ABSTRACT

The Permeability of Hot Mix Asphalt Concrete with Petroleum Contaminated Soils

by
Kuen-yuan Chuang

It is estimated by the United States Environmental Protection Agency (USEPA) that there are 2 to 3.5 million underground storage tanks (USTs) throughout the nation and about 25% of these tanks are leaking. The leakage of petroleum or other organic material presents serious environmental problem due to the uncontrolled release of petroleum products to ground water. Many new techniques have developed to reuse these petroleum contaminated soils generated from sites containing leaking USTs. One such soil reuse method available since 1985 is the use of petroleum contaminated soils in the production of hot mix asphalt.

The stability, durability, and hydraulic conductivity are three important engineering parameters that need to be considered when using petroleum contaminated soils (PCSs) in hot mix asphalt (HMA). In three separate theses, the stability, durability of asphalt concrete mixed with PCSs and the environmental impacts of the process were investigated. In this thesis, the variation in hydraulic conductivity due to the addition of PCSs in to HMA is investigated.

The hydraulic conductivity of Hot Mix Asphalt pavement affects its performance. However, there are no publications that document the hydraulic conductivity of hot mix asphalt concrete made with or without petroleum contaminated soils. In this thesis, six different hot mix asphalt concrete mixes with petroleum contaminated soils and a control mix were designed and the hydraulic conductivity were measured. The measured hydraulic conductivity values are then correlated to the properties of the matrix in the HMA concrete.

THE PERMEABILITY OF HOT MIX ASPHALT CONCRETE WITH PETROLEUM CONTAMINATED SOILS

by
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The Permeability of Hot Mix Asphalt Concrete with Petroleum Contaminated Soils

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CHAPTER 1

INTRODUCTION

1.1 Background

During 1950s and 1960s, the construction of many gasoline stations, chemical manufacturing and processing facilities led to the installation of millions of Underground Storage Tanks (USTs). Several million USTs in the United States contain petroleum products. Ten of thousands of these USTs, including their piping systems, are currently leaking (Fairweather, V., 1990). Many more are expected to leak in the future. Most states vigorously encourage the removal of all tanks after 25 years of service. It is estimated that on average removal of a leaking UST generates 50 to 80 cubic yards of contaminated soil. These figures are projected to increase over next few years.

The leaking USTs have a detrimental effect on the environment. This problem has become a major environmental issue, and has being addressed by the USEPA act 40 CFR-280 and the May 1990 Amendment that enlists the deadlines and financial responsibilities for owner of USTs.

The Petroleum Contaminated Soils (PCSs) generated from leaking USTs with a total hydrocarbon concentration less than 3% are classified as solid waste but cannot be used as clean fill. However, there is a significant amount of soil being removed from contaminated sites and are disposed in secured landfills. Many disposal/recycling technology have been consider to deal with those soils with each method having several disadvantage points. Land filling is the most common method, but the available sites are becoming limited with the increasing governmental regulations. Thermal methods are too expensive and they cause the air pollution. Biological methods are cheaper but take longer time to process soil. A reuse method with more benefit and less disadvantages, which has been used since 1985, is the addition of the petroleum contaminated soil as a partial substitute for virgin aggregates in the production of asphalt concrete.

This technique is now in the development stage, but is a viable solution to reuse the contaminated soil. The total production of Hot Mix Asphalt (HMA) in the United States is over 500 million tons. In 1988, there was a total of approximately 2.3 million miles of roads that were surfaced with asphalt or concrete. Of the surface roads approximately 96% or 2.2 million miles had asphalt pavements. Industrial waste products have been added up to 10% by weight in to asphalt matrix without hurting the strength and performance of asphalt concrete. Base on the annual production of hot mix asphalt, if as a rule 5% of contaminated soil is added to HMA, then it is estimated to consume 25 million tons of solid waste such as PCSs in highway construction.

When PCSs are added to HMA, the hot mix process will incinerate, dilute and solidify the contaminants. Part of the petroleum is used as d fuel and is burned during the production of asphalt concrete. Thus a majority of the contaminants are eliminated beneficially and are used to reduce the fuel cost. The petroleum contaminated soils are diluted and spreaded after they are mixed with the virgin aggregates to produce the asphalt concrete. Because the asphalt cement acts as a binder virgin aggregates and remaining diluted contaminants are solidified and stabilized in the final asphalt concrete matrix.

1.2 Objectives

Hydraulic conductivity is a measure of ease of the passage of air and water into or through the pavement. While the air void content may be an indication of the ability of a compacted paving mixture to transmit air or water through it, a more important parameter of the matrix is the amount of interconnected voids and their access to the surface. A highly permeable asphalt pavement is low in durability, as it allows water and air to go through it or to get absorbed on the asphalt cement. When the water in the asphalt pavement freezes, the increased volume of ice causes extra stresses on asphalt concrete causing it to crack and disintegrate. The roads in the northern United States are exposed to the nature's strickest temperature change, freeze and thaw. In the winter, roads in this area usually freeze in the night and thaw during the day. The durability test show that the HMA concrete will lose majority of its stability after several cycles of Freeze-Thaw treatment (DuBose 1992). Furthermore, passage of water through the asphalt pavements could remove the fine particles in the sub-grades shortening service life. Furthermore, high air permeability accelerate the oxidation process by exposing asphalt cement to air. Oxidized asphalt is hard and brittle causing cracks during the passage of vehicles. Therefore, imperviousness to air and water is a necessity for durability of asphalt concretes. Therefore, permeability is one of the most important engineering factors in design of hot mix asphalt pavements. However, there is very little research on this topic. In this thesis, hydraulic conductivity of a control mix and a mix containing PCSs are tested and the test results are discussed.

CHAPTER 2

THEORY OF PERMEABILITY

2.1 Introduction

The property of water-bearing formation that relates to its pipeline or conduit function is called hydraulic conductivity, k, and defined as the capacity of a porous medium to transmit water. It is expressed in velocity units, i.e., centimeter per second (L/T). Hydraulic conductivity is governed by the size and shape of the voids, the interconnection between voids, and the physical properties of the permeating fluid. The volume of water passing through an asphalt concrete is restricted when there are limited amount of tubes. Since the physical properties of water very with temperature, the hydraulic conductivity is reported at a particular temperature

For HMA concrete, the asphalt content and amount of air voids may be an indication of the hydraulic conductivity of the concrete. For both soil and HMA concrete, the most significant contributor to the hydraulic conductivity is amount of interconnected voids and their access to the surface.

The hydraulic conductivity of porous medium is determined using two different experimental methods, constant head and falling head. In this research, falling head method is used to determine the hydraulic conductivity of HMA concrete.

2.2 Equations for Falling Head Test

For the permeability tests, Brainard-Kilman pressure and volume control system was used to measure the discharge, Q, and the total hydraulic head, h_1 and h_2. There is a schematic drawing of this falling head equipment shown on Figure 1.

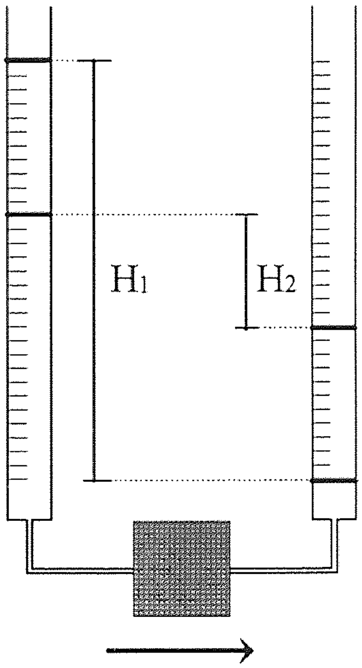


Figure 1 Schematic drawing of falling head permeability test apparatus

The permeant, in this case water, flows from one standpipe through the specimen into the other standpipe. The rate of discharge, *Q*, is calculated by the increase in the water level in the outflow standpipe. However, in B&K measuring panel readings on standpipe are volume readings. Therefore, to obtain the level difference standpipe reading should be multiplied by a factor. The inlet, outlet, and cell pressures are obtained directly from the digital gage. If the first reading is taken at time, $t = 0$ then the elevation difference between two standpipes is noted as H_1 (cm), and the second reading is taken at time $t = t$, then the elevation difference is noted as H_2 (cm) In addition, at any time during the test constant pressures, *Pi* & *Po* (psi), are applied to inlet and outlet standpipes. Then, the total hydraulic head difference, *h* (cm), is defined as equation (2.1).

$$h = H + \frac{(Pi - Po) \times 12^3 \times 2.54}{62.4} \tag{2.1}$$

Henri Darcy (1856), a French engineer, published a simple equation for the discharge velocity of water through saturated soils, which may be expressed as

$$V_{Df} = ki \tag{2.2}$$

where V_{Df} is the Darcy flux velocity (specific discharge), i is the hydraulic gradient.

The hydraulic gradient, i , is defined as the hydraulic head difference, h(cm), divided by the distance, L (cm), along the flow path where the above head difference occurred.

$$i = \frac{h}{L} \tag{2.3}$$

From pipe flow, we know that the rate of discharge, Q (cm^3/sec), is equal to the flow velocity times the cross-sectional area, A (cm^2), or:

$$Q = V_{Df} \times A \tag{2.4}$$

Substituting the equivalent value of V_{Df} form equation above we have:

$$Q = k\frac{h}{L}A \tag{2.5}$$

However, Rate of discharge can also be obtained from the rate of change of levels in standpipes and express as:

$$Q = -\frac{1}{2}a\frac{dh}{dt} \tag{2.6}$$

Where, a (cm^2) is the cross-sectional area of the standpipe. dh is the change in total hydraulic head difference during a time interval dt.

After combining equation 2-5 and 2-6 and rearranging gives the following equation

$$dt = \frac{-aL}{2kA}\left(\frac{dh}{h}\right) \tag{2.7}$$

Integrate the left side with limits of time from zero to t ; and the right side from h_1 to h_2 , gives

$$\int_0^t dt = \frac{-aL}{2kA}\int_{h_1}^{h_2}\left(\frac{1}{h}\right)dh \tag{2.8}$$

Where h_1 is the total hydraulic head difference at time t_1 and h_2 is that at time t_2. We obtain

$$t = \frac{-aL}{2kA}\ln\left(\frac{h_2}{h_1}\right) \tag{2.9}$$

or

$$t = \frac{aL}{2kA}\ln\left(\frac{h_1}{h_2}\right) \tag{2.10}$$

Rearrange the equation above, we get the final equation as:

$$k = \frac{aL}{2At}\ln\left(\frac{h_1}{h_2}\right) \tag{2.11}$$

where:

$$h_1 = H_1 + \frac{(Pi_1 - Po_1)\times 12^3 \times 2.54}{62.4} \tag{2.12}$$

$$h_2 = H_2 + \frac{(Pi_2 - Po_2)\times 12^3 \times 2.54}{62.4} \tag{2.13}$$

Where Pi_1 (psi) is the pressure applied to the inlet side at time equal to zero and Po_1 (psi) is pressure applied to outlet side at the same time. Pi_2 (psi) and Po_2 (psi) each shows the pressure applied to inlet and outlet sides at time equal to t . If applied pressures are constant then $Pi_1 = Pi_2 = Pi$ and $Po_1 = Po_2 = Po$. All the pressure measurement discussed in this chapter are in pound per square inch (psi) and the head, pressure head and elevation head, are in centimeters (cm)

CHAPTER 3

PETROLEUM CONTAMINATED SOIL

3.1 Background

Six contaminated soils, provided by New Jersey Department of Environmental Protection & Energy (NJDEPE) from sites identified as contaminated soils and having less than 1% TPH in each soil were selected for testing and characterizing. The soils were selected in such a manner to cover most of the soil types that occur in nature (gravel, sand, silt and clay, see ASTM D2487-85). The first three soils (PCS#1, PCS#2, and PCS#3) were contaminated with heating oil and the latter three (PCS#4, PCS#5, and PCS#6) were contaminated with gasoline.

3.2 Gradation and Classification

The grain size distribution is a major factor that effects the permeability of a porous medium and hence the performance of HMA concrete. To obtain the relative size's distribution of the different PCSs, the dry sieve method (ASTM D-421) and wet sieve method (ASTM D-422) were performed. The sieve analysis reflects the proportioning of the contaminated soil samples. Hydrometer analysis was performed on the soils which contained clay or silt passing US sieve No.200.

The original form of unified classification system was proposed by Casagrande in 1942 for use in the air field construction under-taken by the Army Crop of Engineers during World War II. In cooperation with the United States Bureau of Reclamation, this system was revised in 1952. At present, the soil classification system (ASTM D-2487) is widely used among engineers. To classify those PCSs, sieve analysis, liquid limit (LL), and plastic limit (PL), tests were also performed. The Plasticity Index (PI) is the difference between the liquid limit and plastic limit of a soil, or

$$PI = LL - PL \tag{3.1}$$

The in situ moisture content of each contaminated soil was measured for reference and for mix design. The grain size distribution of the six petroleum contaminated soils are report on Table 1. The classification and moisture content for these soils is report on Table 2.

Table 1 Grain size distribution of PCSs

	Percent Retained					
Sieve	**PCS #1**	**PCS #2**	**PCS #3**	**PCS #4**	**PCS #5**	**PCS #6**
3/4"	0.0	0.0	0.0	0.0	0.0	2.2
3/8"	0.0	0.0	0.0	0.0	0.0	5.0
US #4	5.0	12.0	0.0	2.0	5.0	5.9
US #10	5.0	7.0	3.0	6.0	10.0	3.0
US #40	52.0	9.0	22.0	42.0	20.0	12.8
US #100	20.0	6.0	54.0	50.0	11.0	58.7
US #200	13.0	3.0	5.0	0.0	9.0	7.3
Finer than #200	5.0	63.0	16.0	0.0	45.0	5.1

Table 2 Classification and moisture content of PCSs (Meegoda et al.,1992)

Contaminated Soils	**Classification**	**Moisture Content**
PCS #1	well graded sand	7.3 %
PCS #2	clayey silt	14.3 %
PCS #3	silty sand	24.7 %
PCS #4	poorly graded sand	14.4 %
PCS #5	silty clay	19.6 %
PCS #6	poorly graded sand with silty sand	10.1 %

3.3 Contamination Level

In New Jersey, The level of contamination equal or higher than 30,000 ppm or 3% will be considered as a hazardous waste. The soils with contamination level lower than this level are classified as the solid waste. For the proper identification of the six petroleum contaminated soils, the contamination level should be determined. The degree of contamination for oil contaminated soil was determined by the soxhlet oil and grease extraction method (USPHS standard method for the analysis of water and waste water). For the gasoline contaminated soils, a similar method, reported by Meegoda, et al.(1989)., was used In this method, gasoline was extracted by carbon disulfide and then injected into the Gas Chromatograph. Using the calibration curves, the gasoline concentrations were determined.

From the test result, the contamination levels of six contaminated soils used in the study ranged from 25 ppm to 6,600 ppm. Contamination levels of all six soils were below 30,000 ppm and hence they were considered as solid wastes. The contamination levels of first three soils, PCS#1, PCS#2, and PCS#3, were 1,100 ppm, 1,200 ppm, and 6,600 ppm respectively. The contamination levels of the remaining three soils, PCS#4, PCS#5, and PCS#6, were 25 ppm, 1500 ppm, and 330 ppm respectively.

Table 3 Contamination analysis of PCSs (Meegoda et al., 1989)

Contaminated Soils	Contaminants	Contamination Levels
PCS #1	Heating Oil	1100 ppm
PCS #2	Heating Oil	1200 ppm
PCS #3	Heating Oil	6600 ppm
PCS #4	Gasoline	25 ppm
PCS #5	Gasoline	1500 ppm
PCS #6	Gasoline	330 ppm

CHAPTER 4

MIXING PETROLEUM CONTAMINATED SOIL IN HOT MIX ASPHALT CONCRETE

4.1 Typical Marshall Mixture Design

The hot mix asphalt (HMA) concrete is construction material which is made of uniformly mixed aggregate, coated with asphalt cement, and compacted to desired density. To obtain sufficient fluidity of asphalt cement for proper mixing and compaction, both aggregates and asphalt cement are heated before mixing, hence the term hot mix asphalt concrete used for this material. The HMA mix design should be developed with several objectives, such as (1) resistance to permanent deformation, (2) fatigue resistance, (3) resistance to low temperature cracking, (4) high durability, (5) resistance to moisture induced damage, (6) high skid resistance, and (7) sufficient workability.

Aggregates and asphalt are combined in a mixing facility in which all the constituent materials are heated, proportioned, and mixed to produce the desired paving mixture. The aggregate in HMA consist of (a) coarse aggregates with sizes ranging from 1.5" to US sieve #4, (b) fine aggregates or sands with sizes passing US sieve #4 and retain on US sieve #200, and (c) mineral filler such as crush stone dust or lime passing US sieve #200. The aggregates are mixed with asphalt cement to obtain HMA concrete. A typical HMA composition consists of 50% coarse aggregate, 40% fine aggregate, 5% mineral filler, and 5% asphalt cement. However, size distribution is perhaps the most important property of an aggregate used in HMA. This effects almost all the important aspects of a HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and resistance to moisture damage. Therefore, aggregate gradation is the most important consideration in asphalt mix design, and the specifications used by most states place limits on the gradation of acceptable aggregate that can be used in HMA. The Mixing and compact temperature are different for each design. Hot mix asphalt paving mixture may produced from a wide range of aggregate combination, each having its own particular characteristics suited for specific design and construction use.

Asphalt concrete is a construction material that must meet those strict requirements. It is a high-quality, carefully controlled hot mixture of asphalt cement and well-graded, high-quality aggregates thoroughly compacted into a uniform dense mass specified as dense-graded paving mix.

4.2 History and Experience of Adding PCSs into HMA

Since 1985, petroleum contaminated soils, one of industrial solid waste, have been used in the production of hot mix asphalt. Typically adding 5-10% of industrial waste products such as recycled asphalt pavements, glass, fly ash, tire rubber, and petroleum contaminated soils (Czarnecki, 1988) are added into hot mix asphalt concrete without sacrificing the strength and performance of HMA concrete. One recently proposed reuse option for PCSs involves the incorporation of PCSs into HMA as a partial substitute for stone aggregates; the mixture is then used for paving. In this process, aggregates mixed with PCSs are heated and dried, then they are mixed thoroughly with hot asphalt cement to form the final product.

In Massachusetts, the Henley-Lundgren Company was allowed to use PCSs as part of their aggregate feed by the Massachusetts Department of Environmental Quality Engineering (Kostecki et al., 1988). PCSs less than 5% by weight of the total feed was incorporated. Even at this small percentage, this plant had the capacity to reuse 8000 tons of PCSs annually. Processing PCSs in HMA plants has several advantages: The aggregate dryer can act as a incinerator to burn some of the petroleum products, the capital investment is in place, and only minor modifications are required, The decontaminated soil can be incorporated into HMA, and small percentages of PCSs in HMA can be economically processed large quantities of PCSs. American Reclamation Corporation in Massachusetts developed a cold mixing process for incorporation of PCSs into asphalt concrete (Neely, 1990). Their tests confirmed that the petroleum contaminant in the soil were combined with the asphalt cement to produce a mixture that will not separate and will not release the petroleum products back into the environment.

A national survey found five states had experience with the reuse of PCSs by adding it in HMA. In Massachusetts, this method is now considered to be the most favored option for disposal of PCSs.

4.3 Grain Size Distribution

The grain size distribution is a major consideration in adding contaminated soils into HMA concrete. It effects almost all the aspects of a HMA, including permeability, stability, durability, workability, etc. Hence, the gradation and classification of both stone aggregates and PCSs are the starting point in determining the applicability of adding PCSs into HMA concrete. A good gradation curve for the design mix should be as smooth as possible, and near the middle of the upper and lower limits of the state specifications. To determine a good design mix, the grain size analysis test must be run for aggregates. Table 2 shows the sieve analysis data for the aggregates and Table 3 shows those for the six PCSs used in this research.

4.4 Properties of Asphalt

Asphalt cement is distilled from the crude petroleum. It is a strong and durable material with excellent adhesive and waterproofing characteristics. The largest use of asphalt cement is in the production of Hot Mix Asphalt (HMA), which is primarily used in the construction of highway or airfield pavement throughout the world.

The process of transformation from plant life to crude oil occurs over millions of years under varied temperature and pressure conditions. Although all kinds of petroleum are basically hydrocarbons, the amount and nature of hydrocarbons vary from crude to crude. Since the asphalt cements are obtained by distillation of petroleum crude, their chemical composition and properties also vary from source to source. The asphalt is classified as AC-2.5, AC-5, AC-10, AC-20, AC-30, or AC-40 base on their viscosity (ASTM D-3381). In this research, the AC-20 asphalt was used to prepare all the testing specimens.

CHAPTER 5

EXPERIMENTAL PROCEDURES TO DETERMINE THE HYDRAULIC CONDUCTIVITY OF HMA WITH PCS

5.1 HMA Specimen with PCS

In this research, the hydraulic conductivity of Hot Mix Asphalt (HMA) concrete was measured using the falling head method. For the preparation of specimens, well-graded aggregates with Petroleum Contaminated Soil (PCS) are heated to 130°C then mixed with asphalt cement heated to 160°C. Three control specimens based on control mix were also prepared and tested. The results of Marshall test showed that the average stability of HMA concrete with PCSs is better than control ones. Therefore, in a similar manner we can compare the hydraulic conductivity of HMA concrete with or without PCSs.

After mixing and compaction, test specimens should have a diameter of 4.0 inches and a height of 6.25 ± 0.2cm. Four height measurements of the specimen should almost the same. For permeability test, three specimens made with same mix were tested at the same time. The procedure of preparation for this hot mix asphalt concrete is described as follows.

5.2 Mixing and Compaction

The procedure of mixing and compaction of hot mix asphalt concrete directly effect the performance and hence the hydraulic conductivity. Therefore, mixing and compaction temperature should be done according to test specifications. The aggregate and PCS are heated and dried in the oven at the temperature between 128°C to 130°C before mixing. The following is the procedure for mixing and compaction.

1. Preparation of the aggregates: Use 1", 1/2", 1/4", 1/8", and US sieve #10 standard sieve to separate each size of aggregates. The grain size range needed are: (a) between

1" and 1/2"; (b) 1/2" and 1/4"; (c) 1/4" and 1/8"; (d) 1/8" and sieve # 10., (e) dust, (f) sand.

2. Weighing of aggregates: Use electronic balance to weight them. The design grain size distribution of aggregate and PCSs are shown on Table 4.
3. Preparation of Petroleum Contaminated Soil (PCS): Use the U.S. standard sieve #10 to separate the soil particles larger than sieve #10 in contaminated soils.
4. Drying and heating the aggregates: Place the aggregates and PCS in metal bucket and place in an oven for 5 to 12 hours. Place the mixing bowl, compacting mold, and trowel also in the oven. Keep the temperature between 128 to 130°C
5. Mixing of aggregates and PCS with asphalt: Remove the metal bucket, with aggregates and PCS in it, and mixing bowl from oven and then pour the hot aggregates and PCS into the mixing bowl. Add the required amount of hot asphalt cement, the asphalt needs to be heated to about 160° C, then mixed for 1.5 minute. The optimum asphalt concentrations for six mixes with PCSs and the control are given in tables
6. Compaction: Place a piece of paper cut to 4" diameter at the bottom of the mold before adding the mixture to the compaction mold. Spade the mixture vigorously with a hot trowel 15 times around the perimeter and 10 times over the interior. Remove the collar and smooth the surface to a slightly rounded shape. Place another piece of paper, that was cut to 4" diameter, on the top of the mixture. Replace the collar, place the mold assembly on the compacting pedestal in the mold holder. Apply 75 blows with the compacting hammer using a free fall of 457 mm (18 in.). Hold the axis of the compacting hammer as nearly perpendicular to the base of the mold assembly as possible during compaction. Remove the base plate and collar, and reverse and reassemble the mold. Apply the same number of compacting blows to the face of the reversed specimen. Remove the specimen from the mold after allowing it to cool down by means of an extrusion jack. Mark the specimen by crayons.

Table 4 Design grain size distribution of aggregate and PCSs (Meegoda et al., 1992)

	Control	PCS #1	PCS #2	PCS #3	PCS #4	PCS #5	PCS #6
1">Size>1/2"	252	276	264	264	252	252	270
1/2">Size>1/4"	288	312	264	264	288	288	300
1/4">Size>1/8"	192	156	156	144	192	144	120
1/8">Size>#10	108	84	96	72	108	72	72
Dust < US #10	180	0	105	216	180	102	258
Sand < US #10	180	0	210	0	0	240	0
PCS < US #10	0	372	105	240	180	102	180

unit: gram

Table 5 Optimum asphalt concentration for the six PCSs and the control (Meegoda et al.,1992)

Type of HMA Concrete	Asphalt Content (%)	Asphalt Weight (gram)
Control	4.75	59.8
Mix with PCS #1	4.50	56.5
Mix with PCS #2	4.50	56.5
Mix with PCS #3	5.00	63.2
Mix with PCS #4	4.25	53.3
Mix with PCS #5	4.50	56.5
Mix with PCS #6	4.50	56.5

5.3 Measurement of Properties of HMA Concrete Specimens and Subsequent Saturation

After testing specimens have been compacted, the dry weight and volume should be measured and the specific gravity, voids in total mix(VTM), volume of voids in mineral aggregate(VMA), and voids filled with asphalt(VFA) should be determined.

The Darcy's law is based on the assumption that medium is saturated. Hence, the hydraulic conductivity of a porous material should be determined only under saturated conditions. In this experiment, a back pressure of 30 psi was applied. Under this pressure, we expect all the specimens to be 100% saturated. However, to accelerate the testing time, we saturated the specimens by moisture conditioning with distilled water at room temperature using vacuum chamber to a degree of saturation of 80% or higher.

5.4 Equipment Setup

This testing equipment includes two portions, (a) chamber cells, (b) control panel. The schematic sketches of these two parts are shown on Fig 1 and Fig 2. Three same chamber cells and HMA specimens are needed for each test. After setting up the specimen inside the cell and adding water, we connect cell to the control panel with special tubes. Make sure all the tubes are properly connected and there are no leaks. Then, the test is started. The procedures for setting up this equipment are shown below.

5.4.1 Chamber Cell

1. Place porous stone on top of the base plate.
2. Place the specimen on top of the porous stone.
3. Place another porous stone on top of the specimen and then place the upper cap on top of that.
4. Check the membrane for leaks by placing air blown membrane inside a water bath.

5. Place the rubber membrane over the specimen, cap, and base plate. Make sure that the membrane completely covers both the cap and base plate.
6. Place O-ring to the base plate and to the upper cap.
7. Position the cylinder of the permeameter cell around the specimen.
8. Place the top plate on the cylinder and fasten the permeameter by tie rods.

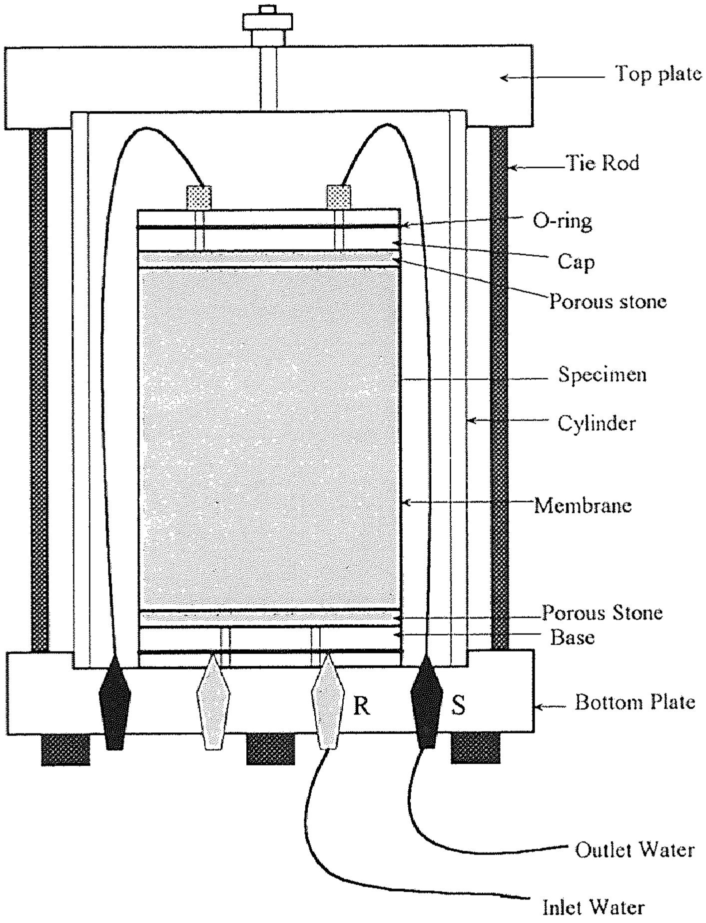


Figure 2 Permeameter chamber cell

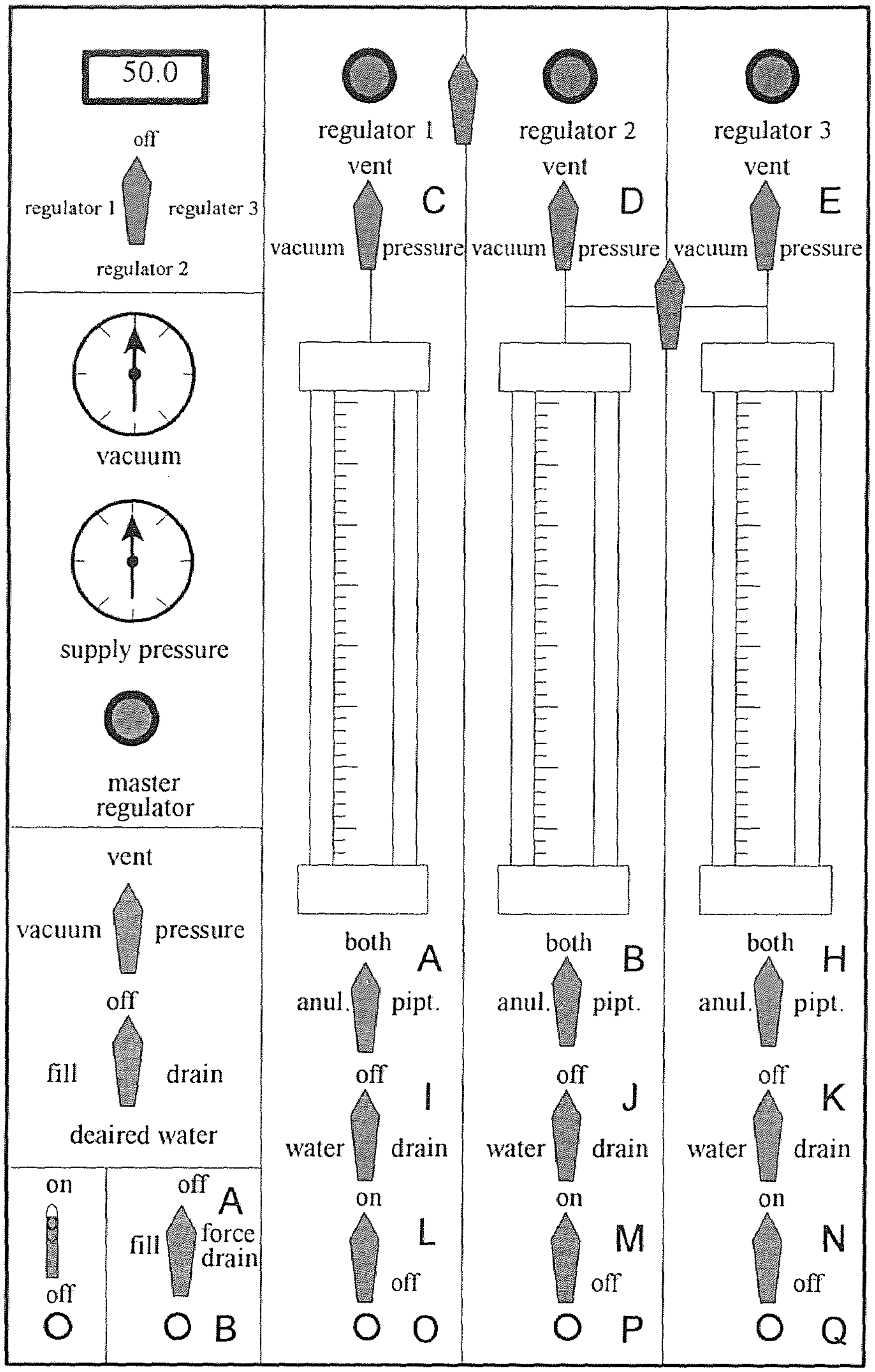


Figure 3 Brainard-Kilman control panel

5.4.2 Control Panel

1. To fill the cell with deaired water, connect the bottom plate and position B with a tube. Release the chamber pressure by means of connecting another tube to top plate. Turn the switch A to "Fill."
2. After the chamber is filled with water, transfer the tube from position B to position O. Remove the tube from the top plate.
3. Connect position P and R by a tube; same as position Q and S.

5.5 Permeability Test

In this experiment, we determine the hydraulic conductivity of HMA concrete by means of measuring the volume of water transmitted through them. The volume of water can be easily measured by the permeability test apparatus shown on figure 2 and figure 3. This test equipment has two major portions, control panel and chamber cells. We can control the chamber, inlet, and outlet pressures separately and read the water volume and hence the level in standpipes on the control panel. The tested specimens are placed in the chamber cells when testing and the pressure is supplied by an air compressor. It is necessary to check the supplied pressure is large enough and all the tubes are connected to proper positions before testing. The three major procedures of falling head hydraulic conductivity testings are shown as following.

1. Pressure settings: Turn on the air compressor and check the supply pressure gauges on control panel of the permeability test apparatus. Use regulator 1, 2, 3 to adjust the pressure of each standpipe, chamber, inlet, and outlet. In this experiment, Cell pressure has been set to 50 psi (344 kPa), inlet pressure to 31 psi (213 kPa), and outlet pressure to 30 psi (206 kPa). The cell pressure was large enough to present leaking from sides and to keep the specimens 100% saturation at all times.
2. Remove air from all the tubes and set the water level in each standpipes; highest at inlet and lowest at outlet.

3. Permeability test: Turn the switch F to "pipette" and G & H to "annulus". Open valves L, M, N, R, S. let water flow through the specimen. Record the volume changes in three standpipes. Adjust the pressures on inlet and outlet standpipes based on the velocity of the flow through the specimen. Reset the water level in three standpipes regularly each time reading is taken.
4. Take readings: Record (1) time, (2) temperature, (3) outlet, inlet, chamber pressure in psi, and (4) water levels in each standpipe continuously during the test three times a day.
5. Stop testing: Twenty-four hours after the in-flow became equal to the out-flow, and when the hydraulic conductivity did not show a further reduction, the permeability test was stopped.
6. Disconnect all the tubes and place another three sample for next test. In this research, we tested twenty-one specimens.

5.6 Data Collection and Calculation

During period of testing, we take three reading each day. The time, water temperature, and standpipe's scale readings should be recorded every time we take reading. After the permeability test was stopped, the equation 5-1 was used to compute the hydraulic conductivity values. The derivation of this equation was shown in the chapter 2.

$$K = \frac{aL}{2At} \times \ln\left(\frac{h_1}{h_2}\right) \tag{5.1}$$

Where a (cm^2)is the cross-sectional area of standpipes; L (cm) is the average height of HMA specimen; A (cm^2) is the cross-sectional area of HMA specimen; t (sec) is the time interval between two consecutive readings; h_1 and h_2 (cm) each expresses the hydraulic head, including pressure head and elevation head at beginning and end of the time period. Finally, the hydraulic conductivity, k, is calculated and express in centimeter per second.

The variation hydraulic conductivity with. time graphs were plotted to show the reduction in hydraulic conductivity. When the hydraulic conductivity reaches the lowest value with no further reduction in time, it was assumed that the sample was 100% saturated and the hydraulic conductivity values are reported at this point.

CHAPTER 6

RESULTS AND DISCUSSIONS

The saturated hydraulic conductivity values for all twenty-one HMA concrete specimens, three for the control and eighteen for HMA made with each soil type, are reported in table 6. All the hydraulic conductivity values are in the range of 6.5×10^{-8} and 5.0×10^{-6}. However, almost all the saturated hydraulic conductivity values, except one specimen made with PCS #4, was less than 5.0×10^{-6} with the global average of 5.0×10^{-7}, and hence can be considered as acceptable.

Table 6 Hydraulic Conductivity values of HMA concrete made with PCSs and the control

Soils type	Hydraulic Conductivity (cm/sec)		
	Specimen #1	Specimen #2	Specimen #3
Control	1.7 E -7	1.3 E -7	3.8 E -7
PCS #1	5.0 E -7	2.7 E -7	2.2 E -7
PCS #2	6.2 E -8	3.5 E -7	6.0 E -8
PCS #3	2.9 E -6	2.6 E -7	1.6 E -6
PCS #4	1.8 E -6	4.5 E -6	1.8 E -7
PCS #5	5.1 E -7	3.7 E -7	1.5 E -6
PCS #6	4.2 E -7	4.1 E -7	5.5 E -7

In geotechnical engineering, it is an accepted fact that d_{10} size controls the hydraulic conductivity of soils. The soil with larger d_{10} size would have larger hydraulic conductivity value. However, there are so many other factors that control hydraulic conductivity of a porous material. The variation of hydraulic conductivity for the same testing material is quite large, however, one order of magnitude variation is considered as acceptable.

For HMA concrete, voids in total mix (VTM), volume of voids in mineral aggregate (VMA), voids filled with asphalt (VFA), the asphalt content, and the amount of interconnected voids are considered as parameters that contribute to the hydraulic conductivity. From the d_{10} size of total aggregate and soil mixture, one should be able to estimate maximum possible hydraulic conductivity of HMA concrete. The HMA specimen with higher asphalt content or higher VFA will give them a lower hydraulic conductivity. On the other hand, the specimen that has higher VTM or VMA would have higher hydraulic conductivity. The distributions of voids in the HMA specimen also play an important role in the permeability of this HMA concrete. If the voids within aggregate and asphalt mass are not interconnect but rather are isolated, the permeability would be quite small. Especially, it has significant effect on that HMA concrete with smaller VFA values.

From the results of this research, we found both the asphalt content and the d_{10} sizes of the design mix for PCS #4 are the smallest when compared with six mixes with PCSs and the control mix. This information can be used to explain fact that the average hydraulic conductivity of these three HMA specimens made with PCS #4 is quite smaller than others.

With higher asphalt content one would expect a lower hydraulic conductivity and is consistent for most of the experiment results. For 4.25% asphalt content HMA specimen the average hydraulic conductivity was of the order 1.0×10^{-6}, for 4.5% asphalt content, the average hydraulic conductivity was of the order 1.0×10^{-7}. However, the specimen made with PCS #3, which an optimum asphalt concentration of 5.0%, should have a lower hydraulic conductivity, but unfortunately not so in this research. When the other properties of these three specimens were investigated it was found for these specimens, the void in the mineral aggregate (VMA) was found to be quite large but the average voids filled with asphalt (VFA) was found to be smaller. In this case the hydraulic conductivity of PCS #3 was effected by these two factors more than the asphalt content.

The voids filled with asphalt (VFA) is define as the percentage of the volume of the VMA that is filled with asphalt cement. The specimen with higher VFA should have a lower hydraulic conductivity. The relationship between VFA and saturated hydraulic conductivity for all the specimens were plotted and is shown in figure 4. From this figure, it can be observe the above argument that the saturated hydraulic conductivity is lower with higher VFA value. The data points located in portion II of figure 4, where the VFA is more than 62%, have a higher correlation coefficient than those in portion I of figure 4. When the hot mix is compacted to form the dense-graded HMA concrete, the VTM should lie among 3 to 5 percent and the permeability of both air and water should be quite low as the voids in this HMA concrete will be evenly distributed and filled by the asphalt cement. Therefore, hydraulic conductivity is linear correlated to VFA, and k will decrease with increase in VFA. However, if the VFA value is low then air voids in the mix will not be well distributed. Hence, some of the mix would have more impermeable layers or more isolated voids to produce low or irregular hydraulic conductivities. On the other hand, the specimens with larger fraction of interconnect voids or crack parallel to the direction of water flow will have higher hydraulic conductivities. Therefore, when the VFA lower then 62% the interconnection of permeable voids will influent the hydraulic conductivity of HMA concrete and it will be hard to examine and predict.

A good hot mix asphalt pavement will have a lower hydraulic conductivity to provide a better service life. The results of this experiment indicate that there is an additional design consideration to be considered in the design of HMA mixtures and that asphalt cement content when express as a fraction of mineral voids (VFA) should be higher than 62% after compaction to have a lower consistent hydraulic conductivity value.

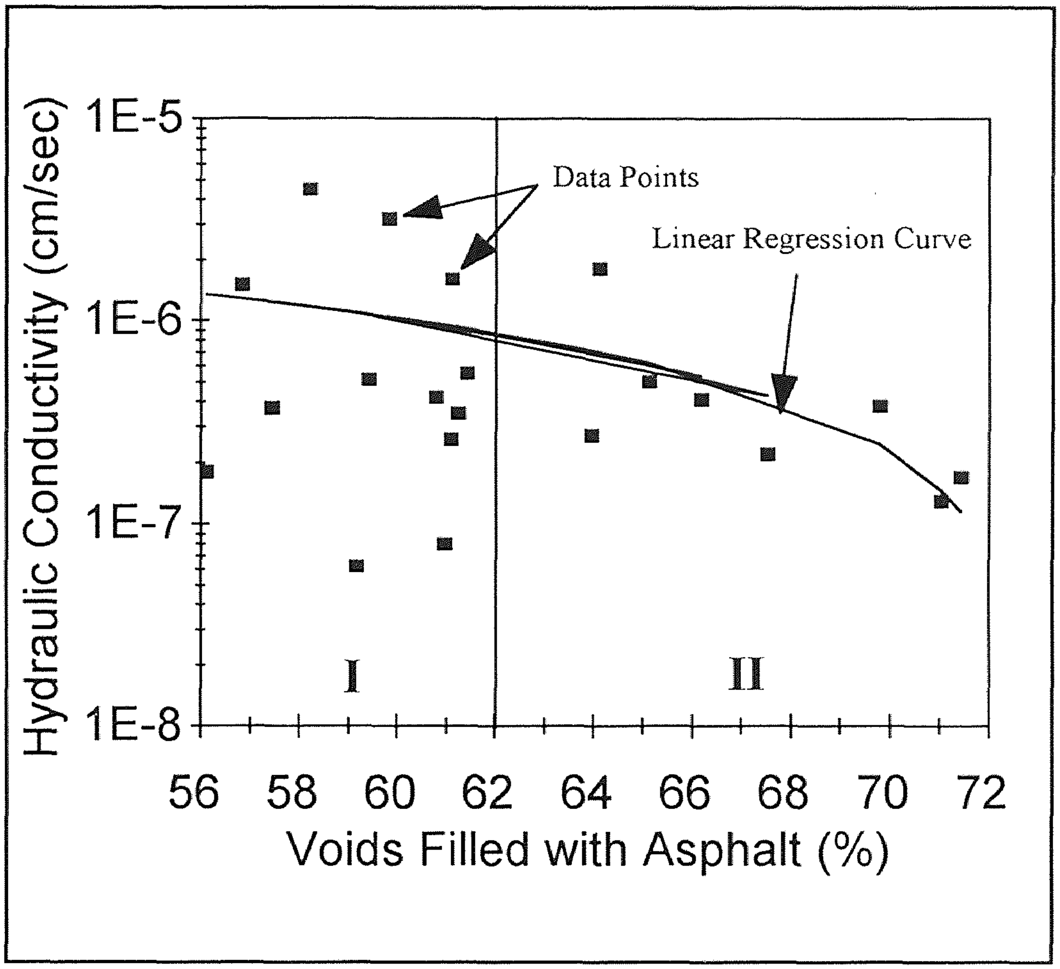


Figure 4 The Hydraulic Conductivity values vs. Voids Filled with Asphalt (VFA)%

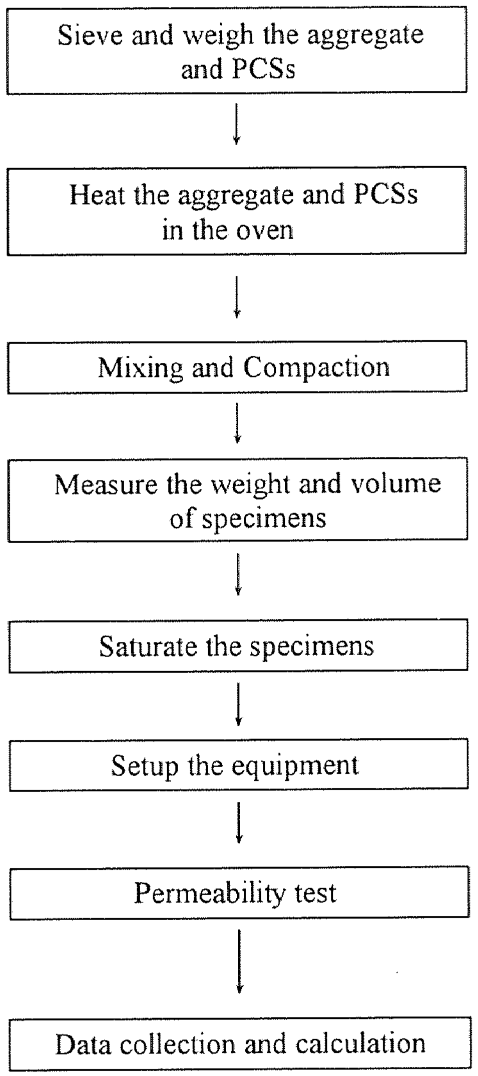


Figure 5 Flow chart of the experiment procedure

Table 7 Mix properties for Marshall mix design

Hot Mix Specimens		Weight-Grams			Spec. Gravity		Vol	Voids-Percent		
Specimen No:	% AC	Dry sample	water+ container	Sample in water	Bulk	theor	AGG	Total	VMA	Filled
Control -1	4.75	1257.4	2986.5	3495.5	2.470	2.588	84.035	4.561	15.965	71.430
Control -2	4.75	1247.9	1933.0	2438.6	2.468	2.588	83.961	4.645	16.039	71.037
Control -3	4.75	1246.8	2973.7	3480.3	2.461	2.588	83.722	4.917	16.278	69.792
PCS #1-1	4.50	1224.1	2433.8	2933.5	2.450	2.599	83.551	5.736	16.449	65.129
PCS #1-2	4.50	1236.8	2426.2	2932.6	2.442	2.599	83.301	6.018	16.699	63.961
PCS #1-3	4.50	1245.1	1953.3	2458.6	2.464	2.599	84.043	5.181	15.957	67.530
PCS #2-1	4.50	1230.9	2605.2	3116.0	2.410	2.599	82.190	7.272	17.810	59.169
PCS #2-2	4.50	1222.6	2597.7	3102.0	2.424	2.599	82.688	6.710	17.312	61.240
PCS #2-3	4.50	1228.9	2592.9	3100.2	2.422	2.599	82.622	6.784	17.378	60.961
PCS #3-1	5.00	1225.7	3332.3	3847.7	2.378	2.578	80.687	7.757	19.313	59.835
PCS #3-2	5.00	1246.4	3325.9	3847.9	2.388	2.578	81.013	7.385	18.987	61.105
PCS #3-3	5.00	1234.0	3320.2	3837.0	2.388	2.578	81.014	7.384	18.986	61.109
PCS #4-1	4.25	1231.4	1943.9	2444.3	2.461	2.609	84.152	5.685	15.848	64.131
PCS #4-2	4.25	1226.7	1938.0	2444.5	2.422	2.609	82.821	7.176	17.179	58.228
PCS #4-3	4.25	1218.6	2925.6	3432.0	2.406	2.609	82.290	7.771	17.710	56.121
PCS #5-1	4.50	1225.8	2977.0	3485.3	2.412	2.599	82.252	7.202	17.748	59.421
PCS #5-2	4.50	1250.7	2970.0	3491.8	2.397	2.599	81.751	7.767	18.249	57.440
PCS #5-3	4.50	1247.6	2964.0	3485.5	2.392	2.599	81.596	7.942	18.404	56.845
PCS #6-1	4.50	1244.5	3222.3	3736.3	2.421	2.599	82.580	6.831	17.420	60.784
PCS #6-2	4.50	1217.0	3229.1	3724.6	2.456	2.599	83.771	5.488	16.229	66.183
PCS #6-3	4.50	1252.6	3231.2	3747.6	2.426	2.599	82.732	6.661	17.268	61.429
Gac:	1.029		Geff:	2.800						

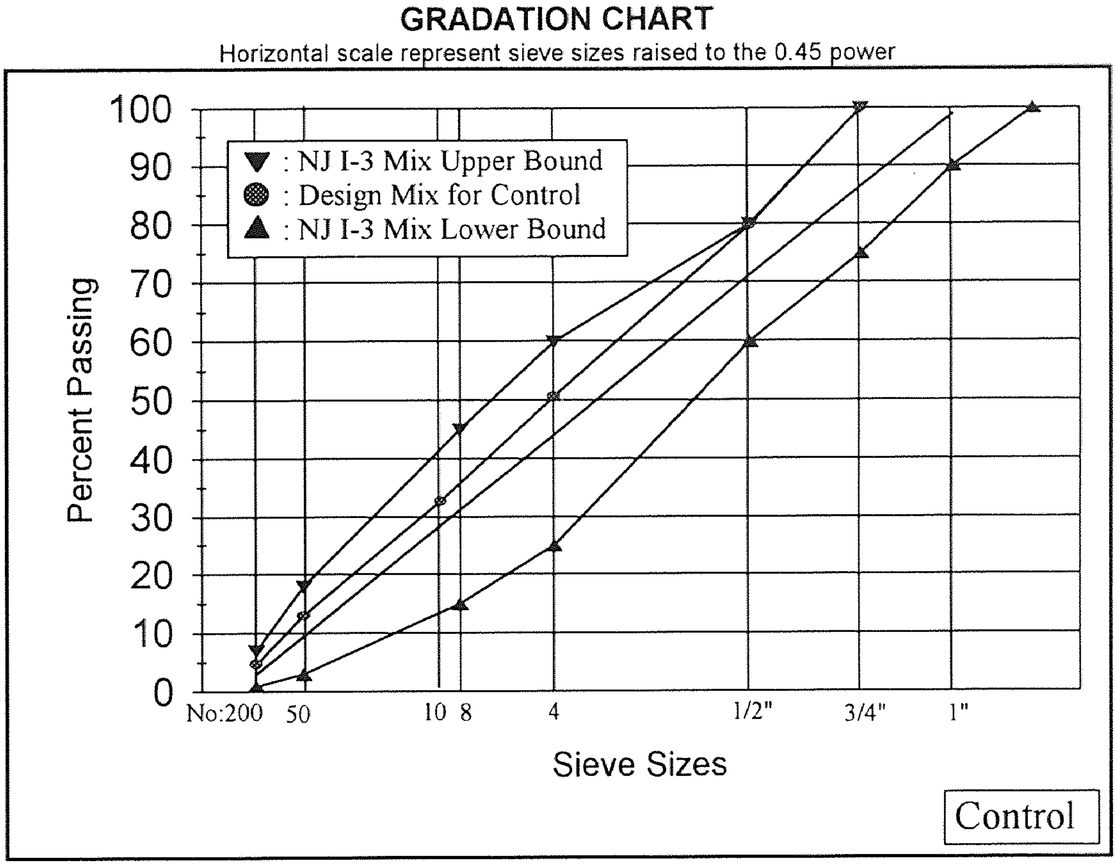


Figure 6 Design grain size distribution of HMA mixture (Control)

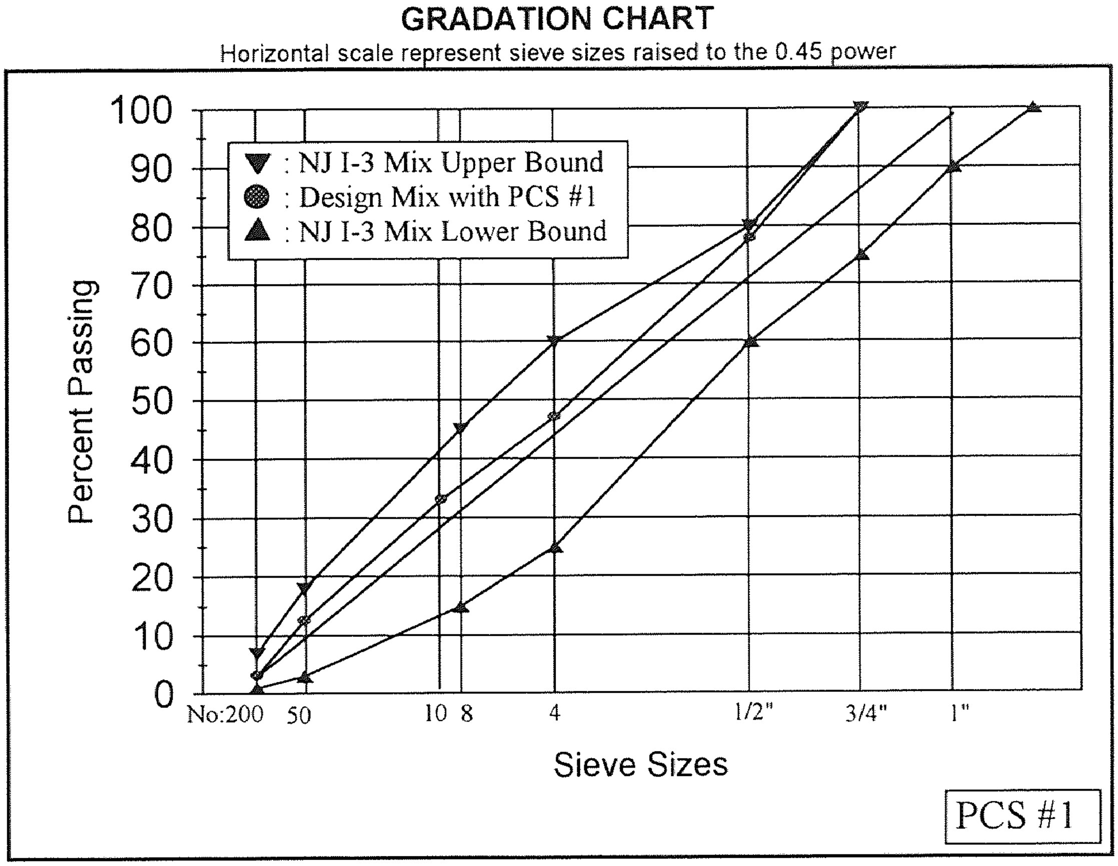


Figure 7 Design grain size distribution of HMA mixture with PCS #1

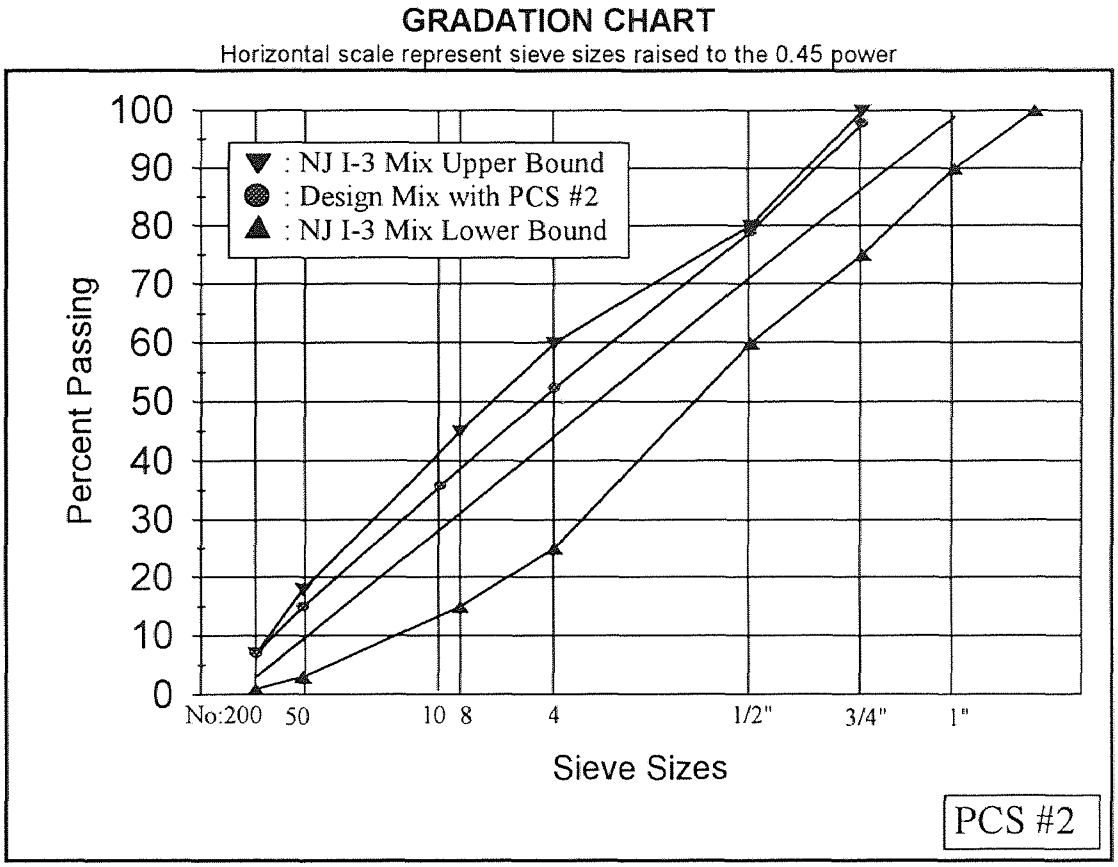


Figure 8 Design grain size distribution of HMA mixture with PCS #2

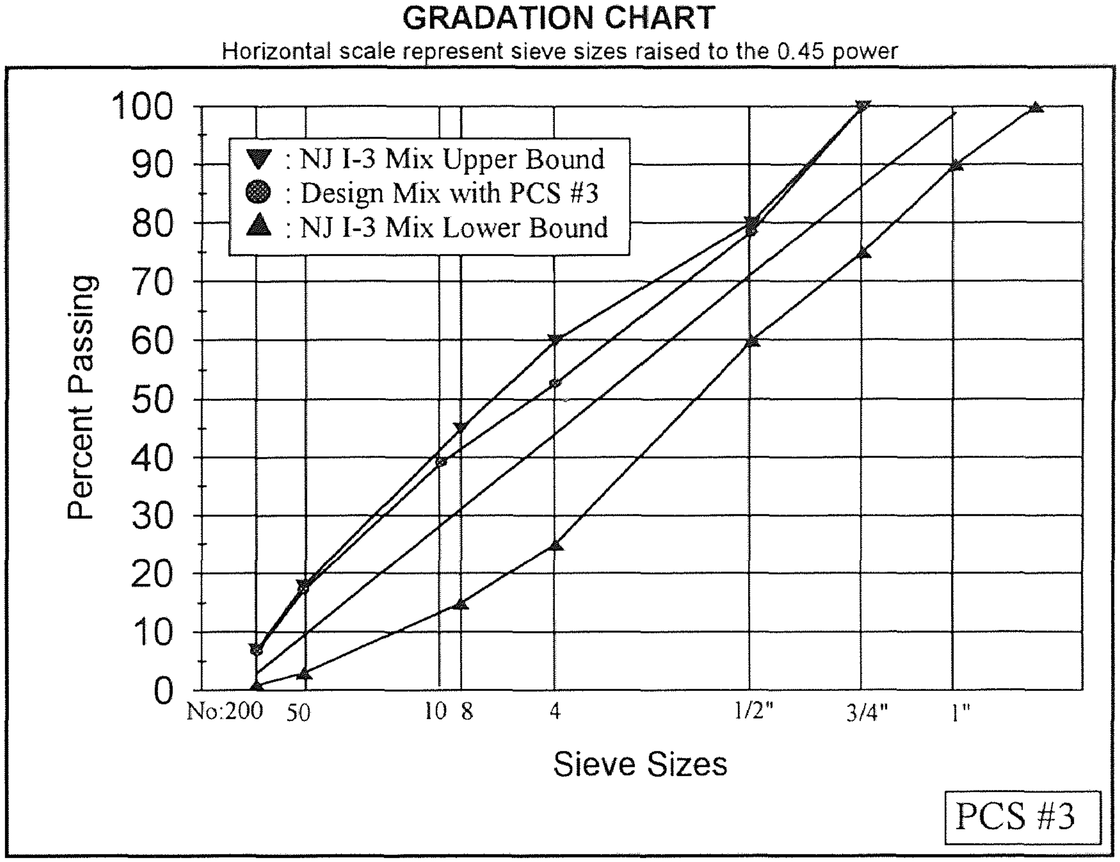


Figure 9 Design grain size distribution of HMA mixture with PCS #3

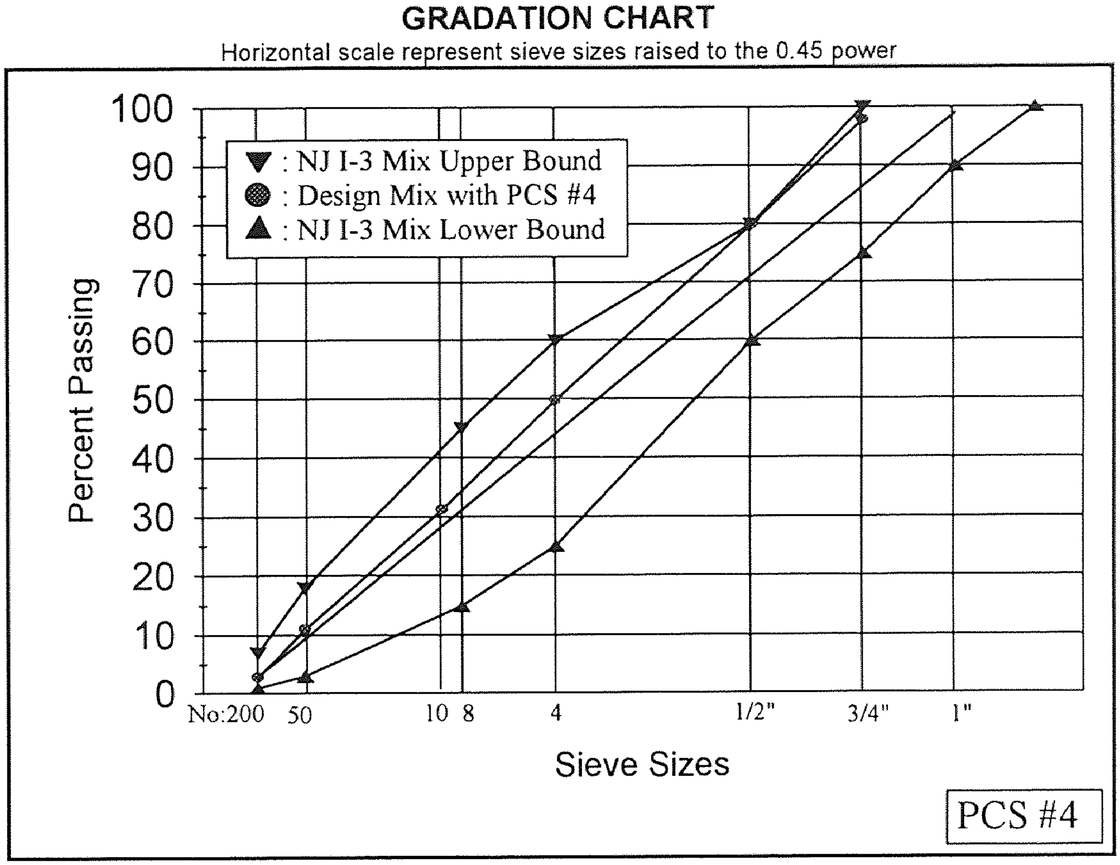


Figure 10 Design grain size distribution of HMA mixture with PCS #4

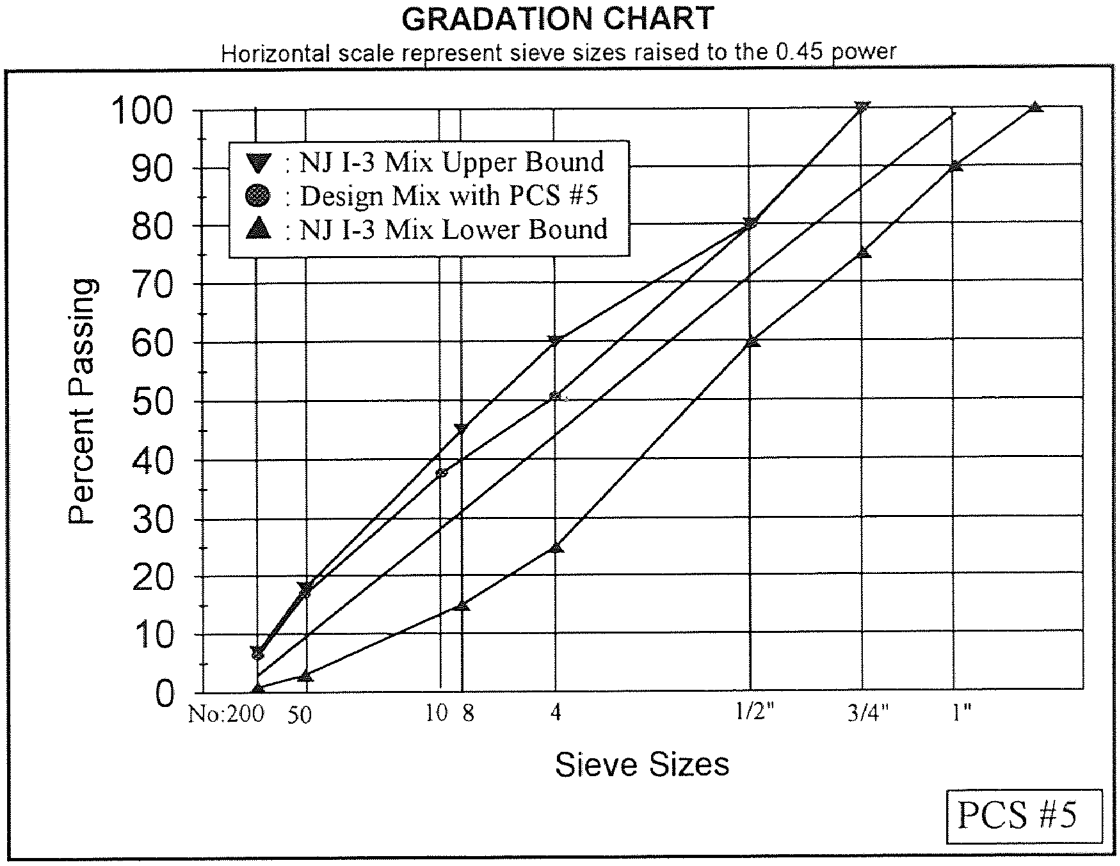


Figure 11 Design grain size distribution of HMA mixture with PCS #5

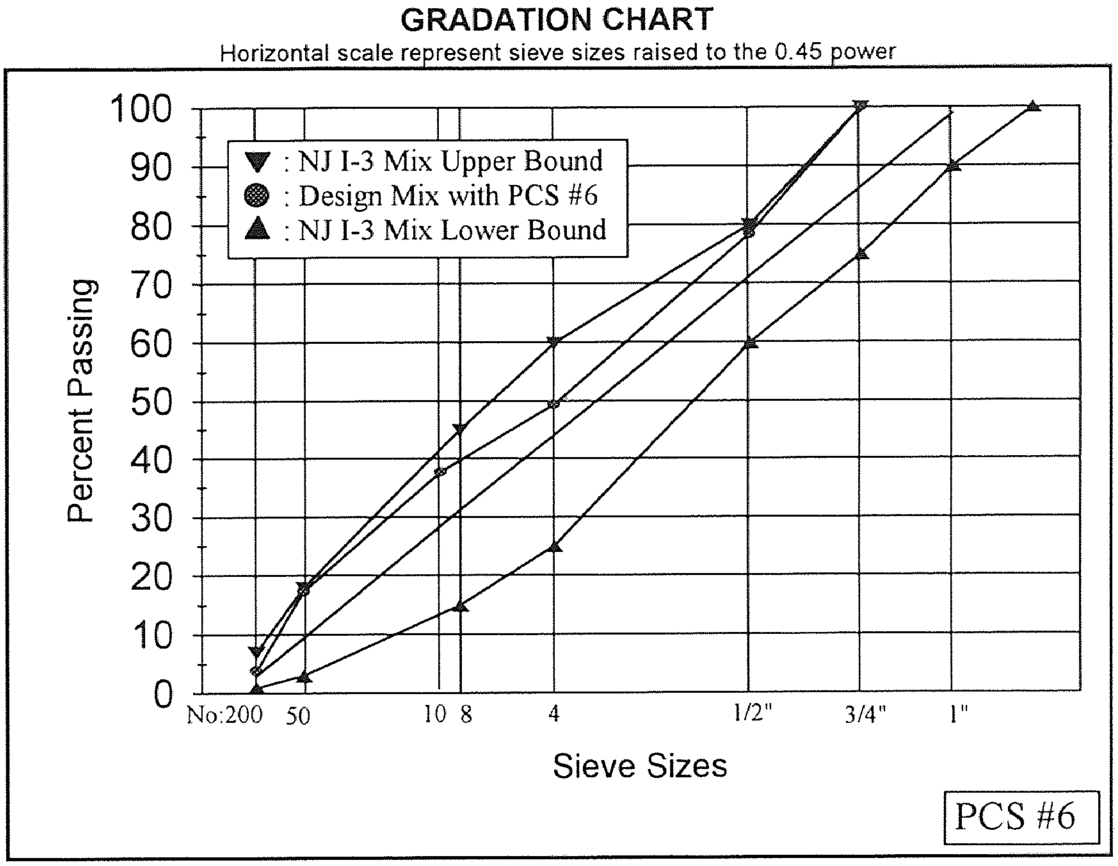


Figure 12 Design grain size distribution of HMA mixture with PCS #6

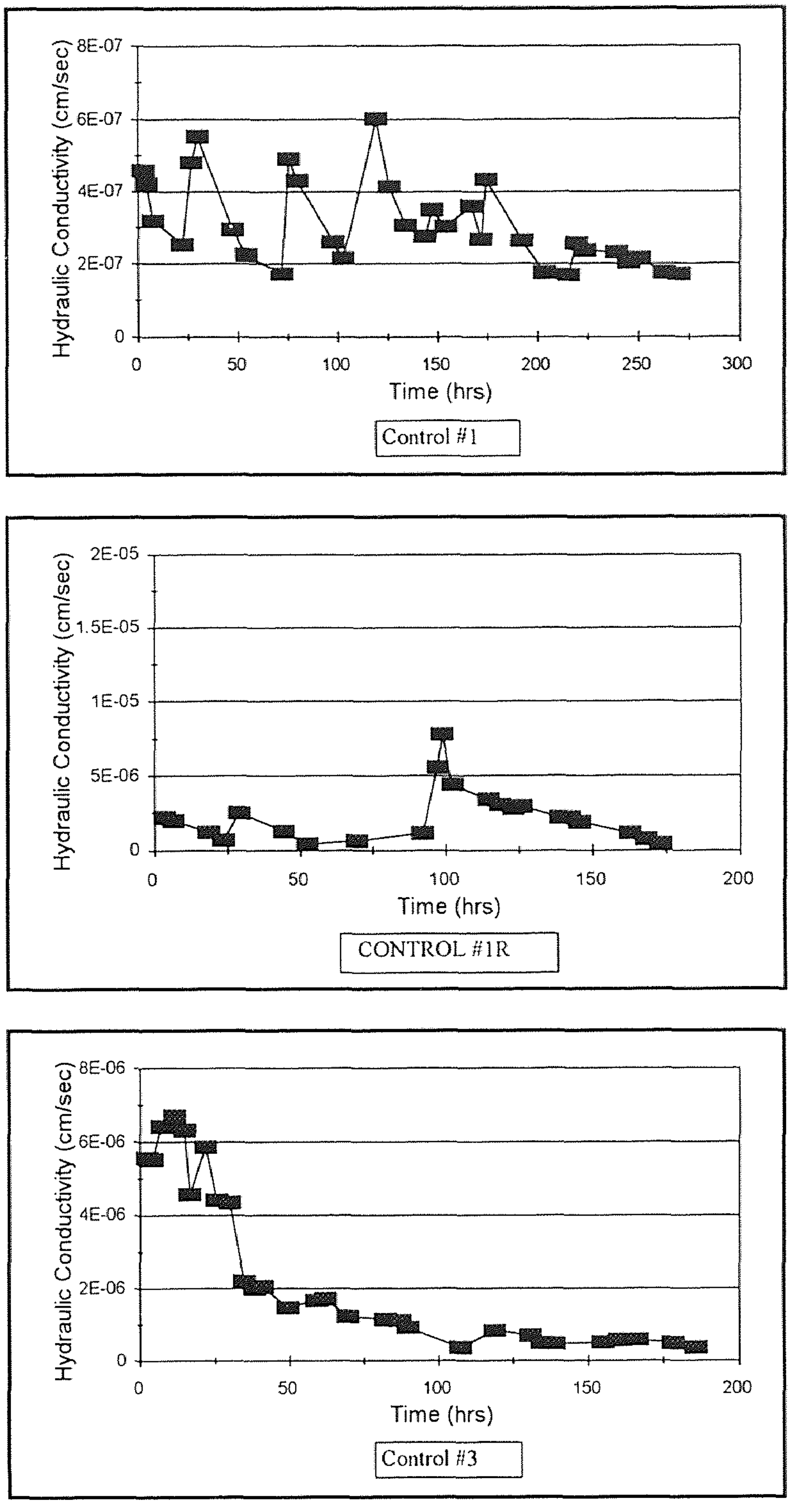


Figure 13 The Hydraulic Conductivity vs. Time of HMA Concrete (Control)

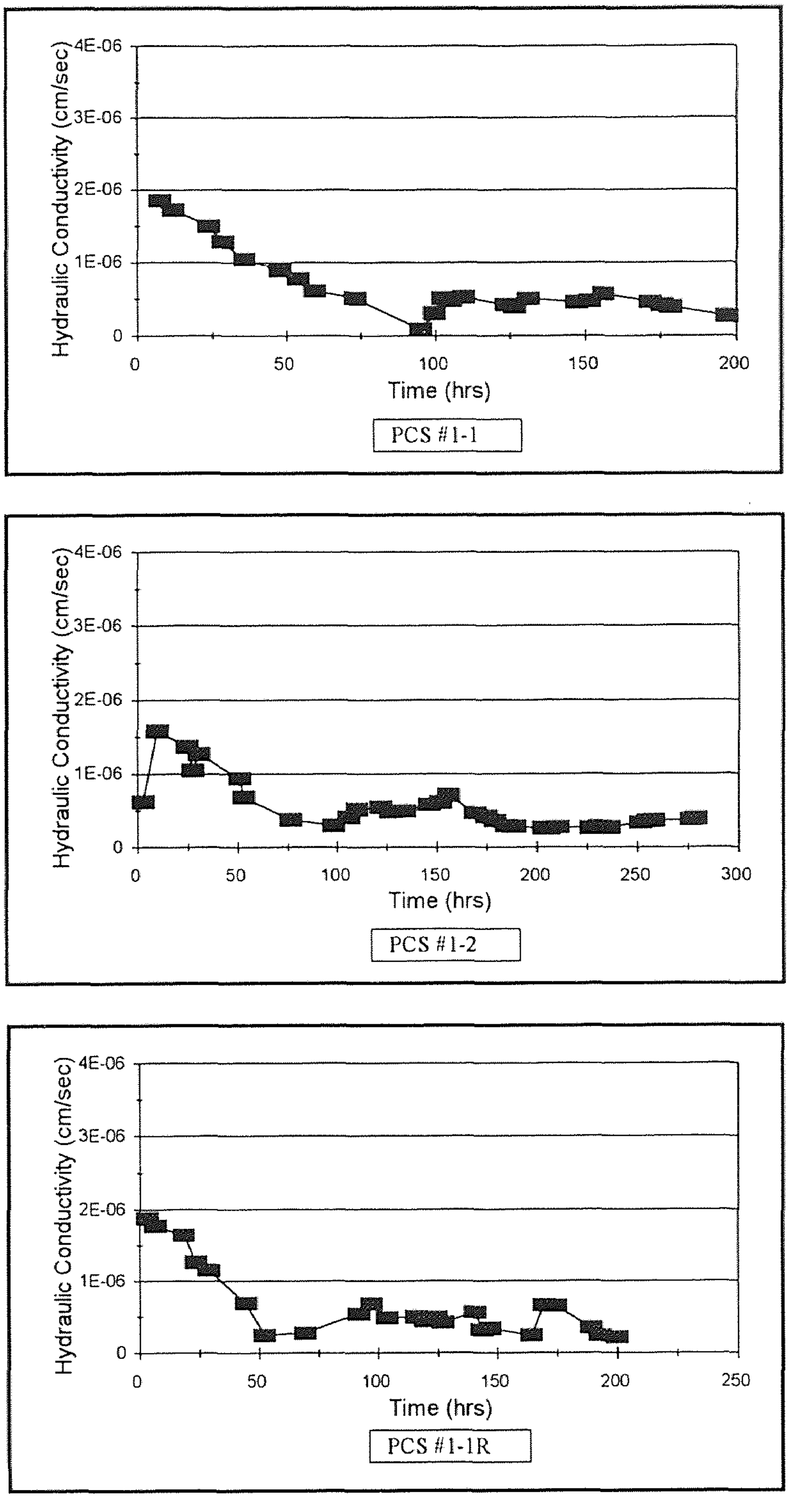


Figure 14 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #1

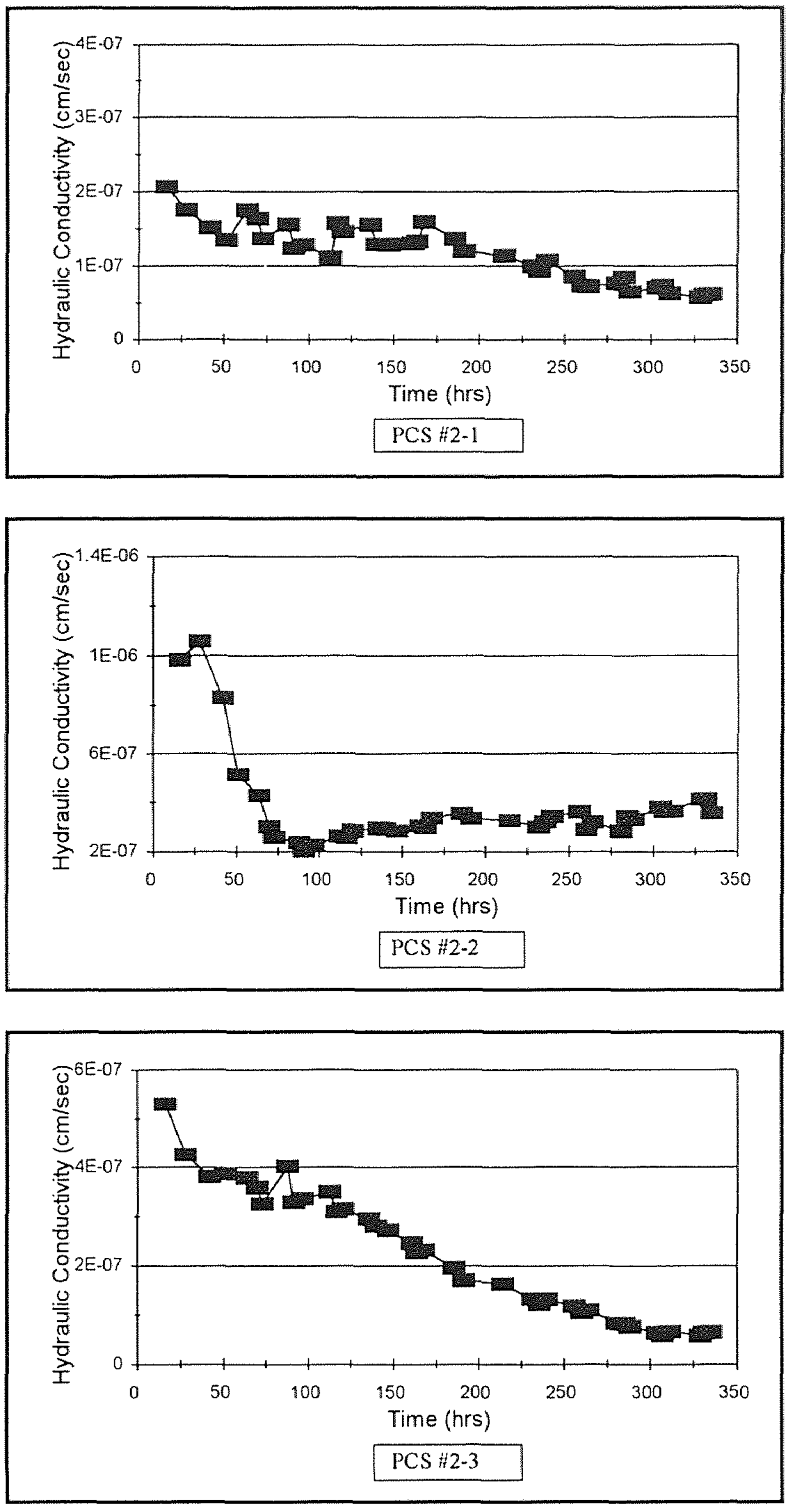
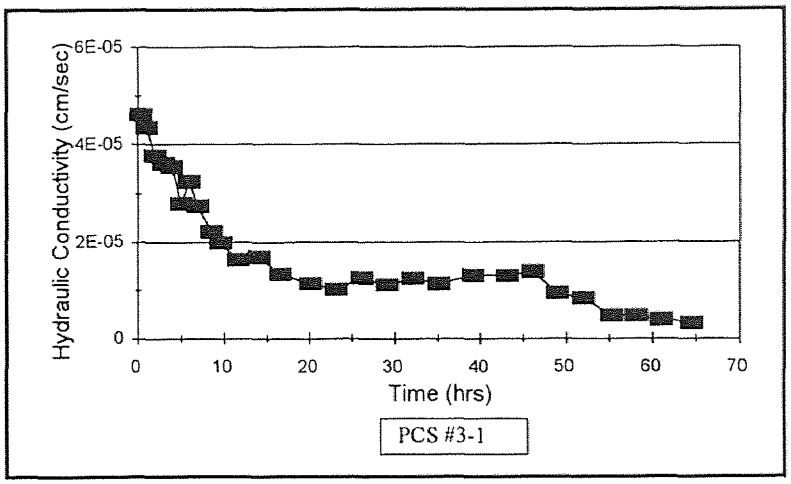
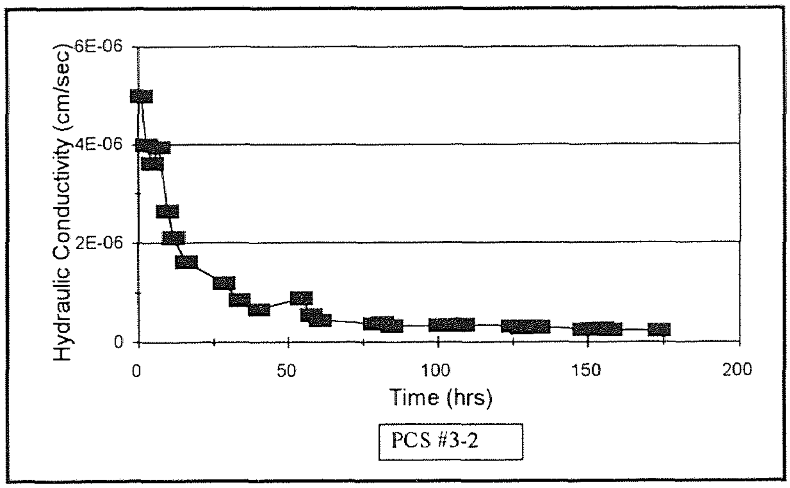


Figure 15 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #2





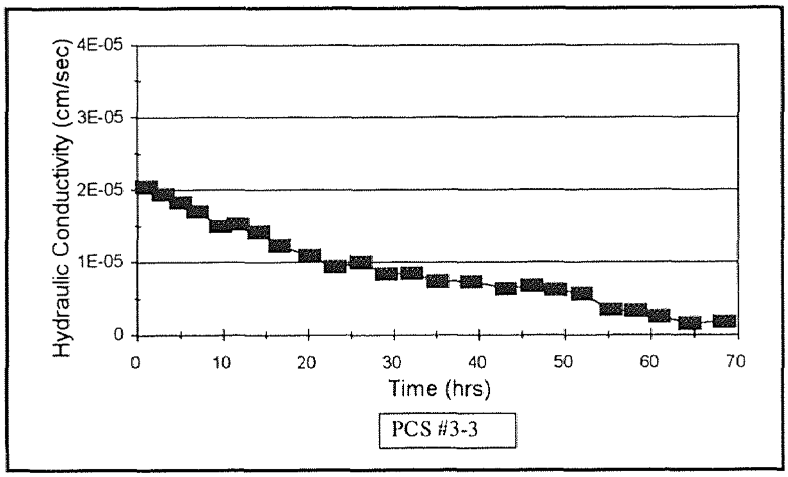


Figure 16 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #3

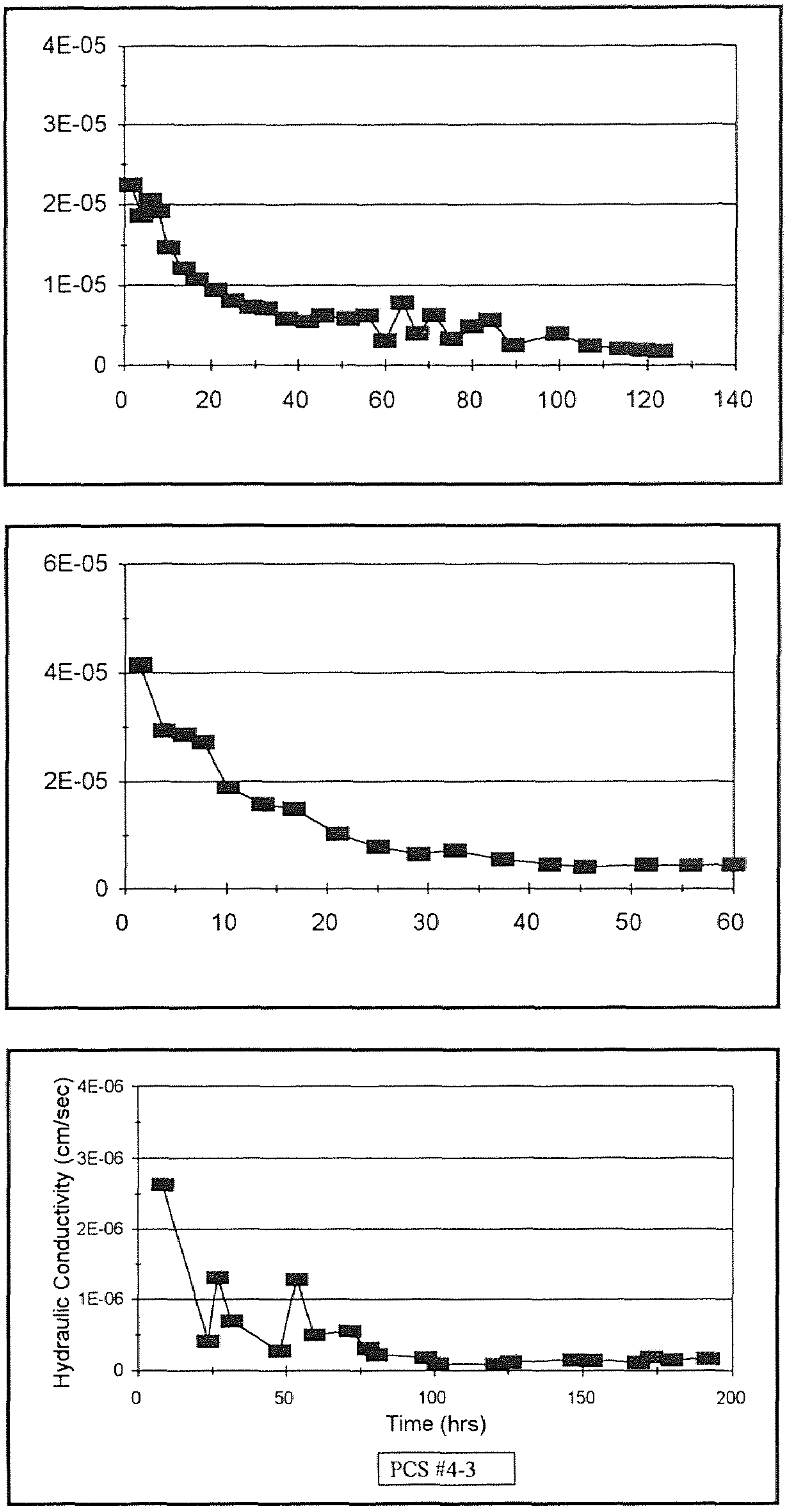
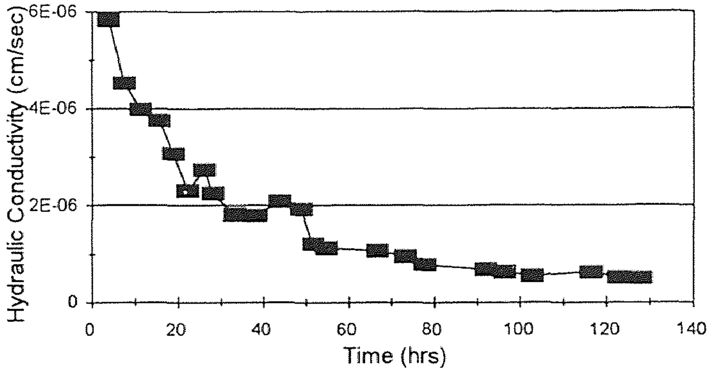
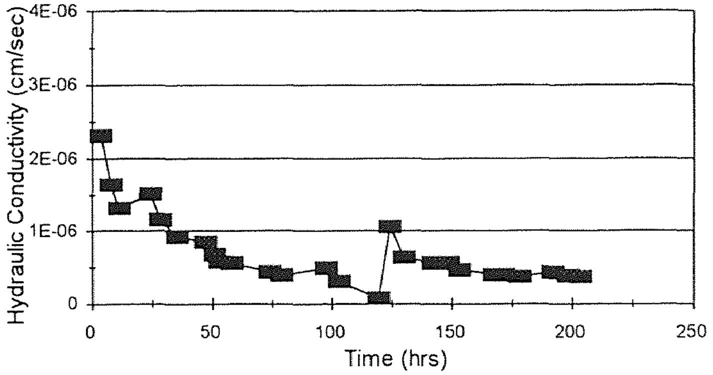


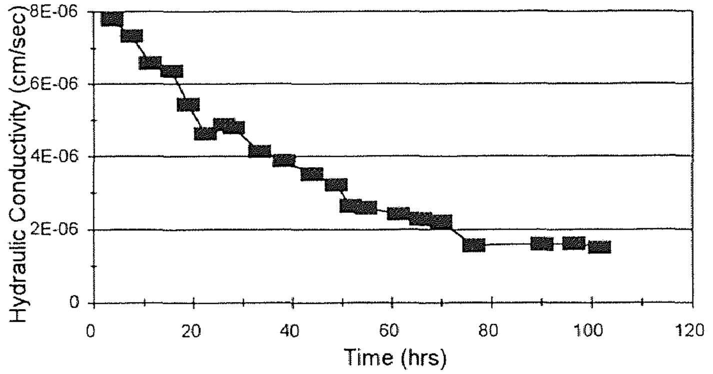
Figure 17 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #4



PCS #5-1

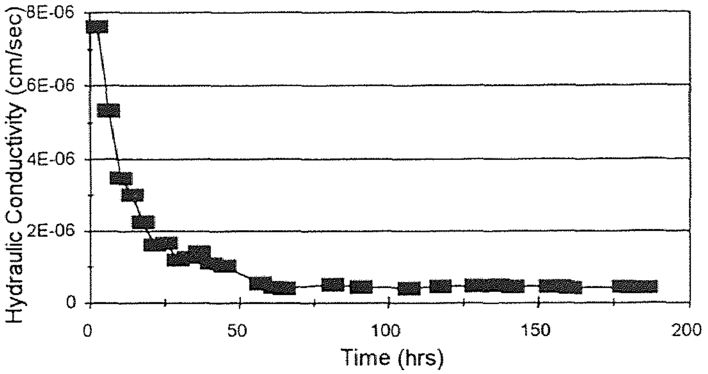


PCS #5-2

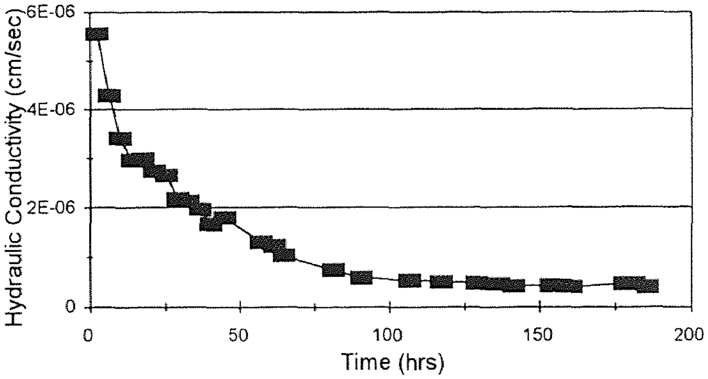


PCS #5-3

Figure 18 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #5



PCS #6-1



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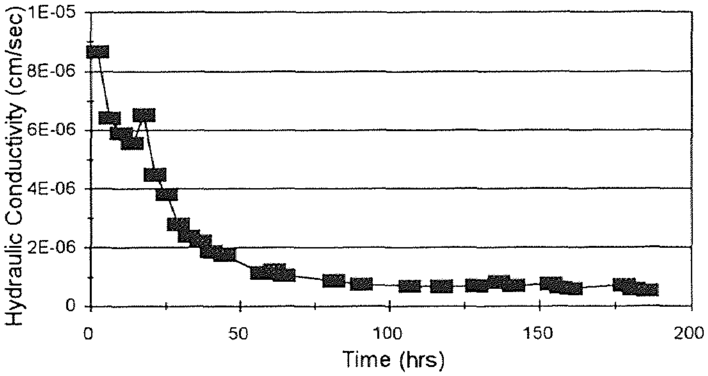

PCS #6-3

Figure 19 The Hydraulic Conductivity vs. Time of HMA Concrete with PCS #6

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