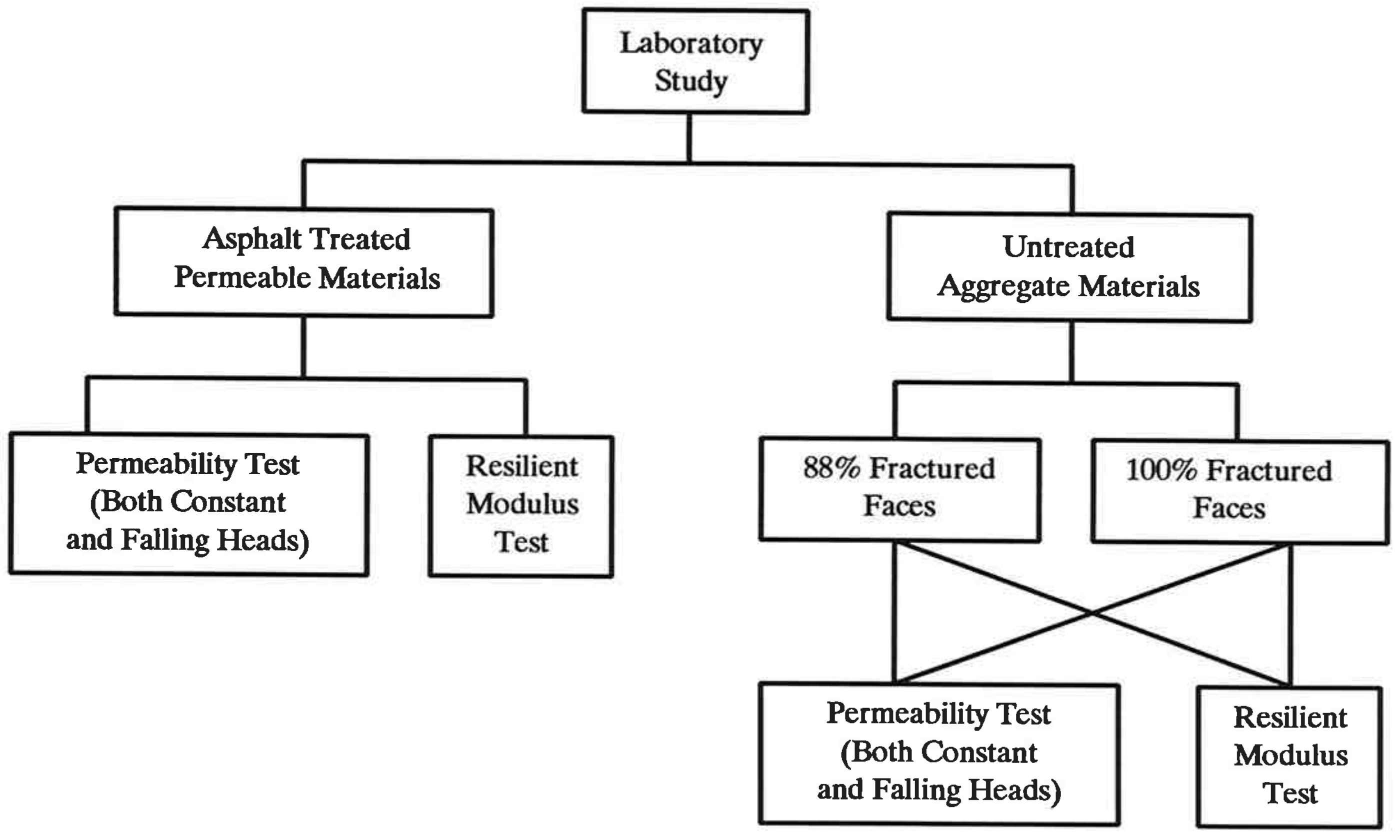



Figure 3.1: Laboratory Study Program

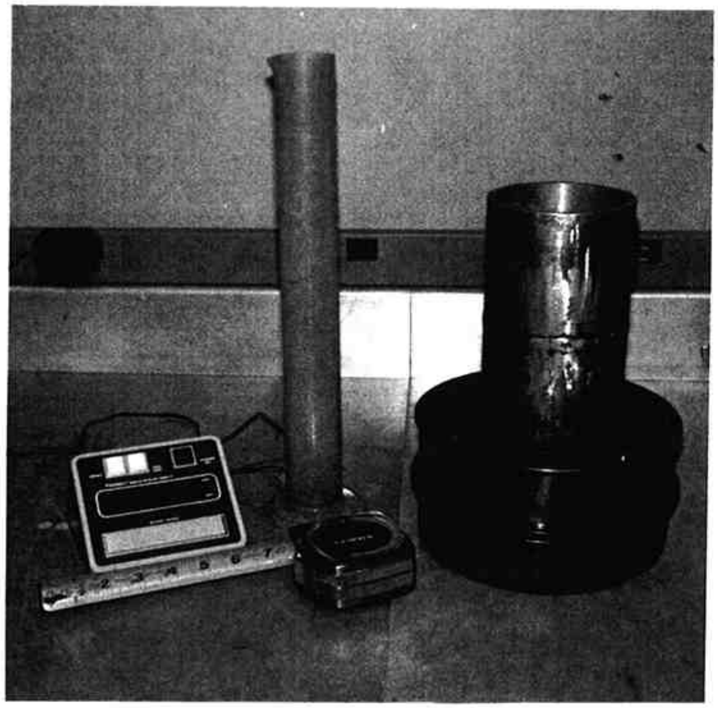


Figure 3.2: Apparatus for Constant Head Permeability Test

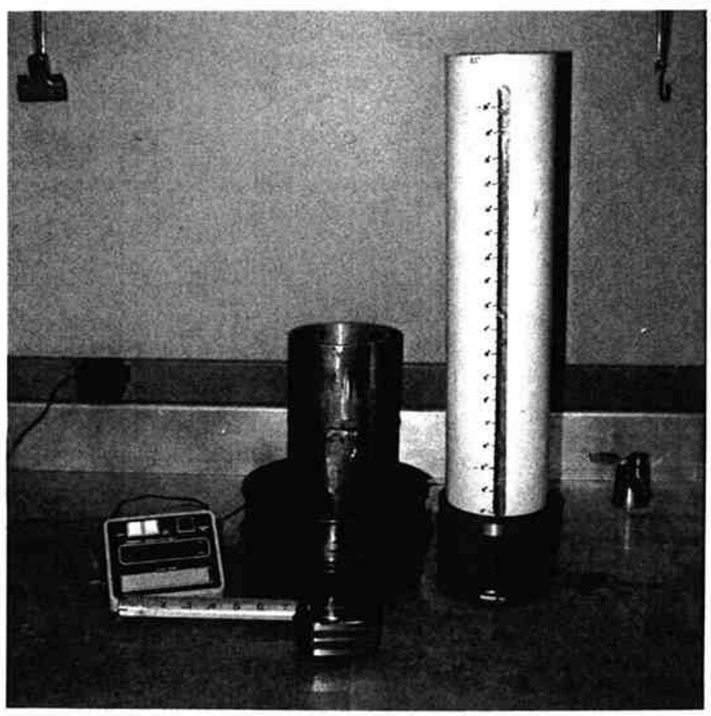


Figure 3.3: Apparatus for Falling Head Permeability Test

Constant Head Permeability Test: This test procedure determines the permeability of a material by maintaining a constant flow head ($h$) on the sample surface and measuring the time needed for collecting a known amount of water. Figure 3.4 shows the relationship of various parameters. The permeability can then be calculated using the equation:

$$k_c = \frac{QL}{Ah} * 7200 \qquad (3\text{-}1)$$

Where:

| | | |
|---|---|---|
| $k_c$ | = | coefficient of permeability (ft/day), from constant head test, |
| $Q$ | = | flow quantity ($in^3$/sec), |
| $L$ | = | flow path length or sample height (in), |
| $A$ | = | flow path area or sample area ($in^2$), and |
| $h$ | = | constant water head (in). |

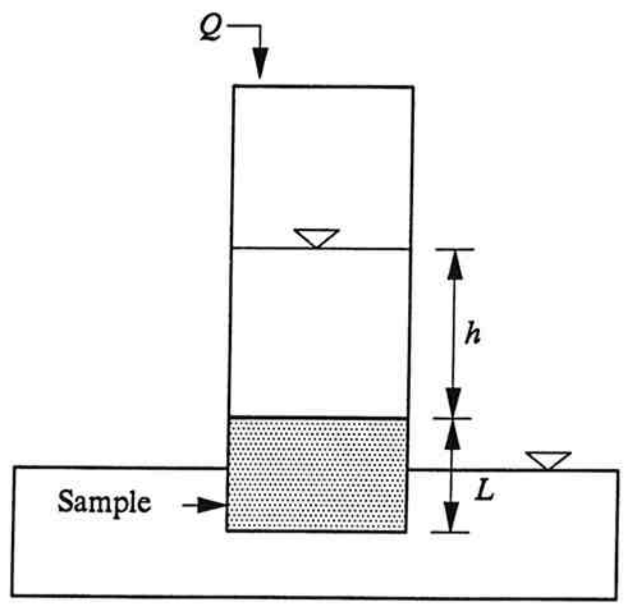



Figure 3.4: Diagram of Constant Head Permeability Test

Falling Head Permeability Test: This test determines the permeability of a material by measuring the time required for water head dropping from a high level ($h_1$) to a low level ($h_2$). Figure 3.5 shows the relationship of various parameters. The permeability is then calculated using the equation:

$$k_f = \frac{L}{T} \ln \frac{h_1}{h_2} * 7200 \qquad (3\text{-}2)$$

Where:

| | | |
|---|---|---|
| $k_f$ | = | coefficient of permeability (ft/day), from falling head test, |
| $L$ | = | flow path length or sample height (in), |
| $T$ | = | time required for water head dropping from $h_1$ to h2 (sec), and |
| $h_1$, $h_2$ | = | water levels (in). |

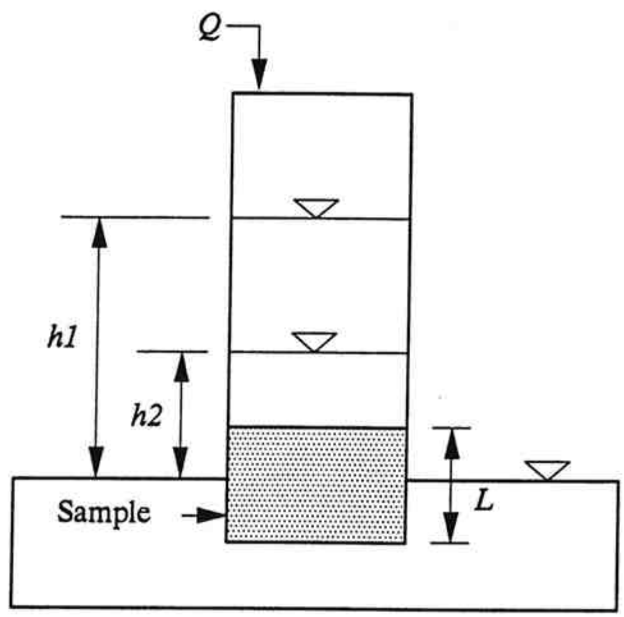



Figure 3.5: Diagram of Falling Head Permeability Test

### 3.1.2 Resilient Modulus Tests

The resilient modulus is a measure of the stiffness and a dynamic test response defined as the ratio of the repeated axial deviator stress to the recoverable axial strain. As the trend moves toward mechanistic design of flexible pavements through numerical analysis of layered systems for strains, stresses and deflections, the use of resilient modulus to characterize material properties becomes necessary.

For this study resilient modulus tests were performed for the purpose of developing layer coefficients of the asphalt treated permeable base and untreated aggregate base materials and determining a relative stability for the untreated materials.

Treated Base Materials: The resilient modulus test on asphalt treated base materials was conducted in accordance with ASTM D4123 standard procedure (ASTM, 1989). The tests were performed by the OSHD Highway Materials Laboratory.

Untreated Base Materials: The resilient modulus test on untreated aggregate base materials was conducted in accordance basically with AASHTO T-274 standard procedure (AASHTO, 1986). The test samples were conditioned at a confining pressure of 15 psi by applying 200 load repetitions at deviator stress levels of 3, 6, 9, 12, and 15 psi. Testing was performed by applying 200 load repetitions of each bulk stress level in the bulk stress sequence of 9, 12, 16, 20, 24, 36, 60 and 6 psi. The tests were performed by Pavement Services, Inc., a private consultant in Portland, Oregon.

## 3.2 Treated Permeable Base Materials

Treated base core samples were obtained from two projects, both constructed in 1990. The Fir Grove Lane-Towers Road project (Zhou, 1990) has a 4-inch asphalt treated permeable material and the Rose Lodge-Polk County Line project (Gower, 1989) has a 3-inch ATPM. Core samples obtained from the project sites were cut and trimmed in the laboratory for permeability and resilient modulus testing. The prepared core samples were typically 1.8 to 2.5 inches thick. The diameter of the core samples was 4 inches. One additional 6-inch core was also taken from each project. The 6-inch core was used in extraction tests to determine actual asphalt content and aggregate gradation. For the Fir Grove Lane-Towers Road project, 2.9% of PBA-2 (Performance Based Asphalt) asphalt was used. For the Rose Lodge-Polk County Line project, 2.4% of AC-15 asphalt was used.

### 3.2.1 Permeability Test Results

A permeability test was performed following the procedures described in Section 3.1.2. Table 3.1 presents a summary of the test results. The test results show that for each test procedure (i.e., constant head versus falling head) the permeability varied substantially. For instance, the permeability for the Fir Grove Lane-Towers Road project ranges from 494 ft/day to 3,568 ft/day with the constant head testing procedure and from 1,032 ft/day to 4,130 ft/day with the falling head testing procedure. The relationship between the two testing procedures is illustrated in Figure 3.6.

Table 3.1: Permeability Test Results on ATPM Core

| Project Name | Sample I.D. | Permeability (ft/day) | |
|---|---|---|---|
| | | Constant Head | Falling Head |
| Fir Grove Lane - Towers Road | 1 | 1520 | 1959 |
| | 2 | 1618 | 1926 |
| | 3 | 2640 | 1920 |
| | 4 | 494 | 1032 |
| | 5 | 970 | 1299 |
| | 6 | 719 | 1086 |
| | 7 | 1693 | 2671 |
| | 8 | 1200 | 2517 |
| | 9 | 3568 | 4130 |
| | 10 | 628 | 1513 |
| | Average | 1505 | 2005 |
| | Standard Deviation | 965 | 929 |
| | Range | 494 - 3568 | 1032 - 4130 |
| Rose Lodge - Polk County Line | 1 | Broken | |
| | 2 | 3379 | 2273 |
| | 3 | 2506 | 1849 |
| | 4 | 3147 | 2273 |
| | 5 | 1518 | 1761 |
| | 6 | 1960 | 1678 |
| | 7 | 2360 | 2012 |
| | 8 | 2499 | 2326 |
| | 9 | 2348 | 2153 |
| | 10 | Broken | |
| | Average | 2465 | 2041 |
| | Standard Deviation | 595 | 253 |
| | Range | 1518 - 3379 | 1678 - 2326 |

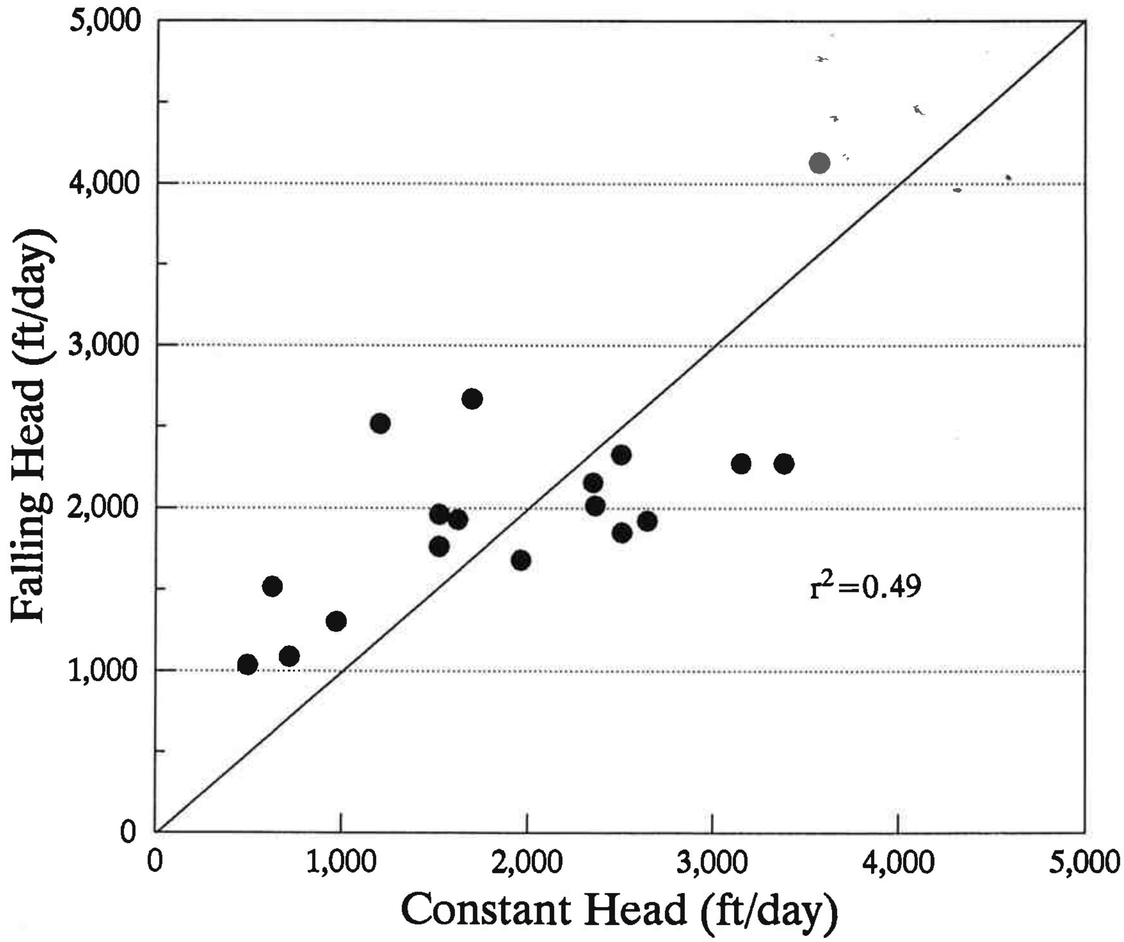



Figure 3.6: Comparison of Constant and Falling Head Test Results

### 3.2.2 Resilient Modulus Test Results

A resilient modulus test was conducted following the procedures described in Section 3.1.3. Table 3.2 shows a summary of the test results. The resilient moduli from both projects are generally similar, with an average of approximately 100 ksi. The resilient modulus tests were performed at room temperature, approximately 77°F.

Bulk specific gravity test results are also presented in Table 3.2. The average bulk specific gravity of the Fir Grove Lane - Towers Road project is about 10% lower than that of the Rose Lodge - Polk County Line project. The estimated air voids for the ATPM material is in the range of approximately 20 to 25%.

Table 3.2: Summary of ATPM Resilient Modulus Test Results

| Sample I.D. | Resilient Modulus (ksi)[1] | Bulk Specific Gravity |
|---|---|---|
| Project: Fir Grove Lane - Towers Road | | |
| 1 | 99 | 2.29 |
| 3 | 137 | 2.26 |
| 4 | 176 | 2.22 |
| 6 | 38 | 2.24 |
| 8 | 153 | 2.27 |
| 10 | 119 | 2.25 |
| Average | 120 | 2.26 |
| Standard Deviation | 48 | 0.02 |
| Project: Rose Lodge - Polk County Line | | |
| 2 | 103 | 2.51 |
| 4 | 64 | 2.54 |
| 5 | 90 | 2.53 |
| 6 | 76 | 2.51 |
| 7 | 94 | 2.55 |
| 9 | 74 | 2.57 |
| Average | 84 | 2.54 |
| Standard Deviation | 15 | 0.02 |

[1]Measured at room temperature, about 77°F.

### 3.2.3 Extraction Test Results

Extraction tests were performed on the 6-inch cores to determine actual asphalt content and aggregate gradation of in-place ATPM. The extraction test was conducted in accordance with the OSHD Test 309 (ODOT, 1986). Table 3.3 summarizes the test results. The results indicate that aggregate gradation for both projects is closer to the high end of the specification limit. There were a few aggregate sizes that exceeded the specification limit. The asphalt content is within the specification limit. The Fir Grove Road project had a 2.9% asphalt content while the Rose Lodge Road project had a 2.4% asphalt content.

Table 3.3: Extraction Test Results

| Aggregate Sieve Size | Percent Passing | | Specification Limit |
|---|---|---|---|
| | Fir Grove Road | Rose Lodge Road | |
| 1" | 100 | 100 | 99 - 100 |
| 3/4" | 94 | (98) | 85 - 95 |
| 1/2" | (68.6) | 66 | 35 - 68 |
| 1/4" | 19 | 19 | 5 - 20 |
| #10 | (6.1) | 5 | 0 - 5 |
| #40 | 4.1 | 3 | - |
| #200 | (2.7) | 1.9 | 0 - 2 |
| Asphalt Content | 2.9 | 2.4 | 2 - 3 |

Note: Values in parenthesis exceeded specification range.

## 3.3 Untreated Permeable Base Materials

Aggregate materials from a local source were obtained. Samples were then prepared in the laboratory for permeability and resilient modulus testing. To evaluate the effect of fractured faces of aggregates on permeability and resilient modulus, aggregates with 88% and 100% fractured faces were tested. The percentage of fractured faces was determined following the OSHD TM-213 test procedure (ODOT, 1986). The OSHD TM-213 is a visual inspection procedure for determining the percent, by weight, of the rock retained on the 1/4" sieve having at least two fractured faces. For comparison, both open- and dense-graded aggregates were evaluated.

### 3.3.1 Aggregate Gradation

Aggregates with six different gradations were evaluated. These gradations are for: 1) existing open-graded aggregate, 2) existing dense-graded aggregate, 3) New Jersey open-graded aggregate, and 4) proposed open-graded aggregate at the low end, center, and high end of the broadband limit. Table 3.4 presents the gradation for each aggregate. It should be pointed out that for the proposed open-graded aggregate, the samples prepared with 88% fractured faces aggregate were fabricated at both upper and lower bound specification limits, and the samples prepared with 100% fractured faces aggregate were fabricated at center value of the specification limit. The gradation difference is illustrated in Figure 3.7. The proposed open-graded aggregate gradation is in fact very similar to New Jersey's (Kozlov, 1984).

Table 3.4: Aggregate Gradation

| a) Aggregate with 88% fractured faces | | | | | |
|---|---|---|---|---|---|
| Aggregate Sieve Size | Existing open[1] Graded (A) | New Jersey[1] (B) | Proposed Upper Bound (C) | Proposed Lower Bound (D) | Existing Dense Graded[1] (H) |
| 1-1/2" | 100 | 100 | 100 | 100 | 97.5 |
| 1" | 97.5 | 97.5 | 100 | 100 | 80 |
| 3/4" | 67.5 | 86 | 98 | 80 | 64 |
| 1/2" | 56.5 | 70 | 85 | 60 | 54 |
| 1/4" | 37.5 | 54 | 60 | 45 | 42 |
| #10 | 7.5 | 12.5 | 20 | 5 | 23 |
| #40 | 4 | 3 | 6 | 0 | 12 |
| #200 | 1 | 1.5 | 5 | 0 | 5 |

| b) Aggregate with 100% fractured faces | | | |
|---|---|---|---|
| Aggregate Sieve Size | New Jersey[1] (E) | Proposed[1] Open Graded (F) | Existing[1] Dense Graded (G) |
| 1-1/2" | 100 | 100 | 97.5 |
| 1" | 97.5 | 100 | 80 |
| 3/4" | 86 | 89 | 64 |
| 1/2" | 70 | 68 | 54 |
| 1/4" | 54 | 53 | 42 |
| #10 | 12.5 | 13 | 23 |
| #40 | 3 | 3 | 12 |
| #200 | 1.5 | 2.5 | 5 |

Note: All values are percent passing by weight
[1] Center value of the specification limit.

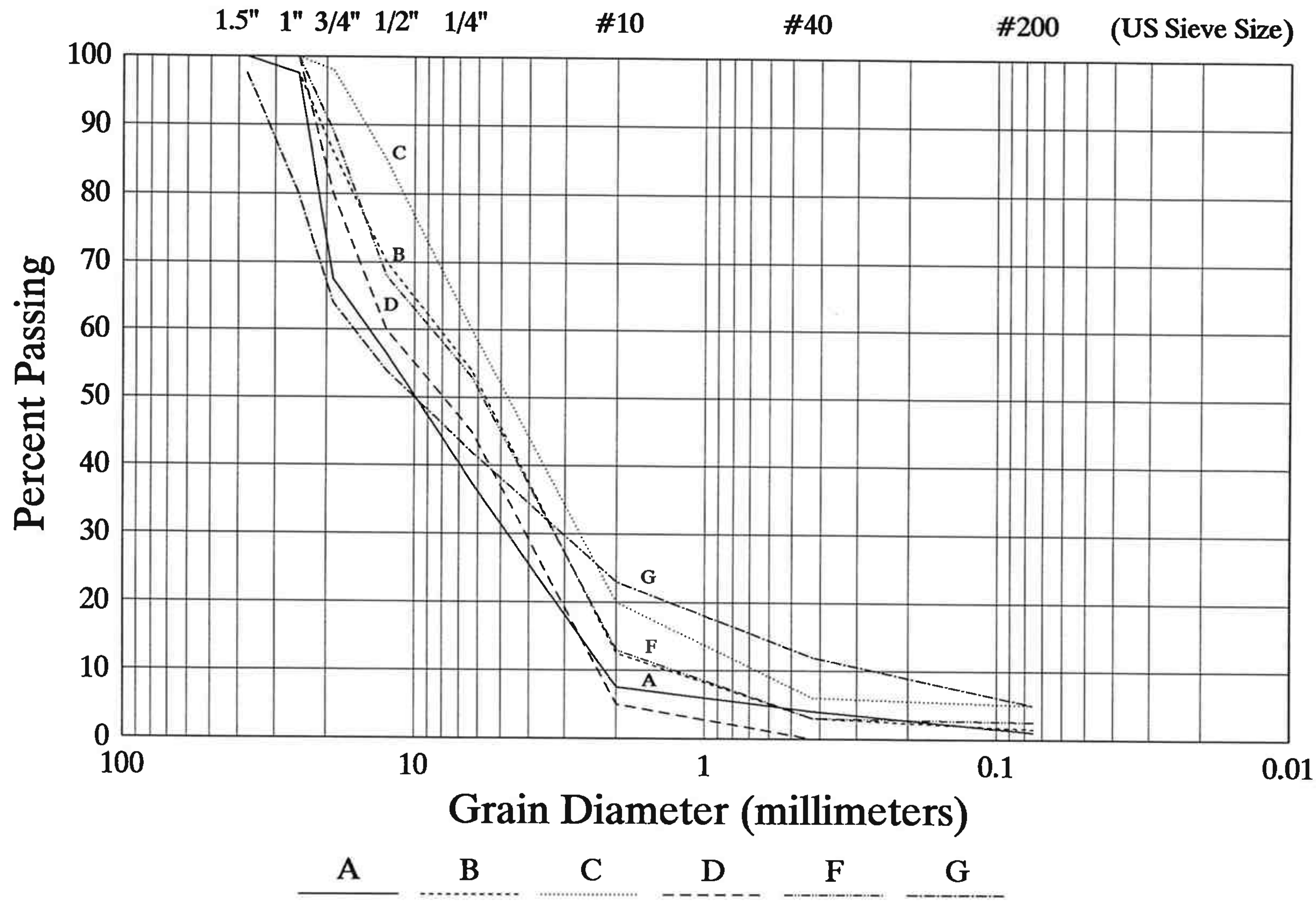



Figure 3.7: Aggregate Gradation

### 3.3.2 Sample Preparation

Ten samples at each gradation were made. Five were tested for permeability and five were tested for resilient modulus. A total of 80 samples were prepared for the laboratory study. All samples were to be made based on their water-density relationships, which were determined prior to the sample preparation. The maximum dry density for each gradation is shown in Table 3.5.

Table 3.5: Maximum Dry Density for Each Gradation

| Gradation | Maximum Dry Density (pcf) | Optimum Water Content (%) |
|---|---|---|
| A | 115.5 | 6.5 |
| B | 112.2 | 4.0 |
| C | 108.6 | 8.0 |
| D | 105.0 | 6.0 |
| H | 120.3 | 5.3 |
| E | 117.6 | 3.5 |
| F | 115.9 | 3.2 |
| G | 123.6 | 3.3 |

Samples for the permeability test were four inches in diameter and 6 inches in height. For the resilient modulus test, samples were six inches in diameter and 12 inches in height. All samples were to be prepared at the optimum moisture contents. The resilient modulus samples were compacted using a Chicago Pneumatic Air Hammer Model CP715 with a capacity of 2,100 blows/minute at 90 psi line pressure.

### 3.3.3 Permeability Test Results

The equipment and testing procedures used for the treated base materials were also used here. Both constant head and falling head permeabilities were determined. The test results are summarized in Table 3.6. Detailed test results may be found in Appendix C.

For comparison between constant and falling head test results, the average permeabilities are also plotted in Figure 3.8.

Table 3.6: Summary of Permeability Test Results for Untreated Base Materials

| Sample I.D. | Constant Head (ft/day) | | Falling Head (ft/day) | |
|---|---|---|---|---|
| | Average | Standard Deviation | Average | Standard Deviation |
| A | 971 | 322 | 1031 | 223 |
| B | 770 | 138 | 723 | 145 |
| C | 226 | 42 | 316 | 77 |
| D | 3018 | 370 | 3694 | 143 |
| E | 2376 | 338 | 1962 | 181 |
| F | 2489 | 309 | 1876 | 169 |
| G | 475 | 150 | 153 | 31 |
| H | 140 | 64 | 76 | 30 |

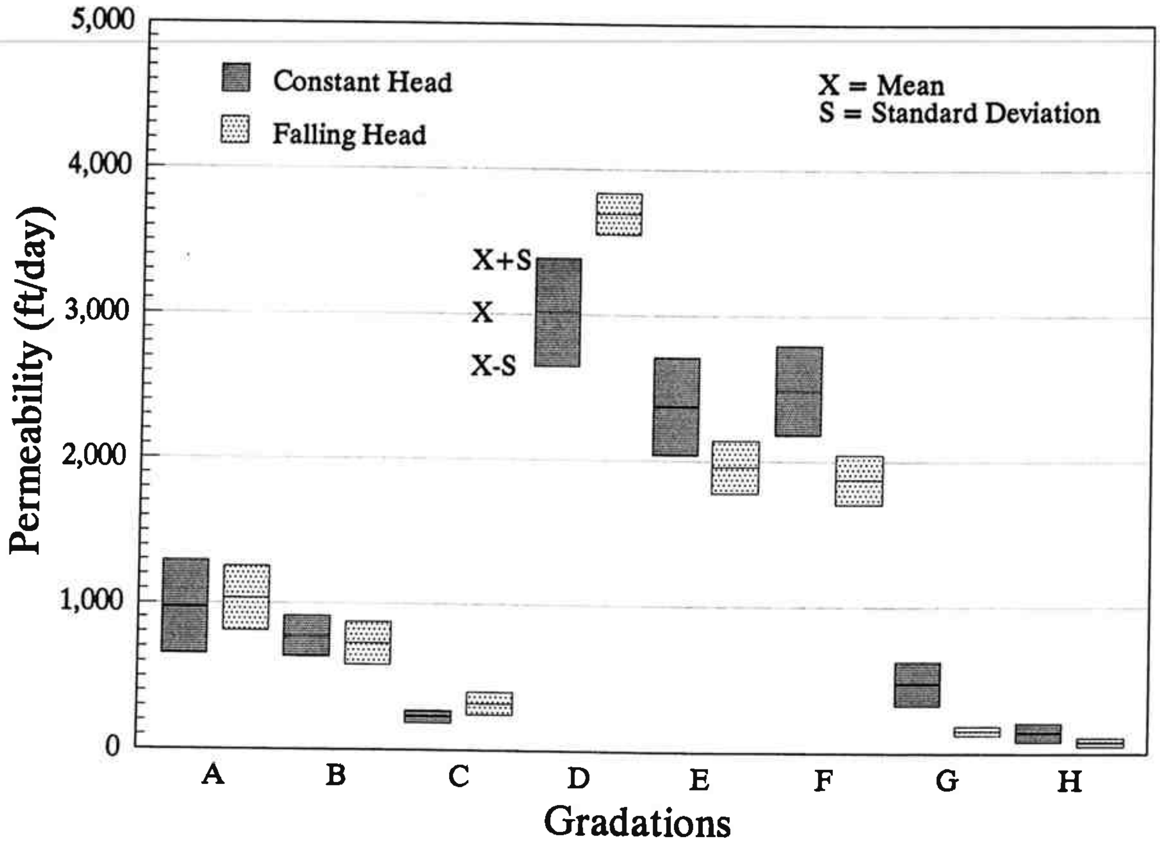



Figure 3.8: Comparison Between Constant and Falling Head Test Results

The permeability test results from both constant and falling head test procedures appear in general to be close for each type of aggregate gradation. The permeability results from the falling head test seem to have a smaller standard deviation than those from the constant head test.

The permeability test results indicate that for open-graded aggregates the percent of fractured faces have a substantial influence on the permeability. For the same type of gradation, as shown by the Gradation E and Gradation B, the aggregate with 100% fractured faces are more permeable than aggregate with 88% fractured faces. The bound limit also influences the permeability significantly. As can be seen for the proposed aggregate gradation, the lower bound gradation D has a much higher permeability than the upper bound gradation C. This is to be expected since gradation D is much coarser than gradation C. Gradation F is the centerline of the proposed gradation band. With 100% fractured faces, the gradation F is expected to have a higher permeability than it is with 88% fractured faces, as shown by the gradation E and gradation B. The results also show that the permeability of the gradation F is closer to that of gradation D which is the lower bound of the proposed gradation limit. This appears to indicate that as the percentage of aggregate fractured faces increases, the permeability of the aggregate material would also increase. For dense-graded aggregate, the difference in permeability due to fractured faces is not substantial.

### 3.3.4 Resilient Modulus Test Results

The resilient modulus tests were performed in accordance with AASHTO T-274. The samples were 6 inches in diameter and 12 inches in height. For each gradation, five samples were made and tested. The test results are summarized in Table 3.7 and the test results for each gradation are illustrated in Figures 3.9 - 3.16. Detailed test results are given in Appendix D.

The resilient modulus results are presented in the following expression:

$$M_R = k_1 \, \theta^{k_2} \tag{3-3}$$

Where:
- $M_R$ = Resilient modulus (psi)
- $k_1$, $k_2$ = Regression coefficients of material
- $\theta$ = Bulk stresses (psi)

This expression shows that the resilient modulus of untreated aggregate is a function of both bulk stress and material properties.

Table 3.7: Summary of Resilient Modulus Test Results for Untreated Aggregate Materials

| Gradation | Modulus = $k_1\theta^{k_2}$ | $R^2$ | Actual Dry Density (pcf)[a] | Actual Water Content (%)[a] |
|---|---|---|---|---|
| A | $2,557\theta^{0.592}$ | 0.92 | 107.6 | 3.4 |
| B | $1,943\theta^{0.619}$ | 0.96 | 104.1 | 3.9 |
| C | $1,786\theta^{0.615}$ | 0.87 | 102.6 | 5.8 |
| D | $3,240\theta^{0.568}$ | 0.94 | 105.4 | 3.4 |
| H | $4,144\theta^{0.525}$ | 0.95 | 120.2 | 4.5 |
| E | $4,054\theta^{0.574}$ | 0.74 | 119.1 | 2.9 |
| F | $3,475\theta^{0.569}$ | 0.81 | 116.3 | 2.6 |
| G | $4,355\theta^{0.511}$ | 0.94 | 124.1 | 2.9 |

[a] Average of test results from five samples for each gradation.

Table 3.7 also includes actual dry density and water content data measured immediately after the resilient modulus test. It is noted that some of the actual dry densities measured during resilient modulus test are slightly higher than the maximum dry densities determined during the development of water-density relationship for the aggregate materials and that the actual moisture content of the samples is slightly lower than optimum water content. The exact cause of inconsistency in dry densities is not known. It may have resulted from variation in sample fabrication which was conducted by two different laboratories. The slightly lower actual water content of the samples may have resulted from the water loss during the modulus testing process.

The resilient modulus test results indicate that for open-graded aggregates the percent of fractured faces have a significant influence on the resilient modulus. For the same type of gradation, the aggregates with 100% fractured faces have a much higher resilient modulus than aggregates with 88% fractured faces, as shown in Figure 3.17. For dense-graded aggregate, the difference in resilient modulus due to fractured faces is not obvious, as can be seen in Figure 3.18.

Figure 3.19 illustrates the test results for the proposed aggregate gradation versus the existing aggregate gradation. The figure clearly shows that the newly proposed FDAB gradation F had a higher resilient modulus than the existing FDAB gradation A.

For comparison, resilient moduli for each gradation are plotted in Figure 3.20.

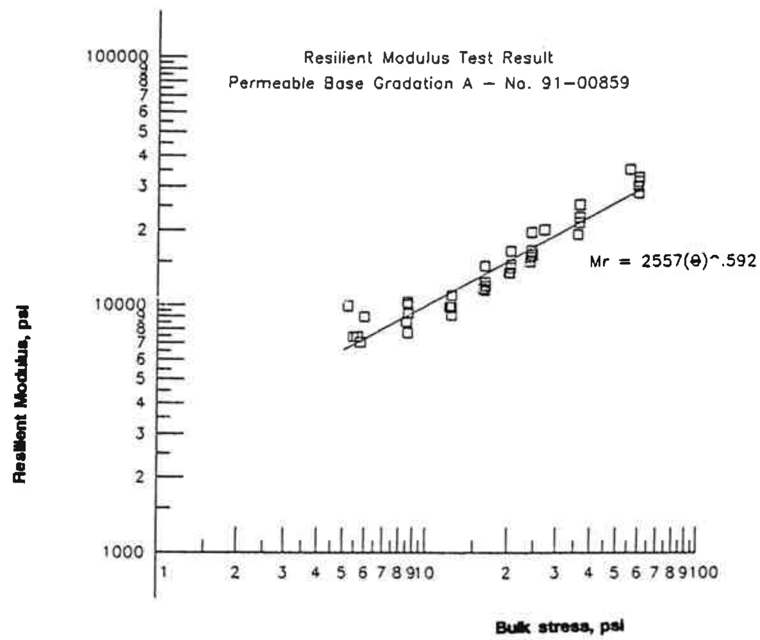



Figure 3.9: Resilient Modulus Test Results for Gradation A

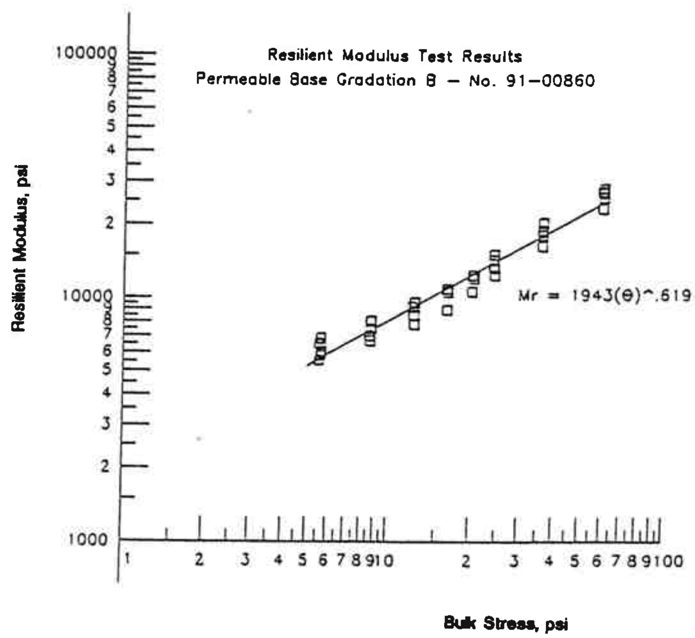



Figure 3.10: Resilient Modulus Test Results for Gradation B

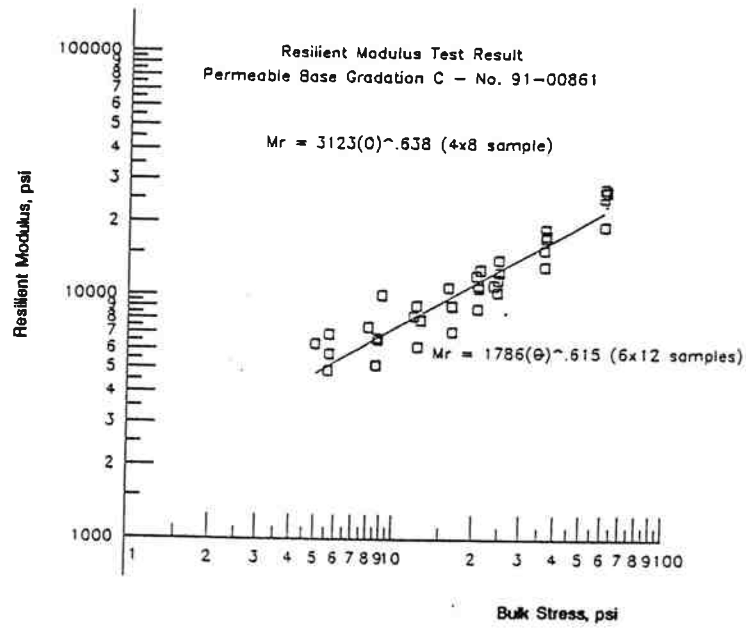



Figure 3.11: Resilient Modulus Test Results for Gradation C

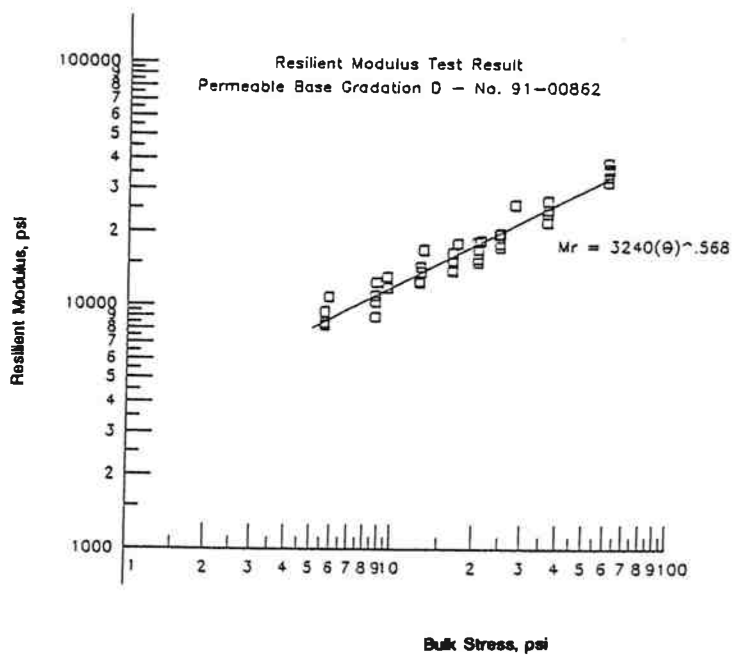



Figure 3.12: Resilient Modulus Test Results for Gradation D

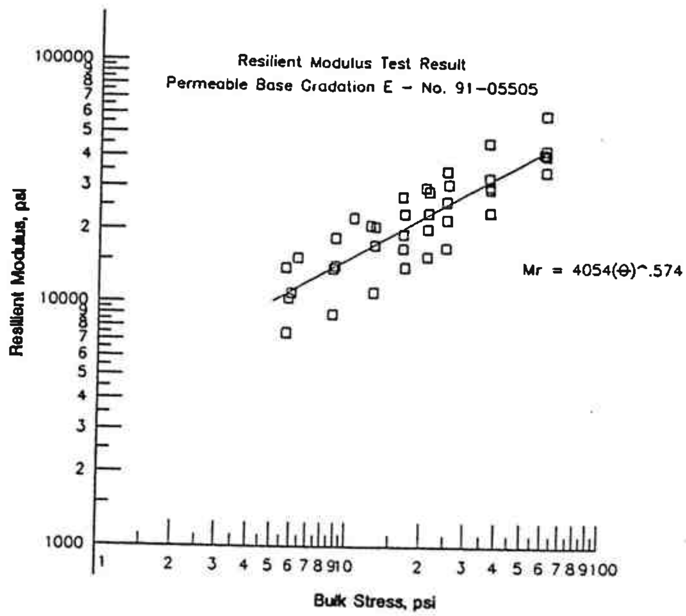



Figure 3.13: Resilient Modulus Test Results for Gradation E

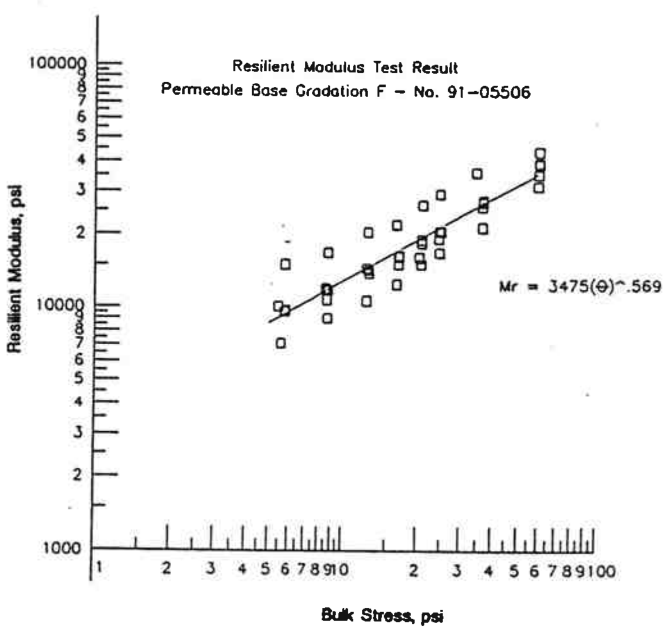



Figure 3.14: Resilient Modulus Test Results for Gradation F

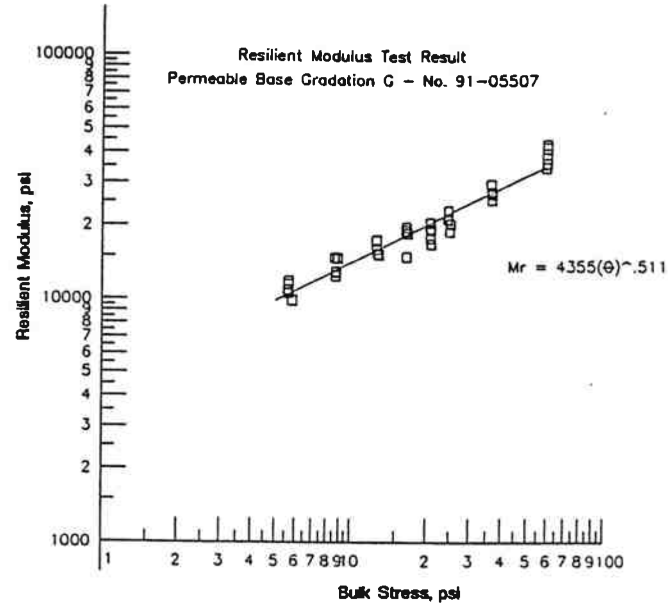



Figure 3.15: Resilient Modulus Test Results for Gradation G

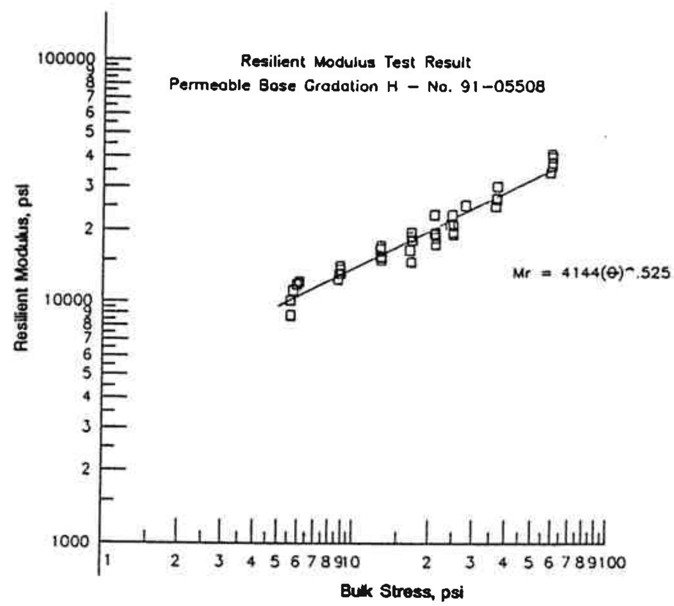



Figure 3.16: Resilient Modulus Test Results for Gradation H

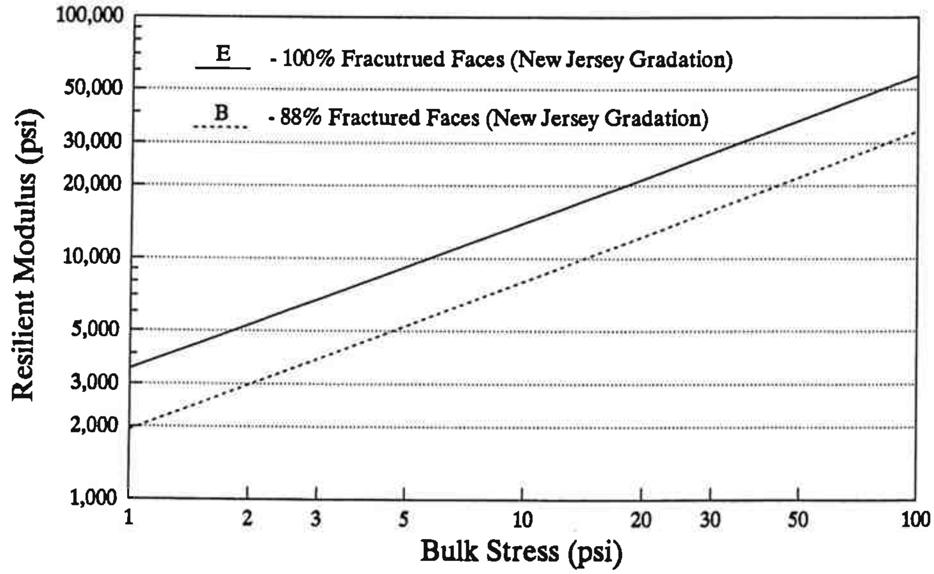



Figure 3.17: Effect of Fractured Faces on Resilient Modulus (For Open-Graded Aggregate)

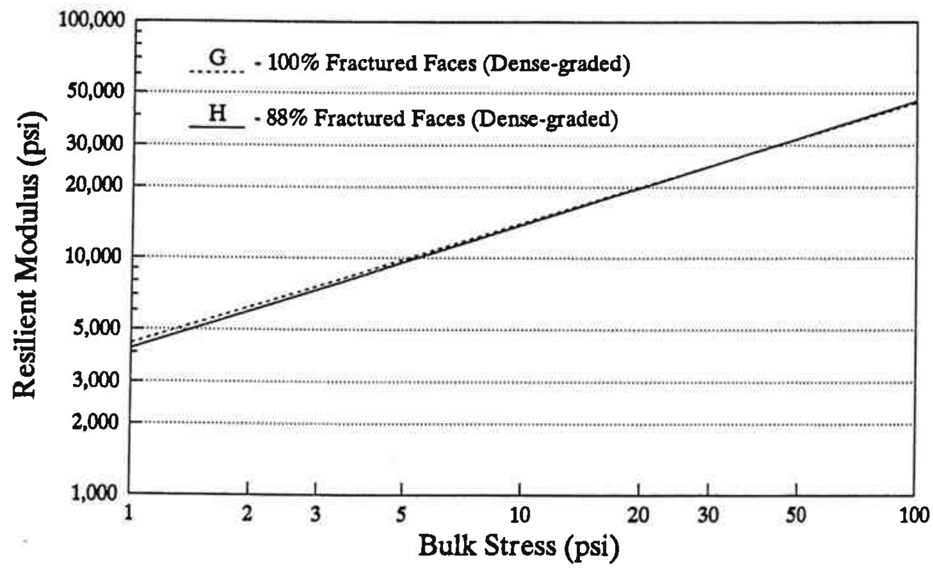



Figure 3.18: Effect of Fractured Faces on Resilient Modulus (For Dense-Graded Aggregate)

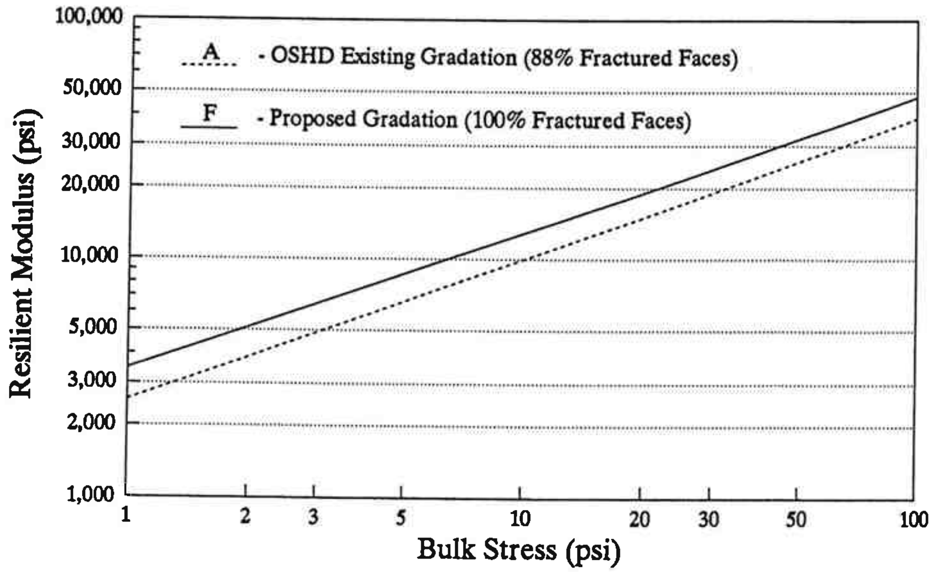



Figure 3.19: Resilient Moduli for the Proposed Gradation versus the Existing Gradation

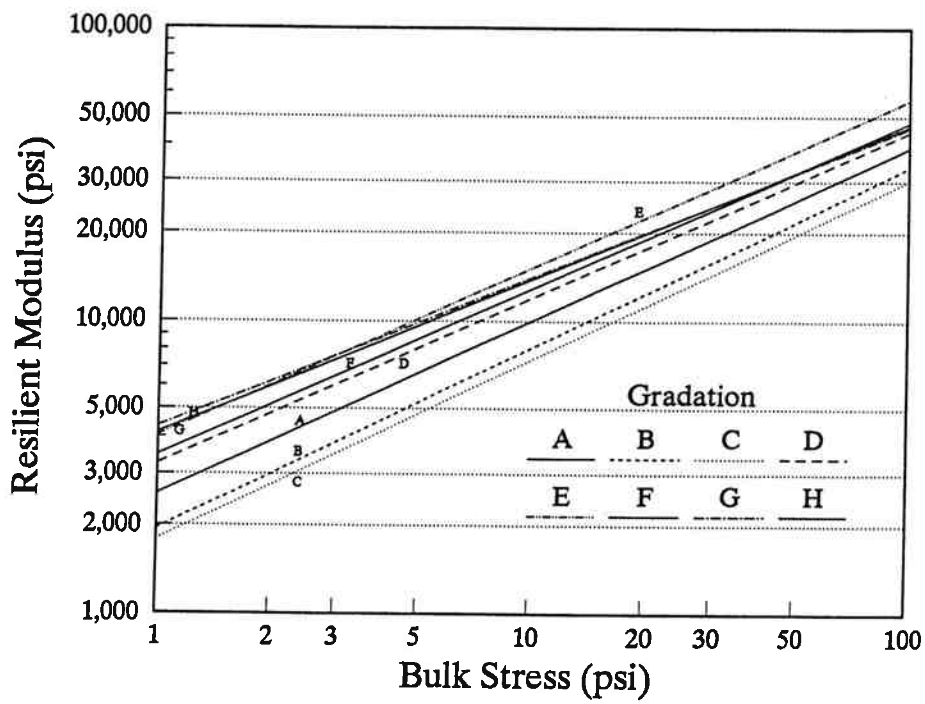



Figure 3.20: Comparison of Resilient Moduli for All Aggregate Gradation Investigated

# 4.0 USE OF RESEARCH RESULTS

To implement the research results, the laboratory test results have been summarized and analyzed as documented in the previous chapter. This chapter describes the development of design inputs and specification for use in Oregon. The design inputs include resilient modulus and layer coefficients. The specification includes recommendation for modification of current OSHD FDAB gradation.

## 4.1 Resilient Modulus and Layer Coefficient

### 4.1.1 Treated Permeable Base Materials

For the Fir Grove Lane - Towers Road project, the average resilient modulus measured in the laboratory is 102 ksi with a standard deviations of 48 ksi. For the Rose Lodge - Polk County Line project, the average resilient modulus is 84 ksi with a standard deviation of 15 ksi. It should be pointed out that the resilient modulus of the ATPM was measured at 77°F temperature without confinement and the stiffness of the ATPM would vary with the change of temperature. Although a modulus-temperature relationship for Oregon's ATPM is not known, it is expected that the modulus will increase when temperature decreases. In Oregon, the ATPM base layer may experience a much lower temperature than 77°F because of its position in the pavement structure. Therefore, the actual modulus may be much higher than those measured in the laboratory.

Considering the temperature effect on the resilient modulus and using a modulus-layer coefficient conversion chart recommended by AASHTO (1986), a corresponding layer coefficient can be read from Figure 4.1. For Oregon's ATPM, the average resilient moduli are adjusted to 68°F temperature using a procedure in the AASHTO Guide for Design of Pavement Structures (AASHTO, 1986). The temperature adjusted resilient moduli are then used for determining the layer coefficient. This would result in a layer coefficient between 0.14 and 0.19.

The drainage coefficient needs to be included in the pavement structural design. For pavements to provide a positive drainage, a minimum permeability of 1,000 ft/day should be achieved. (Cook and Dykins, 1991). Oregon's current ATPM appears to have a sufficient drainage capability, as can be seen from the laboratory test results in Table 3.1. With this drainage capability, a drainage coefficient between 1.15 to 1.25 is recommended for use in Oregon. This recommendation is based on an assumption that the pavements would have a good quality of drainage and 1-5% of the time during the year the pavement structure would be exposed to moisture levels approaching saturation (AASHTO, 1986).

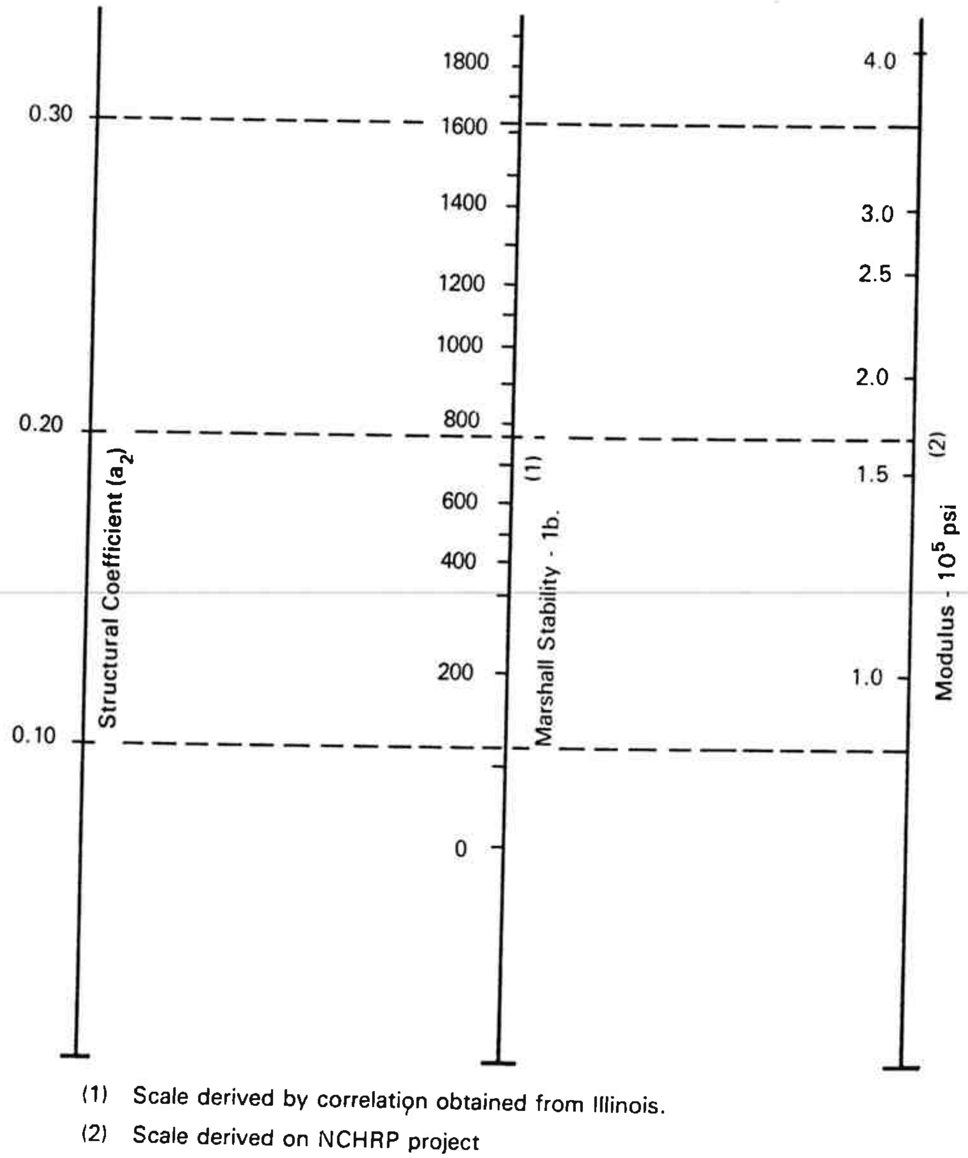



Figure 4.1: Variation in $a_2$ for Bituminous-Treated Bases with Base Strength Parameter (AASHTO, 1986).

### 4.1.2 Untreated Permeable Base Materials

Resilient modulus test results for untreated permeable aggregates are presented in Figure 3.20. The figure shows that the newly proposed FDAB gradation F aggregate with 100% fractured faces had a higher resilient modulus than the existing FDAB gradation A aggregate with 88% fractured faces.

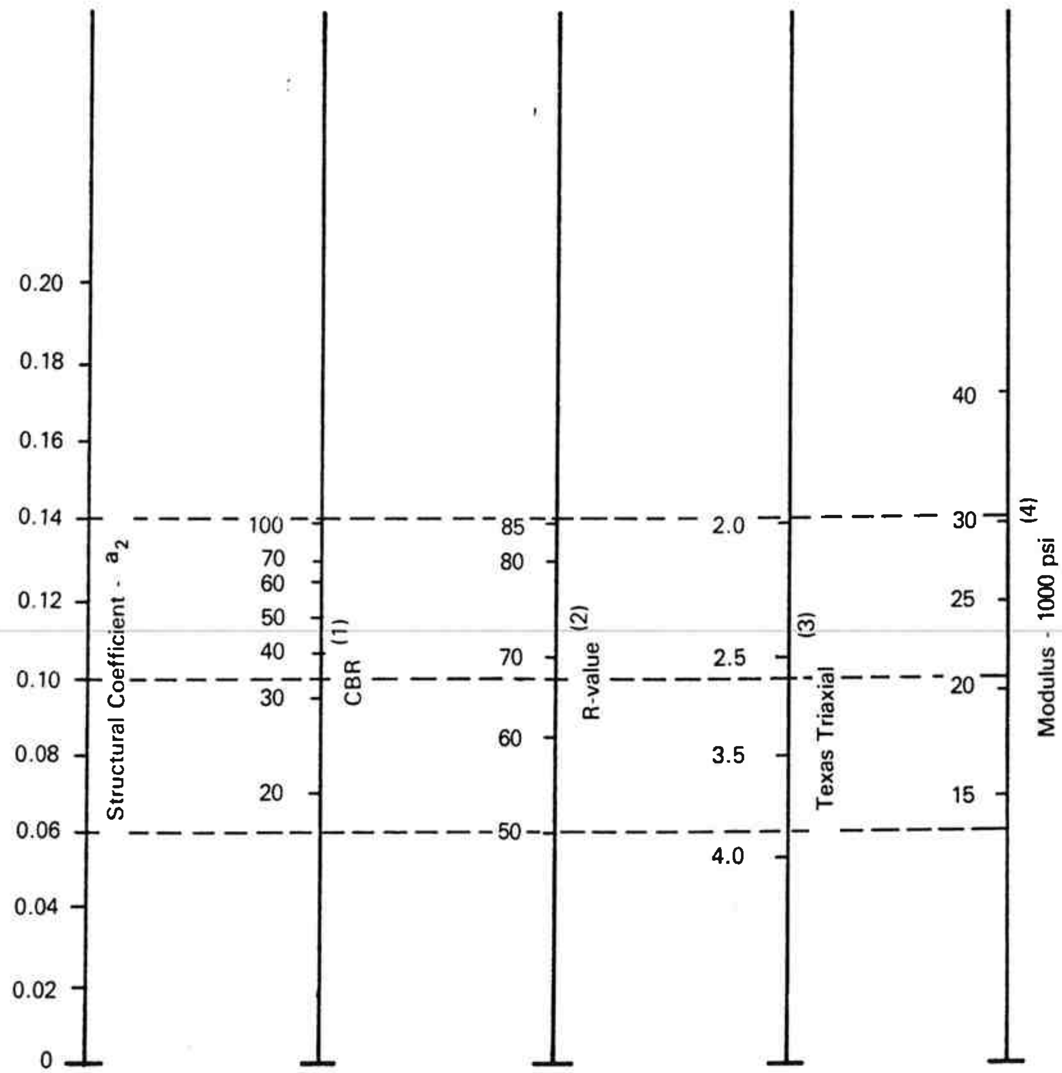
The layer coefficient for the FDAB may be determined using Figure 4.2 for base layer or Figure 4.3 for subbase, knowing resilient modulus, which can be calculated from equation (3-3). For a specific aggregate material, a corresponding equation or relationship should be used to calculate the modulus. It should be pointed out that the resilient modulus for untreated aggregate is a function of stress state in a pavement structure, therefore, an anticipated stress level should be used to determine the resilient modulus. Guidelines for determining stress state may be found in the AASHTO Guide for Design of Pavement Structures (AASHTO, 1986). For pavement design purposes in Oregon, a layer coefficient between 0.08 to 0.14 is recommended for both base and subbase layers. These correspond to a resilient modulus between 16 to 30 ksi for the base and 11 to 20 ksi for the subbase materials.

A drainage coefficient between 1.00 to 1.15 is recommended for use in Oregon. This recommendation is based on an assumption that the pavements would have a good quality of drainage and 5 to 25% of the time during the year the pavement structure would be exposed to moisture levels approaching saturation. Notice that the percent of time moisture levels approaching saturation is higher than that of the ATPM, this is due to concerns about contamination of the FDAB. Also most FDAB designs have not provided longitudinal edge drains and are simply outlet on the shoulder. The shoulders will become contaminated over time. If edge drains are provided, a higher drainage coefficient may be appropriate.

## 4.2 Gradation Specification Changes

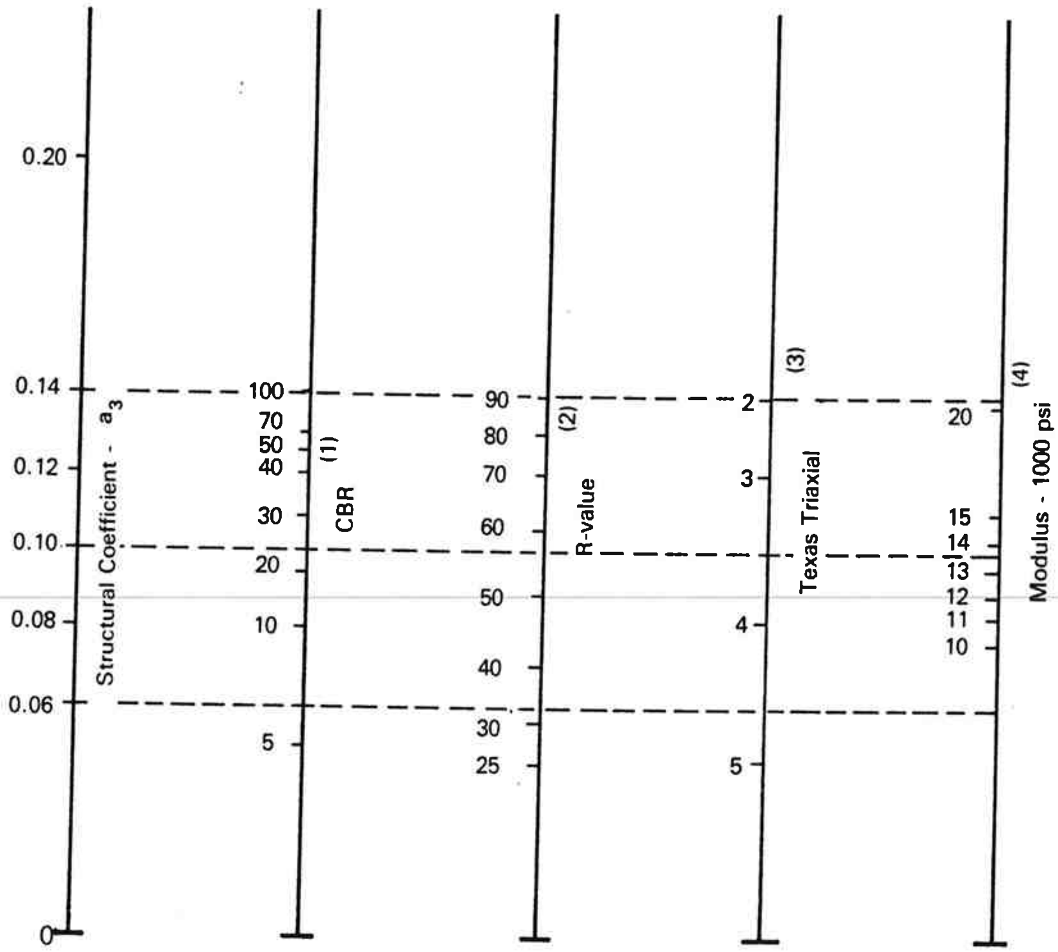
One objective of this research study is to evaluate the existing FDAB gradation and its performance during construction. The project manager questionnaire survey indicated the existing gradation was unstable and difficult to compact during construction. An appropriate modification of this gradation has been made in the consideration of using as much of the existing aggregate stockpile as possible. This modification is represented by Gradation F with 100% fractured faces. The broadband of this modified gradation is shown in Table 4.1.

Laboratory tests on the gradation F showed a substantial increase in resilient modulus as well as in density, compared to the existing gradation. This improvement in material property, due to gradation changes and increased fractured faces percentage, may also improve its constructability and stability. Another major improvement due to the gradation change is a considerable increase in permeability. Compared to the existing gradation, the permeability of the modified gradation is almost doubled.




(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project

Figure 4.2: Variation in Granular Base Layer Coefficient ($a_2$) with Various Base Strength Parameters (Vantil, et al, 1972)




(1) Scale derived from correlations from Illinois.

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.

(3) Scale derived from correlations obtained from Texas.

(4) Scale derived on NCHRP project

Figure 4.3: Variation in Granular Subbase Layer Coefficient ($a_3$) with Various Subbase Strength Parameters (Vantil et al, 1972).

Table 4.1: Proposed Gradation Specification

| Sieve Size | Percent Passing % (Centerline) | Broadband Limit |
|---|---|---|
| 1-1/2" | 100 | 100 |
| 1" | 100 | 100 |
| 3/4" | 89 | 80-98 |
| 1/2" | 68 | 60-85 |
| 1/4" | 53 | 45-60 |
| #10 | 13 | 5-20 |
| #40 | 3 | 0-6 |
| #200 | 2.5 | 0-5 |
| Measured permeability (ft/day) | Constant Head | Falling Head |
| Average<br>Standard deviation | 2,489<br>309 | 1,876<br>169 |

# 5.0 CONCLUSIONS AND RECOMMENDATIONS

As stated in the introduction, the objective of this project is to determine material properties for two types of free-draining base materials, develop appropriate layer and drainage coefficients for use in the design of permeable base sections, and establish a more stable gradation for open-graded aggregate base materials. These objectives have been accomplished. Based on the literature review and the laboratory test results, the following conclusions and recommendations for implementation are offered.

## 5.1 Conclusions

1. Many states are paying great attention to subsurface drainage. Design and construction of a positive drainage system in pavement structures is becoming more common.

2. Typical ATPM layer thickness ranges from three to four inches. Typical asphalt content used in ATPM is two to three percent. Within this range, the amount of asphalt has a minor influence on permeability.

3. The current OSHD's ATPM has a sufficient drainage capability. The resilient modulus of this material is typical of other states' findings.

4. The proposed gradation for open-graded aggregate with 100% fractured faces has a considerably higher permeability than the existing gradation. The aggregate with the proposed gradation also has a higher resilient modulus.

5. The percent of fractured faces has a substantial influence on the permeability of open-graded aggregate. For the same type of gradation, the aggregate with 100% fractured faces is more permeable than the aggregate with 88% fractured faces. For dense-graded aggregate, the difference in permeability due to fractured faces is not significant.

6. The percent of fractured faces has a significant influence on the resilient modulus of open-graded aggregate. For the same type of gradation, the aggregates with 100% fractured faces has a much higher resilient modulus than aggregates with 88% fractured faces. For dense-graded aggregate, the difference in resilient modulus due to fractured faces is not obvious.

## 5.2 Recommendations for Implementation

1. For pavement structural design with ATPM, a layer coefficient of 0.14 to 0.19 is recommended. A drainage coefficient of 1.15 to 1.25 is recommended.

2. The proposed gradation for FDAB is recommended for use. To ensure sufficient drainage and strength, 100% of the material retained above the 1/4 inch sieve should be fractured on at least two faces. In locations where this is not obtainable, 90% fracture on at least two faces should be specified. Where 100% fracture can be specified, a layer coefficient between 0.11 and 0.14 is recommended. Where 90% fracture is specified, a layer coefficient between 0.08 and 0.11 is recommended. The specific value may be determined knowing the anticipated stress in the aggregate.

3. A drainage coefficient of 1.05 to 1.15 is recommended for the FDAB with 100% of the material retained above the 1/4" inch sieve fractured on two faces and 1.00 to 1.05 for 90% fractured on at least two faces.

4. A prime coat is recommended for use on the top of FDAB. This will make the FDAB material easier to run construction equipment on and more stable.

5. Plant mix is recommended when using FDAB to reduce aggregate segregation.

## 5.3 Additional Recommendations

1. A follow-up examination on FDAB constructability with the proposed gradation should be performed in the coming paving season. Any construction-related problems with the proposed gradation should be evaluated. The gradation may be adjusted as necessary.

2. A long-term monitoring program on pavements with a free-draining base layer should be established to evaluate the performance of the pavements.

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# APPENDIX A

## Project Manager Questionnaire Survey Results

## (Free Draining Aggregate Base)

## FREE DRAINING AGGREGATE BASE QUESTIONNAIRE

**1. Please list the free draining aggregate base (FDAB) projects your office has dealt with. Specify the FDAB lift thickness and number of lifts per project.**

| Project Number | Project Name | Total Thickness (in.) | Number of Lifts |
|---|---|---|---|
| 1. | Kern Swamp Road - Weyerhaeuser Road | 14" | Two 7" Lifts |
| 2. | Rock Creek - Anlauf | 13" | 3 Lifts |
| 3. | Penn Road - Cougar Pass | 7" | 2 Lifts |
| 4. | Forest Boundary - Rice Road | 15" | 3 Lifts |
| 5. | Hancock Hill Passing Lane Section | 14" | - |

**2. What was the FDAB design gradation for each project?**

| Sieve Size | Specification 1 % Passing | Specification 2 % Passing |
|---|---|---|
| 1 1/2" | 100 | 100 |
| 1" | 95-100 | 85-100 |
| 3/4" | 55-75 | 55-80 |
| 1/4" | 25-50 | 25-50 |
| No. 10 | 0-15 | 0-15 |
| No. 100 | 0-3 (Dry) | 0-3 |

Note: Specification 1 was used in Projects 1, 3, and 4.
Specification 2 was used in Projects 2 and 5.

**3. Did you have to make any changes to the FDAB design gradations? If so, what were they? Were they successful?**

<table>
<tr><th>Project Number</th><th>Description</th></tr>
<tr><td>1</td><td>Surfacing design urged a change in gradation to provide a more workable material.<br><br>Gradation changes occurred on the 1" and 3/4" sieves as reflected in the following table:
<table>
<tr><th>Sieve Size</th><th>% Passing</th></tr>
<tr><td>1 1/2"</td><td>100</td></tr>
<tr><td>1"</td><td>85-100</td></tr>
<tr><td>3/4"</td><td>55-80</td></tr>
<tr><td>1/4"</td><td>25-50</td></tr>
<tr><td>No. 10</td><td>0-15</td></tr>
<tr><td>No. 100</td><td>0-3 (Dry)</td></tr>
</table>
Despite the changes increasing the band limits for percentage passing the 1" and 3/4" sieves the product was still difficult to produce. Minor fluctuations in passing percentage on the 3/4", 1/4" and No. 10 sieves greatly affected the percentage passing the 100 sieve. Most tests on the 100 sieve were near the upper limit.</td></tr>
<tr><td>4</td><td>Yes. Changed Forest Boundary-Rice Road to Rock Creek-Anlauf spec, then changed the pass 100 from 0-3 to 0-4.5%.</td></tr>
</table>

**4. How were you able to control compaction of the FDAB? Did this work well?**

| Project Number | Description |
|---|---|
| 1 | Each lift was compacted using pneumatic tire rollers conforming to 403.45(a-1) and steel wheel rollers having a minimum gross static weight of 8 tons and a minimum weight of 250 pounds per lineal inch of width on the drive wheel.<br><br>Compaction was by visual inspection. No unusual problem was noted with compaction. The top surface of the compacted base would ravel very easily under construction traffic. |
| 2, 3, 4 | Requested to change compaction testing to visual. The surface of the material never becomes stable and does not provide a suitable surface for paving. Compaction was poor. The grade varies and it is hard to control grade under traffic. |

5. **Did you experience problems with FDAB placement, segregation?**

| Project Number | Description |
|---|---|
| 1 | Plant mix aggregate base was hauled with belly dumps and deposited in windrows. Spreading was accomplished with a blade. This method of placement seemed to work well. Segregation of this material can be minimized by limiting the working of the material to only the amount required for placement in a uniform thickness. Due to the limited fines in this material it is near impossible to avoid some segregation.<br><br>Based on our experience of plant mixing instead of road mixing as tried in other areas, my recommendation would be to place as plant mix. I believe the moisture added in plant mixing tends to minimize segregation during placement by holding the particles together. |
| 2, 3, 4 | Yes. Segregation and stability, not suitable for traffic during stage or temporary construction. Several areas of segregation were evident. |

6. **If the project also involved dense graded aggregate base, was there an appreciable price difference? If so, approximately what was it? What was the approximate price of the FDAB?**

| Project Number | Description |
|---|---|
| 1 | The project original bid was for plant mix open grade aggregate base. Price agreement number 8 deleted a portion of this quantity and substituted 1"-0 aggregate base meeting standard specification. The 1"-0 aggregate base was designated for use in temporary aggregate base for stage construction, aggregate shoulders and driveways. The reason for this change was the experience of other project managers in trying to accommodate traffic over the open graded material, i.e. raveling and material acting similar to driving on "marbles."<br><br>Open graded aggregate base as called for in the plans was bid at $7.80 per ton. We negotiated the same price for the 1"-0 aggregate base. |
| 2, 3, 4 | The approximate price of the FDAB ranged from $8.50 to $11.50 per ton. |
| 5 | The price of the FDAB was $7.00 per ton. |

7. **Do you have any suggestions for improving the workability of the FDAB?**

| Project Number | Description |
|---|---|
| 1 | Recommendations for future projects calling for FDAB:<br><br>a. Specify 1"-0 aggregate base meeting standard specifications for aggregate shoulders, temporary base, driveways and detours.<br><br><u>Reasons</u>:<br><br>(a-1) More stability on shoulders in case of vehicles leaving pavement. Prevents sliding on "loose" material and being "sucked in." We tried some open graded on the shoulders and found it to be unstable when you drive onto the shoulder and braked, it left ruts.<br><br>(a-2) On temporary base, 1"-0 meeting standard specifications is easier to work.<br><br>(a-3) On driveways and approaches there will be less raveling, rutting, and carrying of aggregate onto the pavement. Also 1"-0 is easier for traffic to negotiate because of tighter surface.<br><br>b. Specify plant mix when using FDAB. Moisture mixed in at pug tends to help hold material together and prevent segregation. Road mixing would cause more segregation due to more handling of material. Fines would tend to "settle out."<br><br>c. Change the % passing gradation on the 100 sieve from 0-3 (dry) to 0-5 (dry). The 0-3 is quite difficult to obtain during crushing. Handling material always generates more fine material.<br><br>d. Specify track mounted paver instead of rubber tire paver. Any turning movements on this material tends to dig in and causes ruts or holes.<br><br>e. If material has been in place and dried out over a period of time an application of a fine spray of water and tight rolling, prior to paving, will help prevent raveling. |
| 2, 3, 4 | Use seal coat on top, be very selective of use. More 3/4"-1/4", tighter compaction. |
| 5 | At the stockpile site, run material through a pug with CSS-1 diluted approximately 3:1 to assist in keeping fines properly mixed. Upon mixing at pug 1 to 2% should be enough to help, additional water for compaction could be at time of placement. |

**8. Please identify any specific construction situations or conditions that you believe a FDAB should not be used.**

| Project Number | Description |
|---|---|
| 1 | Aggregate shoulders, temporary base, detours and driveways. See reasons stated in 7 (a-1) through (a-3). |
| 2, 3, 4 | Roadway widenings that involve reverse supers (drainage toward centerline) on steep grades or temporary construction.<br><br>Poor in unpaved areas of stage construction. |
| 5 | Should not be used on hills - problems with tearing and shoving causing the first lift of pavement to have major depth control. |

**9. Would you be willing to provide review comments on any proposed changes that we might develop for the FDAB specifications?**

| Project Number | Description |
|---|---|
| 1, 2, 3, 4, 5 | Yes. |

# APPENDIX B

# LABORATORY PERMEABILITY TEST PROCEDURES

This appendix describes the test procedure used in this project for determining the permeability of treated and untreated permeable base materials in laboratory control situations. Both the falling head and the constant head permeability test procedures are outlined in this section.

**Apparatus**

The test apparatus used in this project are similar to those used by the New Jersey Department of Transportation (Kozlov, 1984). A slight modification was made on the apparatus to eliminate free fall of water at the bottom of the sample. This is done by including a 1-inch size sieve and a pan at the base of the sample into which the water would flow. Figure B-1 shows a schematic of the test apparatus.

The test apparatus may be used for both the falling head and the constant head tests. For the constant head test, the four-inch PVC and the rubber collar are not used. A constant water flow is achieved by controlling the flow rate from a water source.

The apparatus for testing the ATPM and the FDAB are essentially the same. For testing the ATPM, a four-inch high steel mold is used to contain the sample. For testing the FDAB, a nine-inch steel mold and a No. 40 sieve attached to the bottom of the steel mold are used to contain the sample.

**Sample Preparation**

Treated base materials: These may be cores or laboratory prepared samples. The samples are four inches in diameter and two to four inches in height.

Untreated base materials: The samples are four inches in diameter and approximately six inches in height.

**Test Procedures**

Constant head permeability: The constant head permeability test involves setting up the apparatus with the sample inside the steel mold. Run water through the top of the sample and increase the flow until a measurable constant head is achieved. Measure the height from the top of the sample to the water surface. Run water to a container and time it until a known amount of water is collected. Record sample height ($L$), sample area ($A$), constant water height ($h$), amount of water ($vol$), and time ($s$) in a form shown in Table B-1.

Falling head permeability: The falling head permeability test involves setting up the apparatus with the sample inside the steel mold. Run water through the top of the sample and increase the water head to a predetermined height. Let water free fall through two predetermined levels and record the time required. Record sample height ($L$), predetermined level 1 ($h_1$), predetermined level 2 ($h_2$), and time ($s$) in a form shown in Table B-2.

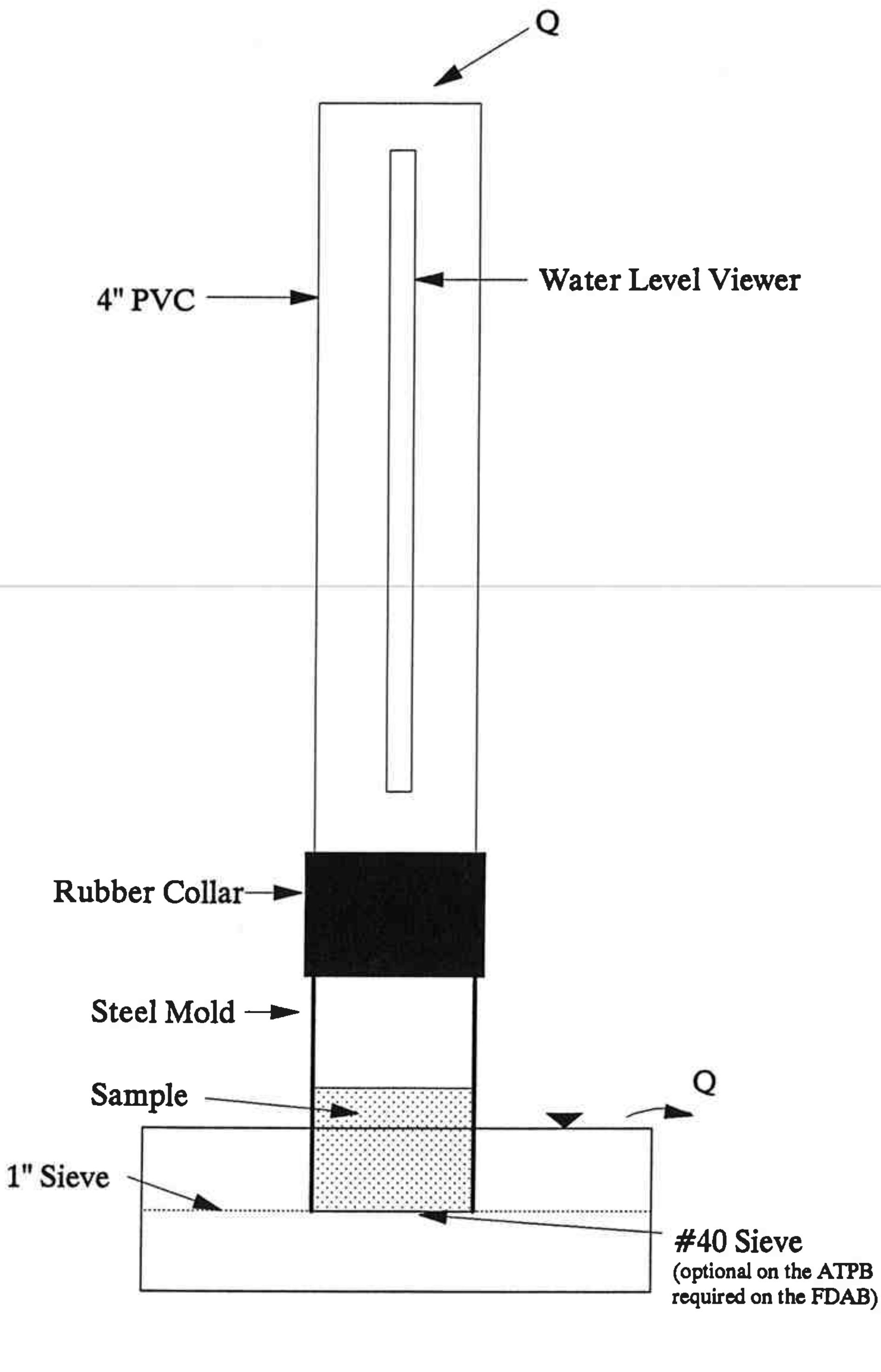


Figure B-1: Permeability Test Apparatus

## Table B-1: Free Draining Material Properties
## Constant Head Data Sheet

PROJECT: ____________

| SAMPLE # | SAMPLE HEIGHT L | AREA | | FLOW | | | | HEAD | | | | PERMEABILITY | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | D (in) | A (sqin) | VOL (ml) | Time (s) | Q (ml/s) | Q (cuin/s) * | h (in) ** | $H_{mold}$ (in) ** | $H_w$ (in) ** | H (in) ** | k (in/s) | k (ft/d) *** |
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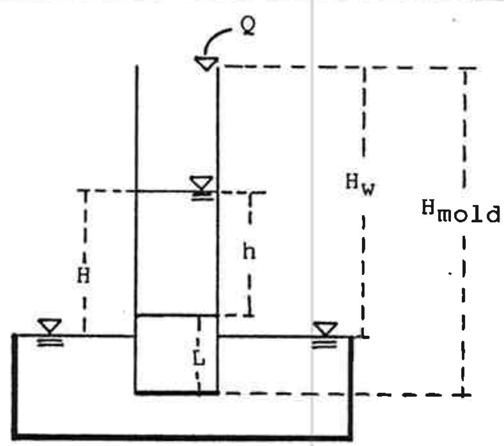
* Flow (cuin/s) = 0.06102 Flow (ml/s)
** $H = h + L - H_{mold} + H_w$
*** k (ft/d) = 7200 k (in/s)




$$k = \frac{QL}{AH}$$

## Table B-2: Free Draining Material Properties
## Falling Head Data Sheet

PROJECT: ____________________

| SAMPLE # | SAMPLE HEIGHT L (in) | TIME (s) | HEAD | | | | | | PERMEABILITY | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | a (in) | b (in) | $H_{mold}$ (in) | $H_w$ (in) | $h_1$ (in) * | $h_2$ (in) ** | k (in/s) | k (ft/d) *** |
| | | | | | | | | | | |
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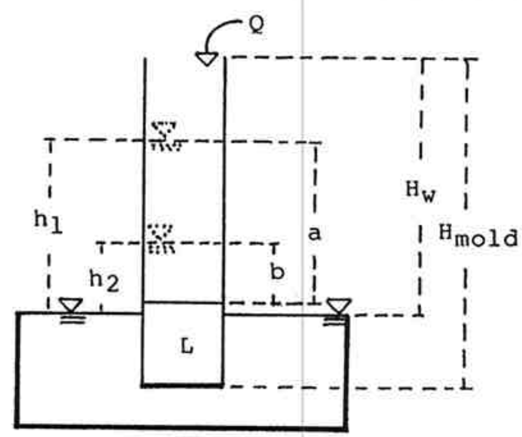
* $h_1 = a + L - H_{mold} + H_w$
** $h_2 = b + L - H_{mold} + H_w$
*** k (ft/d) = 7200 k (in/s)




$$k = \frac{L}{T_{ave}} \ln \frac{(h_1)}{(h_2)}$$

**Calculation**

Constant head permeability: The permeability can be determined using the following equation:

$$k=\frac{QL}{Ah} * 7200 \tag{B-1}$$

Where: $k$ = Permeability (ft/day),
$Q$ = Flow ($in^3$/sec),
$L$ = Sample height (in),
$A$ = Sample area ($in^2$), and
$h$ = Constant head (in).

Falling head permeability: The permeability can be determined using the following equation:

$$k=\frac{L}{T}\ln(\frac{h_1}{h_2}) * 7200 \tag{B-2}$$

Where: $k$ = Permeability (ft/day),
$L$ = Sample height (in),
$T$ = Time for water falling through two predetermined levels (sec),
$h_1$= First predetermined water level (in), and
$h_2$= Second predetermined water level (in).

# APPENDIX C

# LABORATORY PERMEABILITY TEST RESULTS FOR UNTREATED AGGREGATE MATERIALS

# LABORATORY PERMEABILITY TEST RESULTS

| | CONSTANT HEAD PERMEABILITY | | | | | FALLING HEAD PERMEABILITY | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample I.D. | Sample Height | Flow Volume | Flow Time | Head h | Permeability (Ft/Day) | Flow Time | Head h1 | Head h2 | Permeability (Ft/Day) |
| A-1 | 6.250 | 500 | 11.7 | 1.500 | 1,624 | 28.4 | 27 | 12 | 1,285 |
| | 6.250 | 500 | 13.2 | 2.375 | 1,249 | 28.8 | 27 | 12 | 1,267 |
| | 6.250 | 500 | 14.0 | 2.250 | 1,201 | 29.4 | 27 | 12 | 1,241 |
| A-2 | 6.189 | 500 | 13.2 | 2.375 | 1,249 | 27.9 | 27 | 12 | 1,295 |
| | 6.189 | 500 | 13.2 | 1.630 | 1,409 | 28.5 | 27 | 12 | 1,268 |
| | 6.189 | 500 | 13.0 | 2.125 | 1,318 | 28.7 | 27 | 12 | 1,259 |
| A-3 | 6.063 | 500 | 18.0 | 2.813 | 856 | 46.9 | 27 | 12 | 755 |
| | 6.063 | 500 | 21.7 | 2.563 | 737 | 48.9 | 27 | 12 | 724 |
| | 6.063 | 500 | 21.5 | 2.750 | 724 | 56.3 | 27 | 12 | 629 |
| A-4 | 6.000 | 500 | 21.3 | 2.813 | 723 | 38.9 | 27 | 12 | 901 |
| | 6.000 | 500 | 28.5 | 2.625 | 556 | 40.0 | 27 | 12 | 876 |
| | 6.000 | 500 | 24.0 | 2.938 | 630 | 40.7 | 27 | 12 | 861 |
| A-5 | 6.125 | 500 | 20.2 | 2.719 | 775 | 34.1 | 27 | 12 | 1,049 |
| | 6.125 | 500 | 20.2 | 2.750 | 771 | 34.6 | 27 | 12 | 1,034 |
| | 6.125 | 500 | 21.0 | 2.750 | 742 | 35.1 | 27 | 12 | 1,019 |
| | **Average:** | | | | **971** | | | | **1,031** |
| | **Standard Deviation:** | | | | **322** | | | | **223** |
| B-1 | 6.125 | 500 | 17.2 | 2.438 | 949 | 37.9 | 27 | 12 | 944 |
| | 6.125 | 500 | 16.4 | 2.375 | 1,004 | 38.6 | 27 | 12 | 926 |
| | 6.125 | 500 | 18.5 | 2.500 | 874 | 39.2 | 27 | 12 | 912 |
| B-2 | 6.000 | 500 | 20.6 | 2.500 | 783 | 51.4 | 27 | 12 | 682 |
| | 6.000 | 500 | 24.9 | 2.813 | 618 | 53.8 | 27 | 12 | 651 |
| | 6.000 | 500 | 28.2 | 2.875 | 541 | 54.7 | 27 | 12 | 640 |
| B-3 | 6.250 | 500 | 17.7 | 2.500 | 914 | 41.2 | 27 | 12 | 886 |
| | 6.250 | 500 | 17.8 | 2.500 | 909 | 42.6 | 27 | 12 | 857 |
| | 6.250 | 500 | 19.1 | 2.875 | 803 | 44.2 | 27 | 12 | 826 |
| B-4 | 6.000 | 500 | 20.4 | 2.563 | 783 | 56.9 | 27 | 12 | 616 |
| | 6.000 | 500 | 22.0 | 2.938 | 687 | 60.4 | 27 | 12 | 580 |
| | 6.000 | 500 | 26.9 | 2.625 | 589 | 63.1 | 27 | 12 | 555 |
| B-5 | 5.938 | 500 | 19.8 | 2.875 | 769 | 53.6 | 27 | 12 | 647 |
| | 5.938 | 500 | 20.6 | 2.938 | 733 | 59.5 | 27 | 12 | 583 |
| | 5.938 | 500 | 25.3 | 2.906 | 599 | 64.3 | 27 | 12 | 539 |
| | **Average:** | | | | **770** | | | | **723** |
| | **Standard Deviation:** | | | | **138** | | | | **145** |

Note: Sample height in inches; flow volume in ml; flow time in seconds; water head in inches.

## LABORATORY PERMEABILITY TEST RESULTS

| Sample I.D. | CONSTANT HEAD PERMEABILITY: Sample Height | Flow Volume | Flow Time | Head h | Permeability (Ft/Day) | FALLING HEAD PERMEABILITY: Flow Time | Head h1 | Head h2 | Permeability (Ft/Day) |
|---|---|---|---|---|---|---|---|---|---|
| C-1 | 6.000 | 500 | 48.5 | 2.438 | 336 | 76.0 | 27 | 12 | 461 |
| | 6.000 | 200 | 28.7 | 2.438 | 227 | 78.6 | 27 | 12 | 446 |
| | 6.000 | 250 | 36.9 | 2.875 | 207 | 79.5 | 27 | 12 | 441 |
| C-2 | 5.813 | 300 | 48.1 | 3.000 | 186 | 128.7 | 27 | 12 | 264 |
| | 5.813 | 300 | 49.5 | 2.938 | 182 | 135.5 | 27 | 12 | 250 |
| | 5.813 | 300 | 57.7 | 2.625 | 164 | 141.8 | 27 | 12 | 239 |
| C-3 | 5.813 | 300 | 42.6 | 2.250 | 236 | 118.9 | 27 | 12 | 285 |
| | 5.813 | 300 | 44.3 | 2.250 | 227 | 123.1 | 27 | 12 | 276 |
| | 5.813 | 300 | 45.8 | 2.500 | 211 | 126.9 | 27 | 12 | 267 |
| C-4 | 5.813 | 300 | 33.4 | 2.625 | 284 | 92.8 | 27 | 12 | 366 |
| | 5.813 | 300 | 36.8 | 2.688 | 255 | 96.0 | 27 | 12 | 354 |
| | 5.813 | 300 | 38.0 | 2.625 | 249 | 97.4 | 27 | 12 | 348 |
| C-5 | 5.875 | 300 | 44.4 | 2.818 | 207 | 131.1 | 27 | 12 | 262 |
| | 5.875 | 300 | 45.8 | 2.625 | 207 | 137.9 | 27 | 12 | 249 |
| | 5.875 | 300 | 46.1 | 2.625 | 206 | 144.2 | 27 | 12 | 238 |
| | **Average:** | | | | **226** | | | | **316** |
| | **Standard deviation:** | | | | **42** | | | | **77** |
| D-1 | 6.000 | 500 | 5.3 | 2.438 | 3,074 | 14.0 | 27 | 12 | 2,502 |
| | 6.000 | 500 | 6.1 | 2.500 | 2,645 | 14.5 | 27 | 12 | 2,416 |
| | 6.000 | 500 | 6.9 | 2.063 | 2,507 | 14.3 | 27 | 12 | 2,450 |
| D-2 | 5.875 | 10000 | 98.1 | 2.563 | 3,252 | 12.4 | 27 | 12 | 2,766 |
| | 5.875 | 10000 | 132.0 | 2.375 | 2,490 | 12.7 | 27 | 12 | 2,701 |
| | 5.875 | 10000 | 131.7 | 2.625 | 2,399 | 13.1 | 27 | 12 | 2,618 |
| D-3 | 5.875 | 10000 | 97.8 | 2.063 | 3,537 | 12.5 | 27 | 12 | 2,744 |
| | 5.875 | 10000 | 104.7 | 2.750 | 2,961 | 12.7 | 27 | 12 | 2,701 |
| | 5.875 | 10000 | 119.8 | 2.375 | 2,743 | 13.1 | 27 | 12 | 2,618 |
| D-4 | 6.000 | 10000 | 90.5 | 2.563 | 3,532 | 12.2 | 27 | 12 | 2,871 |
| | 6.000 | 10000 | 101.2 | 2.250 | 3,317 | 12.8 | 27 | 12 | 2,737 |
| | 6.000 | 10000 | 107.6 | 2.438 | 3,028 | 12.2 | 27 | 12 | 2,871 |
| D-5 | 6.000 | 10000 | 99.9 | 2.313 | 3,326 | 12.1 | 27 | 12 | 2,895 |
| | 6.000 | 10000 | 98.0 | 2.313 | 3,391 | 12.7 | 27 | 12 | 2,758 |
| | 6.000 | 10000 | 116.5 | 1.875 | 3,065 | 12.7 | 27 | 12 | 2,758 |
| | **Average:** | | | | **3,018** | | | | **2,694** |
| | **Standard Deviation:** | | | | **370** | | | | **143** |

Note: Sample height in inches; flow volume in ml; flow time in seconds; water head in inches.

# LABORATORY PERMEABILITY TEST RESULTS

| Sample I.D. | Sample Height | Flow Volume | Flow Time | Head h | Permeability (Ft/Day) | Flow Time | Head h1 | Head h2 | Permeability (Ft/Day) |
|---|---|---|---|---|---|---|---|---|---|
| | **CONSTANT HEAD PERMEABILITY** | | | | | **FALLING HEAD PERMEABILITY** | | | |
| E-1 | 6.000 | 500 | 7.6 | 2.190 | 2,230 | 19.7 | 27 | 12 | 1,778 |
| | 6.000 | 500 | 8.6 | 2.310 | 1,933 | 20.5 | 27 | 12 | 1,709 |
| | 6.000 | 500 | 8.3 | 2.125 | 2,063 | 21.4 | 27 | 12 | 1,637 |
| E-2 | 6.125 | 500 | 7.2 | 2.250 | 2,333 | 16.2 | 27 | 12 | 2,208 |
| | 6.125 | 500 | 7.5 | 2.313 | 2,218 | 17.9 | 27 | 12 | 1,998 |
| | 6.125 | 500 | 7.3 | 2.000 | 2,395 | 19.2 | 27 | 12 | 1,863 |
| E-3 | 6.188 | 500 | 5.9 | 2.000 | 2,963 | 15.9 | 27 | 12 | 2,272 |
| | 6.188 | 500 | 6.1 | 2.188 | 2,781 | 17.7 | 27 | 12 | 2,041 |
| | 6.188 | 500 | 5.8 | 2.375 | 2,842 | 18.3 | 27 | 12 | 1,974 |
| E-4 | 6.000 | 500 | 7.5 | 2.125 | 2,283 | 18.2 | 27 | 12 | 1,925 |
| | 6.000 | 500 | 8.8 | 2.250 | 1,907 | 18.9 | 27 | 12 | 1,854 |
| | 6.000 | 500 | 9.0 | 2.188 | 1,883 | 19.1 | 27 | 12 | 1,834 |
| E-5 | 6.000 | 500 | 6.6 | 2.313 | 2,518 | 15.9 | 27 | 12 | 2,203 |
| | 6.000 | 500 | 6.5 | 2.000 | 2,689 | 17.2 | 27 | 12 | 2,037 |
| | 6.000 | 500 | 6.2 | 2.500 | 2,603 | 16.7 | 27 | 12 | 2,098 |
| | **Average:** | | | | **2,376** | | | | **1,962** |
| | **Standard Deviation:** | | | | **338** | | | | **181** |
| F-1 | 6.000 | 10000 | 135.7 | 2.125 | 2.524 | 18.4 | 27 | 12 | 1,904 |
| | 6.000 | 500 | 6.9 | 2.125 | 2,482 | 19.3 | 27 | 12 | 1,815 |
| | 6.000 | 500 | 6.2 | 2.500 | 2,603 | 19.9 | 27 | 12 | 1,760 |
| F-2 | 5.750 | 500 | 7.5 | 2.380 | 2,186 | 17.9 | 27 | 12 | 1,876 |
| | 5.750 | 500 | 7.9 | 2.630 | 1,994 | 21.0 | 27 | 12 | 1,599 |
| | 5.750 | 500 | 8.5 | 2.380 | 1,929 | 22.1 | 27 | 12 | 1,519 |
| F-3 | 5.880 | 500 | 6.2 | 2.130 | 2,759 | 16.4 | 27 | 12 | 2,093 |
| | 5.880 | 500 | 5.8 | 2.190 | 2,920 | 18.5 | 27 | 12 | 1,856 |
| | 5.880 | 500 | 5.8 | 2.880 | 2,622 | 19.2 | 27 | 12 | 1,788 |
| F-4 | 5.880 | 500 | 5.8 | 2.190 | 2,920 | 16.3 | 27 | 12 | 2,106 |
| | 5.880 | 500 | 5.7 | 2.630 | 2,770 | 17.7 | 27 | 12 | 1,940 |
| | 5.880 | 500 | 6.2 | 2.560 | 2,574 | 18.9 | 27 | 12 | 1,816 |
| F-5 | 5.810 | 500 | 6.2 | 2.310 | 2,677 | 15.8 | 27 | 12 | 2,147 |
| | 5.810 | 500 | 7.2 | 2.440 | 2,257 | 17.2 | 27 | 12 | 1,972 |
| | 5.810 | 500 | 7.3 | 2.750 | 2,121 | 17.4 | 27 | 12 | 1,950 |
| | **Average:** | | | | **2,489** | | | | **1,876** |
| | **Standard deviation:** | | | | **309** | | | | **169** |

Note: Sample height in inches; flow volume in ml; flow time in seconds; water head in inches.

# LABORATORY PERMEABILITY TEST RESULTS

| | CONSTANT HEAD PERMEABILITY | | | | | FALLING HEAD PERMEABILITY | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample I.D. | Sample Height | Flow Volume | Flow Time | Head h | Permeability (Ft/Day) | Flow Time | Head h1 | Head h2 | Permeability (Ft/Day) |
| G-1 | 5.810 | 500 | 26.6 | 2.250 | 630 | 182.0 | 27 | 12 | 186 |
| | 5.810 | 500 | 22.0 | 2.190 | 769 | 204.0 | 27 | 12 | 166 |
| | 5.810 | 500 | 22.2 | 2.250 | 755 | 193.9 | 27 | 12 | 175 |
| G-2 | 5.938 | 500 | 37.3 | 2.375 | 441 | 234.9 | 27 | 12 | 148 |
| | 5.938 | 500 | 48.5 | 2.438 | 336 | 276.6 | 27 | 12 | 125 |
| | 5.938 | 500 | 48.7 | 2.500 | 331 | 351.4 | 27 | 12 | 99 |
| G-3 | 6.000 | 500 | 33.0 | 2.438 | 494 | 257.8 | 27 | 12 | 136 |
| | 6.000 | 500 | 33.0 | 2.250 | 509 | 252.0 | 27 | 12 | 139 |
| | 6.000 | 500 | 33.0 | 2.250 | 509 | 148.5 | 27 | 12 | 236 |
| G-4 | 5.875 | 500 | 45.6 | 2.375 | 360 | 235.2 | 27 | 12 | 146 |
| | 5.875 | 500 | 58.4 | 2.813 | 263 | 194.1 | 27 | 12 | 177 |
| | 5.875 | 500 | 59.3 | 2.750 | 261 | 226.3 | 27 | 12 | 152 |
| G-5 | 5.875 | 500 | 31.9 | 2.500 | 505 | 242.3 | 27 | 12 | 142 |
| | 5.875 | 500 | 33.0 | 2.625 | 479 | 250.2 | 27 | 12 | 137 |
| | 5.875 | 500 | 33.2 | 2.563 | 481 | 259.5 | 27 | 12 | 132 |
| | **Average:** | | | | **475** | | | | **153** |
| | **Standard Deviation:** | | | | **150** | | | | **31** |
| H-1 | 5.813 | 53 | 35.6 | 2.375 | 49 | 555.2 | 27 | 20 | 23 |
| | 5.813 | 52 | 45.5 | 2.563 | 36 | 626.5 | 27 | 20 | 20 |
| | 5.813 | 53 | 51.2 | 2.438 | 34 | 661.9 | 27 | 20 | 19 |
| H-2 | 5.938 | 100 | 31.1 | 2.375 | 106 | 316.7 | 27 | 12 | 109 |
| | 5.938 | 100 | 32.6 | 2.313 | 102 | 370.5 | 27 | 12 | 94 |
| | 5.938 | 100 | 33.2 | 2.438 | 98 | 357.5 | 27 | 12 | 97 |
| H-3 | 5.813 | 100 | 19.0 | 2.438 | 171 | 331.9 | 27 | 12 | 102 |
| | 5.813 | 100 | 19.8 | 2.313 | 168 | 352.8 | 27 | 12 | 96 |
| | 5.813 | 100 | 19.9 | 2.250 | 168 | 451.0 | 27 | 12 | 75 |
| H-4 | 6.063 | 100 | 14.7 | 2.438 | 222 | 374.7 | 27 | 12 | 94 |
| | 6.063 | 100 | 13.5 | 2.313 | 246 | 343.3 | 27 | 12 | 103 |
| | 6.063 | 100 | 15.8 | 2.250 | 213 | 369.8 | 27 | 12 | 96 |
| H-5 | 5.875 | 100 | 19.5 | 2.500 | 165 | 459.9 | 27 | 12 | 75 |
| | 5.875 | 100 | 20.0 | 2.250 | 168 | 487.3 | 27 | 12 | 70 |
| | 5.875 | 100 | 21.0 | 2.438 | 155 | 517.8 | 27 | 12 | 66 |
| | **Average:** | | | | **140** | | | | **76** |
| | **Standard Deviation:** | | | | **64** | | | | **30** |

Note: Sample height in inches; flow volume in ml; flow time in seconds; water head in inches.

# APPENDIX D

# LABORATORY RESILIENT MODULUS TEST RESULTS FOR UNTREATED AGGREGATE MATERIALS

## LABORATORY RESILIENT MODULUS TEST RESULTS FOR UNTREATED AGGREGATE MATERIALS

**(88% Fractured Faces)**

| Sample I.D. | $k_1$ | $k_2$ | Dry Density (pcf) | $W/C_I$(%) | $W/C_F$(%) |
|---|---|---|---|---|---|
| A-1 | 3,031 | 0.579 | 109.3 | 4.0 | 3.4 |
| A-2 | 2,421 | 0.601 | 108.9 | 4.0 | 3.3 |
| A-3 | 2,517 | 0.567 | 106.5 | 4.0 | 3.4 |
| A-4 | 3,003 | 0.542 | 108.2 | 4.0 | 3.4 |
| A-5 | 1,821 | 0.689 | 105.3 | 4.0 | 3.3 |
| B-1 | 2,117 | 0.615 | 104.0 | 4.0 | 3.8 |
| B-2 | 1,783 | 0.648 | 107.3 | 4.0 | 3.9 |
| B-3 | 1,934 | 0.619 | 102.1 | 4.0 | 4.0 |
| B-4 | 1,766 | 0.612 | 100.7 | 4.0 | 3.9 |
| B-5 | 2,153 | 0.602 | 106.4 | 4.0 | 3.9 |
| C-1 | 2,559 | 0.550 | 105.5 | 7.5 | 4.8 |
| C-2 | 1,412 | 0.697 | 108.5 | 7.5 | 2.3 |
| C-3 | 1,636 | 0.653 | 106.4 | 7.5 | 6.8 |
| C-4 | 1,942 | 0.593 | 97.4 | 7.5 | 4.8 |
| C-5 | 1,481 | 0.606 | 95.2 | 7.5 | 4.6 |
| D-1 | 4,454 | 0.491 | 104.2 | 5.0 | 3.0 |
| D-2 | 2,336 | 0.678 | 104.5 | 5.0 | 3.3 |
| D-3 | 3,420 | 0.572 | 106.9 | 5.0 | 2.9 |
| D-4 | 3,032 | 0.569 | 106.6 | 5.0 | 4.8 |
| D-5 | 3,077 | 0.553 | 105.0 | 5.0 | 2.9 |
| H-1 | 4,204 | 0.524 | 120.4 | 5.4 | 5.2 |
| H-2 | 3,360 | 0.562 | 119.3 | 6.0 | 4.0 |
| H-3 | 4,534 | 0.528 | 120.3 | 5.6 | 4.0 |
| H-4 | 4,767 | 0.473 | 120.7 | 5.1 | 4.7 |
| H-5 | 4,118 | 0.525 | 120.3 | 5.0 | 4.0 |

$W/C_I$ = Initial Water Content

$W/C_F$ = Final Water Content

## LABORATORY RESILIENT MODULUS TEST RESULTS FOR UNTREATED AGGREGATE MATERIALS

**(100% Fractured Faces)**

| Sample I.D. | $k_1$ | $k_2$ | Dry Density (Pcf) | $W/C_I$(%) | $W/C_F$(%) |
|---|---|---|---|---|---|
| E-1 | 4,985 | 0.608 | 122.0 | - | 2.5 |
| E-2 | 2,199 | 0.658 | 117.6 | 4.0 | 3.0 |
| E-3 | 6,602 | 0.460 | 118.6 | 3.5 | 2.8 |
| E-4 | 4,149 | 0.561 | 118.0 | 3.4 | 3.4 |
| E-5 | 3,773 | 0.572 | - | 3.0 | - |
| F-1 | 2,291 | 0.627 | 115.9 | 3.0 | - |
| F-2 | 3,855 | 0.518 | 116.9 | 2.9 | 2.0 |
| F-3 | 3,047 | 0.606 | 115.9 | 3.0 | 3.0 |
| F-4 | 6,028 | 0.489 | 116.9 | 2.9 | - |
| F-5 | 3,143 | 0.603 | 115.9 | 4.0 | 3.0 |
| G-1 | 4,035 | 0.520 | 124.1 | 2.9 | 2.9 |
| G-2 | 4,550 | 0.468 | 123.7 | 3.2 | 3.0 |
| G-3 | 4,427 | 0.521 | 124.7 | 3.0 | 3.0 |
| G-4 | 4,828 | 0.486 | 124.2 | 3.0 | 3.0 |
| G-5 | 3,970 | 0.561 | 123.6 | 3.0 | - |

$W/C_I$ = Initial Water Content

$W/C_F$ = Final Water Content

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation A – Lab Number 91-00859
March 1991

## Sample Preparation Data

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| 1 | 108.2 | 4.0 | 6 x 12 |
| 2 | 108.9 | 4.0 | 6 x 12 |
| 3 | 106.5 | 4.0 | 6 x 12 |
| 4 | 107.7 | 4.0 | 6 x 12 |
| 5 | 105.0 | 4.0 | 6 x 12 |
| Average | 107.3 | | |
| Std. Dev. | 1.5 | | |
| Coeff. Var. | 1.4% | | |

## Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 10,244 | 9 | 9,279 | 8 | 8,538 | 9 | 10,043 | 9 | 7,730 |
| 12 | 9,803 | 12 | 9,797 | 12 | 9,763 | 12 | 10,918 | 12 | 9,109 |
| 16 | 14,344 | 16 | 11,616 | 16 | 11,451 | 16 | 12,346 | 17 | 11,945 |
| 20 | 16,454 | 20 | 13,504 | 20 | 13,398 | 20 | 14,507 | 20 | 14,085 |
| 24 | 19,517 | 24 | 15,571 | 24 | 14,900 | 24 | 15,898 | 24 | 16,498 |
| 36 | 25,307 | 27 | 20,000 | 36 | 19,136 | 36 | 21,394 | 36 | 22,490 |
| 56 | 35,210 | 60 | 30,104 | 60 | 28,174 | 60 | 31,446 | 61 | 32,636 |
| 5 | 9,921 | 5 | 7,406 | 6 | 7,431 | 6 | 8,947 | 6 | 7,050 |

## K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.4816 | 3.3839 | 3.4008 | 3.4776 | 3.2604 | 3.4017 |
| Log Std Err of Mr Est | 0.0696 | 0.0452 | 0.0311 | 0.0426 | 0.0386 | 0.0565 |
| R Squared | 0.9007 | 0.9550 | 0.9773 | 0.9531 | 0.9761 | 0.9174 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.5789 | 0.6012 | 0.5672 | 0.5423 | 0.6890 | 0.5951 |
| Log Std Err of K2 | 0.0785 | 0.0533 | 0.0353 | 0.0491 | 0.0440 | 0.0290 |
| K1 | 3,031 | 2,421 | 2,517 | 3,003 | 1,821 | 2,521 |
| K2 | 0.579 | 0.601 | 0.567 | 0.542 | 0.689 | 0.595 |

**Resilient Modulus Test Results – AASHTO T274**
**Permeable Base Gradation B – Lab Number 91-00860**
**March 1991**

## Sample Preparation Data

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| 1 | 107.3 | 4.0 | 6 x 12 |
| 2 | 103.0 | 4.0 | 6 x 12 |
| 3 | 102.1 | 4.0 | 6 x 12 |
| 4 | 99.9 | 4.0 | 6 x 12 |
| 5 | 104.9 | 4.0 | 6 x 12 |
| Average | 103.4 | | |
| Std. Dev. | 2.8 | | |
| Coeff. Var. | 2.7% | | |

## Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 8,070 | 9 | 7,023 | 9 | 7,499 | 9 | 6,695 | 9 | 8,035 |
| 13 | 9,564 | 12 | 8,574 | 12 | 9,217 | 13 | 7,807 | 13 | 9,670 |
| 16 | 10,622 | 16 | 10,914 | 17 | 10,620 | 16 | 8,975 | 16 | 10,914 |
| 20 | 12,426 | 21 | 12,389 | 21 | 12,066 | 20 | 10,661 | 20 | 12,391 |
| 24 | 15,111 | 24 | 13,300 | 24 | 13,246 | 25 | 12,421 | 24 | 14,302 |
| 37 | 20,375 | 36 | 18,757 | 37 | 18,160 | 36 | 16,365 | 36 | 18,965 |
| 61 | 28,251 | 61 | 27,121 | 61 | 25,950 | 61 | 23,354 | 60 | 27,471 |
| 6 | 6,856 | 6 | 6,034 | 6 | 5,834 | 6 | 5,570 | 6 | 6,506 |

## K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.3257 | 3.2512 | 3.2864 | 3.2469 | 3.3331 | 3.2885 |
| Log Std Err of Mr Est | 0.0349 | 0.0257 | 0.0173 | 0.0298 | 0.0259 | 0.0383 |
| R Squared | 0.9757 | 0.9880 | 0.9940 | 0.9821 | 0.9860 | 0.9640 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.6145 | 0.6481 | 0.6189 | 0.6124 | 0.6021 | 0.6193 |
| Log Std Err of K2 | 0.0396 | 0.0292 | 0.0197 | 0.0338 | 0.0293 | 0.0194 |
| K1 | 2,117 | 1,783 | 1,934 | 1,766 | 2,153 | 1,943 |
| K2 | 0.615 | 0.648 | 0.619 | 0.612 | 0.602 | 0.619 |

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation C – Lab Number 91-00861
March 1991

## Sample Preparation Data

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| 1 | 103.0 | 7.5 | 6 x 12 |
| 2 | 105.2 | 7.5 | 6 x 12 |
| 3 | 102.2 | 7.5 | 6 x 12 |
| 4 | 97.1 | 7.5 | 6 x 12 |
| 5 | 93.8 | 7.5 | 6 x 12 |
| 6 | 112.7 | 7.5 | 4 x 8 |
| Average of 6x12 | 100.3 | | |
| Std. Dev. of 6x12 | 4.7 | | |
| Coeff. Var. of 6x12 | 4.7% | | |

## Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 10,098 | 8 | 7,426 | 9 | 6,717 | 9 | 6,586 | 8 | 5,214 | 9 | 12,646 |
| 12 | 9,157 | 12 | 8,285 | 12 | 7,991 | 12 | 7,925 | 12 | 6,182 | 13 | 15,954 |
| 16 | 10,864 | 16 | 9,131 | 16 | 9,152 | 16 | 9,088 | 16 | 7,138 | 17 | 18,967 |
| 20 | 12,156 | 21 | 12,883 | 21 | 11,098 | 21 | 10,811 | 20 | 8,898 | 21 | 20,392 |
| 24 | 14,134 | 24 | 11,091 | 25 | 12,529 | 24 | 11,708 | 24 | 10,416 | 24 | 22,873 |
| 36 | 18,889 | 37 | 17,819 | 36 | 17,466 | 36 | 15,570 | 36 | 13,312 | 36 | 31,230 |
| 62 | 27,120 | 60 | 25,538 | 60 | 26,729 | 61 | 27,775 | 61 | 19,442 | 60 | 44,713 |
| 5 | 6,333 | 9 | 5,164 | 6 | 5,758 | 6 | 6,940 | 6 | 4,938 | 6 | 10,162 |

## K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | 6 | Samples 1-5 |
|---|---|---|---|---|---|---|---|
| Log K1 | 3.4081 | 3.1500 | 3.2139 | 3.2883 | 3.1707 | 3.4946 | 3.2519 |
| Log Std Err of Mr Est | 0.0451 | 0.0626 | 0.0405 | 0.0701 | 0.0439 | 0.0165 | 0.0745 |
| R Squared | 0.9541 | 0.9309 | 0.9712 | 0.9022 | 0.9616 | 0.9945 | 0.8733 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.5499 | 0.6967 | 0.6529 | 0.5927 | 0.6061 | 0.6377 | 0.6154 |
| Log Std Err of K2 | 0.0492 | 0.0775 | 0.0459 | 0.0796 | 0.0494 | 0.0193 | 0.0380 |
| K1 | 2,559 | 1,412 | 1,636 | 1,942 | 1,481 | 3,123 | 1,786 |
| K2 | 0.550 | 0.697 | 0.653 | 0.593 | 0.606 | 0.638 | 0.615 |

**Resilient Modulus Test Results – AASHTO T274**
**Permeable Base Gradation D – Lab Number 91-00862**
**March 1991**

Sample Preparation Data

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| 1 | 103.7 | 5.0 | 6 x 12 |
| 2 | 105.1 | 4.0 | 6 x 12 |
| 3 | 106.8 | 5.0 | 6 x 12 |
| 4 | 105.9 | 5.0 | 6 x 12 |
| 5 | 104.7 | 5.0 | 6 x 12 |
| Average | 105.2 | | |
| Std. Dev. | 1.2 | | |
| Coeff. Var. | 1.1% | | |

**Resilient Modulus Test Data**

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 10 | 13,139 | 10 | 11,843 | 9 | 12,476 | 9 | 11,044 | 9 | 10,382 |
| 13 | 16,975 | 13 | 13,796 | 13 | 14,467 | 12 | 12,392 | 13 | 12,605 |
| 17 | 18,027 | 17 | 15,064 | 17 | 16,476 | 17 | 13,911 | 17 | 14,099 |
| 21 | 18,537 | 21 | 17,127 | 20 | 18,258 | 20 | 15,645 | 20 | 15,095 |
| 25 | 19,869 | 25 | 19,739 | 24 | 19,590 | 25 | 18,020 | 25 | 17,477 |
| 36 | 24,879 | 28 | 25,972 | 36 | 26,992 | 36 | 23,932 | 36 | 22,036 |
| 61 | 36,723 | 61 | 36,242 | 61 | 38,657 | 61 | 34,055 | 61 | 32,327 |
| 6 | 10,889 | 9 | 8,985 | 6 | 9,426 | 6 | 8,487 | 6 | 8,301 |

K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.6488 | 3.3685 | 3.5340 | 3.4817 | 3.4882 | 3.5106 |
| Log Std Err of Mr Est | 0.0300 | 0.0422 | 0.0251 | 0.0292 | 0.0235 | 0.0454 |
| R Squared | 0.9705 | 0.9588 | 0.9853 | 0.9802 | 0.9862 | 0.9369 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.4906 | 0.6783 | 0.5724 | 0.5693 | 0.5530 | 0.5678 |
| Log Std Err of K2 | 0.0349 | 0.0574 | 0.0285 | 0.0330 | 0.0267 | 0.0239 |
| K1 | 4,454 | 2,336 | 3,420 | 3,032 | 3,077 | 3,240 |
| K2 | 0.491 | 0.678 | 0.572 | 0.569 | 0.553 | 0.568 |

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation E – Lab Number 91–05505
December 1991

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| Sample Preparation Data | | | |
| 1 | 122.0 | – | 6 x 12 |
| 2 | 117.6 | 4.0 | 6 x 12 |
| 3 | 118.6 | 4.0 | 6 x 12 |
| 4 | 118.0 | 3.0 | 6 x 12 |
| 5 | 117.6 | 3.0 | 6 x 12 |
| Average | 118.8 | | |
| Std. Dev. | 1.9 | | |
| Coeff. Var. | 1.6% | | |

Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 10 | 22,532 | 9 | 9,001 | 9 | 18,574 | 9 | 14,276 | 9 | 13,900 |
| 12 | 20,931 | 13 | 11,096 | 13 | 20,675 | 13 | 17,368 | 13 | 17,324 |
| 16 | 27,545 | 17 | 14,083 | 17 | 23,460 | 17 | 19,267 | 17 | 16,874 |
| 20 | 30,028 | 21 | 15,602 | 21 | 29,017 | 21 | 23,605 | 21 | 20,253 |
| 25 | 35,176 | 25 | 17,035 | 25 | 31,008 | 25 | 26,337 | 25 | 22,174 |
| 36 | 46,122 | 37 | 23,893 | 37 | 33,119 | 37 | 30,619 | 37 | 29,781 |
| 61 | 60,279 | 61 | 35,273 | 60 | 41,750 | 61 | 40,976 | 61 | 43,166 |
| 6 | 15,375 | 6 | 7,536 | 6 | 14,025 | 6 | 11,055 | 6 | 10,487 |

K1–K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.6977 | 3.3423 | 3.8197 | 3.6179 | 3.5767 | 3.6079 |
| Log Std Err of Mr Est | 0.0232 | 0.0257 | 0.0241 | 0.0146 | 0.0338 | 0.1061 |
| R Squared | 0.9875 | 0.9883 | 0.9789 | 0.9946 | 0.9733 | 0.7421 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.6085 | 0.6580 | 0.4597 | 0.5610 | 0.5724 | 0.5743 |
| Log Std Err of K2 | 0.0280 | 0.0293 | 0.0276 | 0.0168 | 0.0387 | 0.0549 |
| K1 | 4,985 | 2,200 | 6,602 | 4,148 | 3,773 | 4054 |
| K2 | 0.608 | 0.658 | 0.460 | 0.561 | 0.572 | 0.574 |

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation F – Lab Number 91-05506
December 1991

| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
|---|---|---|---|
| 1 | 115.9 | 3.0 | 6 x 12 |
| 2 | 116.9 | 3.0 | 6 x 12 |
| 3 | 115.9 | 3.0 | 6 x 12 |
| 4 | 116.9 | 3.0 | 6 x 12 |
| 5 | 115.9 | 4.0 | 6 x 12 |
| Average | 116.3 | | |
| Std. Dev. | 0.5 | | |
| Coeff. Var. | 0.5% | | |

Sample Preparation Data

Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 9,060 | 8 | 11,970 | 9 | 10,791 | 9 | 16,833 | 9 | 11,771 |
| 12 | 10,689 | 12 | 14,559 | 13 | 13,841 | 13 | 20,483 | 13 | 14,273 |
| 17 | 12,520 | 17 | 15,120 | 17 | 16,376 | 16 | 22,077 | 17 | 16,202 |
| 21 | 15,126 | 20 | 16,126 | 21 | 18,454 | 21 | 26,600 | 21 | 19,050 |
| 25 | 16,823 | 24 | 19,251 | 25 | 20,658 | 25 | 29,436 | 25 | 20,689 |
| 37 | 21,548 | 37 | 26,109 | 37 | 27,285 | 35 | 36,332 | 37 | 27,805 |
| 60 | 31,791 | 60 | 35,570 | 61 | 39,207 | 61 | 44,230 | 61 | 39,846 |
| 6 | 7,136 | 5 | 10,111 | 6 | 9,776 | 6 | 15,081 | 6 | 9,620 |

K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.3600 | 3.5860 | 3.4839 | 3.7802 | 3.4973 | 3.5410 |
| Log Std Err of Mr Est | 0.0204 | 0.0387 | 0.0249 | 0.0211 | 0.0217 | 0.0863 |
| R Squared | 0.9918 | 0.9596 | 0.9869 | 0.9852 | 0.9899 | 0.8147 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.6270 | 0.5184 | 0.6056 | 0.4889 | 0.6026 | 0.5690 |
| Log Std Err of K2 | 0.0232 | 0.0434 | 0.0285 | 0.0244 | 0.0249 | 0.0440 |
| K1 | 2,291 | 3,855 | 3,047 | 6,029 | 3,142 | 3,475 |
| K2 | 0.627 | 0.518 | 0.606 | 0.489 | 0.603 | 0.569 |

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation G – Lab Number 91-05507
December 1991

| Sample Preparation Data | | | |
|---|---|---|---|
| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
| 1 | 124.1 | 3.0 | 6 x 12 |
| 2 | 123.7 | 3.0 | 6 x 12 |
| 3 | 124.7 | 3.0 | 6 x 12 |
| 4 | 124.2 | 3.0 | 6 x 12 |
| 5 | 123.6 | 3.0 | 6 x 12 |
| Average | 124.1 | | |
| Std. Dev. | 0.4 | | |
| Coeff. Var. | 0.4% | | |

Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 12,936 | 9 | 12,504 | 9 | 14,798 | 9 | 14,726 | 9 | 13,027 |
| 13 | 15,387 | 13 | 15,311 | 13 | 17,507 | 13 | 17,407 | 13 | 16,094 |
| 17 | 18,740 | 17 | 14,933 | 17 | 19,776 | 17 | 19,119 | 17 | 18,610 |
| 21 | 17,877 | 21 | 16,904 | 21 | 19,262 | 21 | 19,355 | 21 | 20,638 |
| 25 | 20,404 | 25 | 19,000 | 25 | 21,162 | 25 | 21,453 | 25 | 23,120 |
| 37 | 27,009 | 37 | 25,653 | 37 | 27,682 | 37 | 27,417 | 37 | 29,801 |
| 60 | 34,890 | 61 | 36,254 | 61 | 42,019 | 61 | 38,213 | 61 | 43,324 |
| 6 | 9,942 | 6 | 11,900 | 6 | 10,676 | 6 | 11,015 | 6 | 11,573 |

K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.6058 | 3.6580 | 3.6461 | 3.6838 | 3.5988 | 3.6390 |
| Log Std Err of Mr Est | 0.0245 | 0.0508 | 0.0389 | 0.0270 | 0.0271 | 0.0403 |
| R Squared | 0.9827 | 0.9169 | 0.9587 | 0.9767 | 0.9823 | 0.9423 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.5201 | 0.4696 | 0.5205 | 0.4863 | 0.5606 | 0.5111 |
| Log Std Err of K2 | 0.0282 | 0.0577 | 0.0441 | 0.0307 | 0.0308 | 0.0205 |
| K1 | 4,035 | 4,550 | 4,427 | 4,828 | 3,970 | 4,355 |
| K2 | 0.520 | 0.470 | 0.521 | 0.486 | 0.561 | 0.511 |

Resilient Modulus Test Results – AASHTO T274
Permeable Base Gradation H – Lab Number 91-05508
December 1991

| Sample Preparation Data | | | |
|---|---|---|---|
| Sample No. | Molded Dry Density pcf | Molded Water Content % | Dimensions Dia. x Height inches |
| 1 | 120.4 | 5.0 | 6 x 12 |
| 2 | 119.3 | 6.0 | 6 x 12 |
| 3 | 120.3 | 6.0 | 6 x 12 |
| 4 | 120.7 | 5.0 | 6 x 12 |
| 5 | 120.3 | 5.0 | 6 x 12 |
| Average | 120.2 | | |
| Std. Dev. | 0.5 | | |
| Coeff. Var. | 0.4% | | |

Resilient Modulus Test Data

| 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|
| Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi | Bulk Stress psi | Mr psi |
| 9 | 13,145 | 9 | 12,409 | 9 | 14,183 | 9 | 13,200 | 9 | 13,744 |
| 13 | 15,444 | 13 | 15,015 | 13 | 17,297 | 13 | 15,592 | 13 | 16,727 |
| 17 | 18,771 | 17 | 14,724 | 17 | 19,654 | 17 | 18,284 | 17 | 16,575 |
| 21 | 19,309 | 21 | 17,532 | 21 | 23,146 | 21 | 18,662 | 21 | 19,583 |
| 24 | 21,240 | 25 | 19,319 | 25 | 23,165 | 25 | 19,740 | 25 | 21,004 |
| 37 | 26,888 | 37 | 25,178 | 37 | 30,323 | 28 | 25,334 | 37 | 27,131 |
| 61 | 40,045 | 60 | 36,900 | 60 | 41,121 | 59 | 34,696 | 61 | 38,088 |
| 6 | 11,206 | 6 | 8,812 | 6 | 12,196 | 6 | 11,861 | 6 | 10,143 |

K1-K2 Regression

| | 1 | 2 | 3 | 4 | 5 | All Data |
|---|---|---|---|---|---|---|
| Log K1 | 3.6237 | 3.5263 | 3.6565 | 3.6782 | 3.6147 | 3.6174 |
| Log Std Err of Mr Est | 0.0292 | 0.0355 | 0.0165 | 0.0330 | 0.0281 | 0.0391 |
| R Squared | 0.9764 | 0.9700 | 0.9921 | 0.9588 | 0.9782 | 0.9461 |
| No. of Observations | 8 | 8 | 8 | 8 | 8 | 40 |
| Degrees of Freedom | 6 | 6 | 6 | 6 | 6 | 38 |
| K2 | 0.5235 | 0.5624 | 0.5277 | 0.4731 | 0.5251 | 0.5245 |
| Log Std Err of K2 | 0.0332 | 0.0404 | 0.0192 | 0.0400 | 0.0320 | 0.0202 |
| K1 | 4,204 | 3,359 | 4,534 | 4,767 | 4,118 | 4,144 |
| K2 | 0.523 | 0.562 | 0.528 | 0.473 | 0.525 | 0.525 |