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Date 4/29/94

THE EFFECTS OF WATER CONTENT VARIATION ON LABORATORY SAMPLES SIMULATING LOW PERMEABLE CLAY BARRIERS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Daniel Raymond Boles

May 1994

DEDICATION

This thesis is dedicated to my parents

Dr. Raymond L. Boles Jr. and Carolyn M. Boles,

who instilled in me the perseverance, work ethic, and appreciation of knowledge

that allowed me to complete my thesis and degrees

and to

Amy E. Lindsey,

whose daily encouragement and support were essential

to the completion of my degree and thesis.

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ABSTRACT

Two methods for measuring the hydraulic conductivity of laboratory samples simulating low permeable clay barriers have been used to explore the effects of water content variation on the samples. A silty clay, classified as CH by the Unified Soil Classification System and typical to East Tennessee, from the West Chestnut Borrow Area was used to build the laboratory samples. The flexible-wall permeameter, which used a small scale sample measuring approximately 10 cm (4 in) by 7 cm (3 in) and the lysimeter, which used a field-scale sample measuring approximately 75 cm (29.5 in) by 7.6 cm (3 in) were the instruments used to determine the hydraulic conductivity.

Both sets of samples were subjected to wetting and drying cycles while the density, water content and hydraulic conductivity were measured. The flexible-wall samples had decreased hydraulic conductivity as the samples became denser and drier. The lysimeter sample had an increased hydraulic conductivity as the samples became denser and drier. The predominant differences in the two samples were that the lysimeter samples tended to have preferential flow paths formed during the initial compaction while the flexible-wall samples did not appear to form similar water conduits. Also, during the drying cycles the lysimeter samples experienced cracking which contributed to the increase in hydraulic conductivity while the flexible-wall samples remained intact throughout the drying cycles.

These differences in behavior were due to the fact that the flexible-wall samples behaved as a singular soil aggregate and the lysimeter samples behaved as a group of soil aggregates which acted as a clay barrier.

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PART I

INTRODUCTION

PURPOSE OF CLAY BARRIERS AND LINERS

Clay liners and covers, when used in landfills, are the primary barrier between water and waste. The purpose of the final clay barrier on a landfill is to (1) minimize infiltration of water due to precipitation after the landfill is completed, (2) limit the uncontrolled release of gases, (3) prevent the intrusion of vectors (animals which propagate disease), (4) limit the possibility of fires, (5) provide a surface that is suitable for the growth of grassy vegetation, and (6) provide a land surface worthy of reclamation (Hatheway and McAneny, 1987). In order for the landfill cap to perform these tasks it must be able to resist (1) temperature extremes and freeze/thaw cycles, (2) wet and dry cycles, (3) deep penetration by large plant roots and burrowing animals, (4) settlement caused by waste compaction and foundation soil, (5) surcharge loads due to material storage or soil stockpile, (6) slope slumping or creep, (7) vehicular loading, (8) wind and water erosion, (9) earthquake loading, (10) loading due to a water surcharge, and (11) alterations from gas due to the decomposition of waste (Koerner and Daniel, 1992).

According to Resource Recovery and Conservation Act Regulations (EPA, 1990), stated in CFR 40 part 264.310 and part 265.310, the landfill cap must (1) provide minimization of liquid passage through the closed landfill, (2) provide minimal liquid passage with minimal maintenance, (3) promote drainage off the landfill and prevent erosion, and (4) accommodate subsidence of the landfill without affecting the integrity of the cap. These requirements must be maintained by the owner or operator of the landfill for thirty years after final closure.

HYDRAULIC CONDUCTIVITY OF CLAY BARRIERS AND LINERS

Water must be reasonably prevented from flowing through the waste layers of landfills in order to prevent leachate or water from entering the groundwater or local water systems. Clay covers (caps) prevent water from entering through the top surface of the landfill. Clay liners provide a controlled release, of liquid waste and water combined with waste from the landfill.

The clay barrier method of containing waste is used for both hazardous and sanitary landfill structures. Generally, the clay barrier must have a hydraulic conductivity equal to or less than 1 x 10^{-7} cm/s. This is achievable with many clays, and usually reflects the properties immediately after compaction. However, environmental factors inevitably have an affect on clay barriers. When the clay is subjected to atmospheric drying, or desiccation, cracks can develop. These cracks provide new preferential flow paths, thus changing the hydraulic conductivity of the barrier. This change in hydraulic conductivity may cause the water and waste to flow faster and allow passage of contaminated water (leachate) onto land or into clean water sources.

SCOPE

This thesis will explore the effects of varying water content on laboratory samples which simulate clay barriers. Two types of laboratory devices will be used to investigate hydraulic conductivity. The flexible-wall permeameter, which uses a Shelby tube type sample which is generally 2.8 in (7.11 cm) in diameter, will be used to investigate samples representing a homogenous clay matrix. The lysimeter, which uses a 29.5 in

(75 cm) sample, will be used to investigate a more heterogeneous clay matrix that may include cracks. The water content of both samples will be manipulated in order to observe the changes which occur in the hydraulic conductivity and dry density. The water content change affects the dry density of both sample types differently, which creates different changes in hydraulic conductivity for each sample type. The determination of these changes is the goal of this investigation.

DISCREPANCIES IN HYDRAULIC CONDUCTIVITY MEASUREMENT

Recent research indicates that there are discrepancies between laboratory conductivity measurements and field conductivity measurements. These discrepancies may be attributed to many different sources, from the initial selection of soil to the care of the soil after compaction in the field. Variation in clod size of the clay has been cited by Benson and Daniel (1990) as a contributor to differences in hydraulic conductivity measurements. The studies showed the larger the clod size during compaction, the higher the hydraulic conductivity values. Laboratory measurements of hydraulic conductivity may be misleading, because in the laboratory soil is often broken down to a greater extent than it is broken down during construction. Clod size should only be increased or decreased in the laboratory if it is going to be altered in the field. Any laboratory alteration of the soil should be similar to field alterations. In order for hydraulic conductivity data to be comparable, clod size must be similar.

Benson and Daniel (1990) also contend that water content of the clods during compaction has an affect on the hydraulic conductivity. All soils have an optimum water content at which a maximum density may be achieved. When soil has a higher water content than the optimum it may be described as wet of optimum. When the soil has a lower water content than the optimum it may be described as dry of optimum. With soil clods that are wet of optimum, the clod size is less important because the clods are easily moldable. The clods, when compacted, will reshape more readily and close the larger interclod voids. This, however, is also dependent on the amount of energy used when compacting. When large clods are dry of optimum, more energy is needed to compact these clods to hydraulic conductivities which are acceptable for clay barriers. Large clods, when dry of optimum, do not compact well even under high energy. When wet of optimum, large clods do not need as much energy to be properly compacted to hydraulic conductivities near or below 1×10^{-7} cm/s. In the field, large clods may typically be wet of optimum on the surface but dry of optimum in the center because when the clay is placed in a lift and moistened, only the outer portion of the clod can absorb the water before the lift is compacted (Daniel, 1984). Small clods and large clods wet of optimum, may experience significant shrink/swell volume changes. However, if these small clods are compacted dry of optimum with larger amounts of energy, acceptable hydraulic conductivities can be achieved (Benson and Daniel 1990). In addition, the low initial water content will prevent large volume changes during drying, which causes cracking and subsequently increase the hydraulic conductivity.

Elsbury, et al. (1990) agree with Benson and Daniel (1990) about the detrimental effects of large clods when they are dry of optimum. When samples on the dry side of optimum were compacted using large clods, which had a minimum size of 19 mm (0.75

in), the measured permeability was 25,000 times larger than equal sized samples which were compacted wet of optimum. The interclod pores of the dry side samples were large enough to be clearly visible, while the wet side sample appeared visibly homogenous.

Phifer (1993), through the use of X-ray diffraction, attributes low measurements of hydraulic conductivity to clod theory when clays are compacted wet of optimum water content. Because current practices of construction use kneading type compaction, these wet clods that are easily remolded, decrease the amount of interclod pore space in the clay barrier and minimize flow through the barrier.

Shackelford and Javed (1991) attribute differences in laboratory and field hydraulic conductivity to the size of the sample. They concluded that for identical compaction conditions, the larger the sample size used, the higher the hydraulic conductivity achieved. The larger samples had hydraulic conductivities from 0.6 to 2.4 orders of magnitude greater than that of the small samples. The difference in hydraulic conductivity between small samples and field scale samples may be due to difficulties in achieving a representative sample of the soil with a small specimen. Preferential flow paths are more likely to form from initial conditions in a large scale sample because it is not confined during construction.

CAUSES FOR FAILURE OF CLAY BARRIERS AND LINERS

Failure of a clay barrier occurs when the hydraulic conductivity increases and allows liquid to enter or exit the barrier faster than the designed rate. Often, when the hydraulic conductivity of a soil is measured, the portion of the soil which may cause a barrier to fail (have high hydraulic conductivity) is precisely the portion of the soil which is not tested. A sample which has roots, rocks or poor cohesion will be avoided because of difficulty to acquire and test (Daniel, 1984). Failure of clay barriers in landfills can occur through improper construction methods, misinterpretation of clay properties, subsidence of the barrier due to poor compaction or decomposition of waste, degradation of the barrier due to chemical leachate interaction, or desiccation of the barrier.

Various aspects have been previously investigated with regard to the hydraulic conductivity of clay barriers. These studies identify several factors related to clay barrier performance, desiccation, test method and poor design and construction. These factors are simulated cracks, sample size and type, liner thickness, soil properties, desiccation and clod size.

Simulated Cracks

Vipulanandan and Leung (1992) stated that desiccation cracks can increase the hydraulic conductivity of clay barriers to a minimum of 10 times its original conductivity and subsequently explored methods by which to measure this change. They tried three methods for placing simulated cracks in clay samples that were approximately 10.16 cm (4 in) in diameter and 11.58 cm (4.56 in) in length. In the first method, permeable tubes with diameters up to 5 mm (0.20 inches) were filled with sand and placed in the clay to provide preferential flow paths via simulated cracks. The volume of the void created by one tube did not exceed 410 mm^3 (0.025 in^3). However, these tubes became clogged with clay and no notable change in the hydraulic conductivity was noted. The second method was to insert rods with a diameter of less than 1 mm into the clay sample to specified depths chosen by the tester. These rods were inserted and removed prior to starting the hydraulic conductivity test. When the hydraulic conductivity test was started the holes resealed and no change in conductivity was noted. The final method involved the insertion of hollow stainless steel needles with inside diameters of 0.45 mm (0.018 inches) into the clay samples. This method allowed the hydraulic conductivity of the clay to be controlled by the experimenter.

Figure 1-1 (Vipulanandan and Leung, 1992) shows how the hydraulic conductivity increases as the number of preferential flow paths increase. The conductivity of the soil was measured using a double ring rigid wall permeameter. Measurements of conductivity were taken under conditions of an uncracked sample and samples, with 6, 12, 18 and 24 cracks (pushed syringes). The pore volume of samples increased as the number of preferential flow paths increased and the hydraulic conductivity of the sample increased as well. A sample which had 24 cracks and a pore volume of 1.00 increased 5.5 times its original conductivity of less than 3×10^{-8} cm/s to greater than 1×10^{-7} cm/s.

In this case the 4 in (10.2 cm) diameter sample size was relatively small compared to actual barriers. As sample size decreased, the possibility of defects developing within the soil matrix decreased, which produced a lower hydraulic conductivity. As sample size increased, the possibility of defects developing within the soil matrix increased and the hydraulic conductivity increased as well.

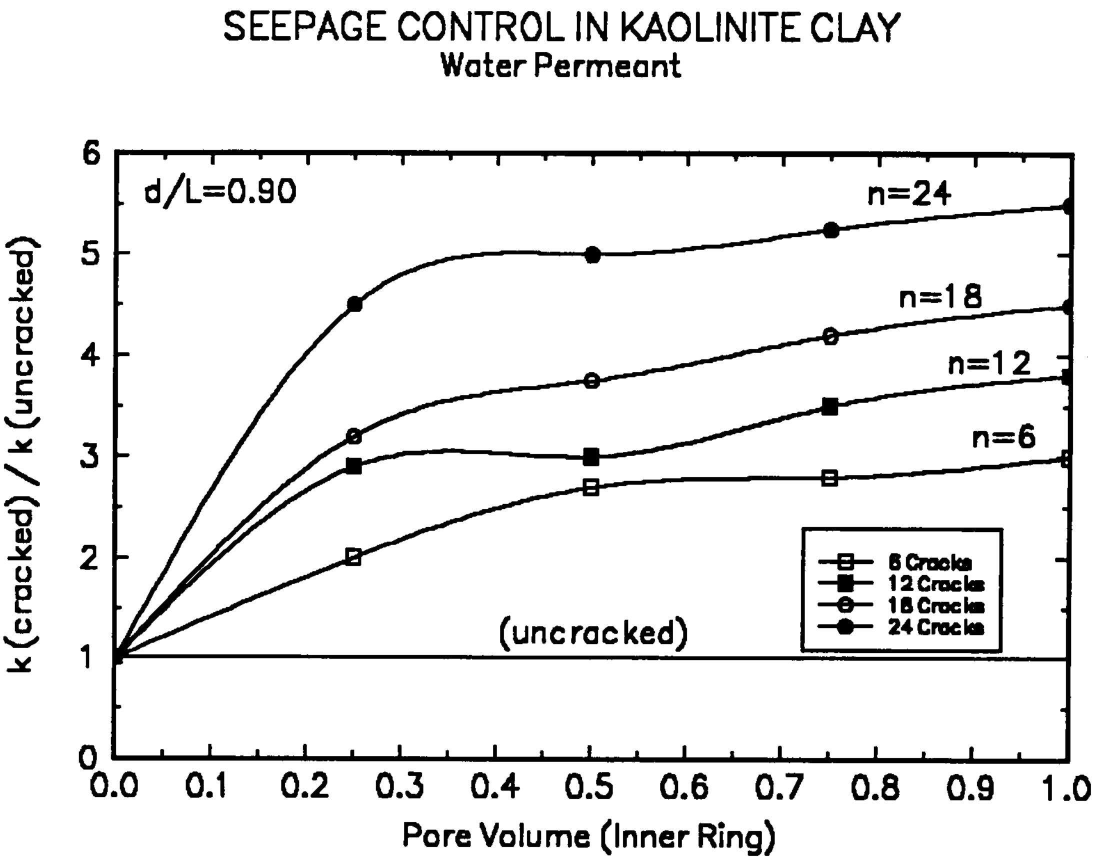

Figure 1-1 - Ratio of uncracked hydraulic conductivity to cracked hydraulic conductivity versus pore volume (after Vipulanandan and Leung, 1992)

Lysimeter Testing

Lysimeters can be used to test hydraulic conductivity of in situ soil or large laboratory samples. A lysimeter is a device containing a field size sample of soil and a filter layer of sand or other highly permeable material underneath that is used to measure water movement. When the lysimeter is used in the field the drainage layer is omitted because the device is placed beneath a sample that has been previously compacted. A filter fabric is placed between the highly permeable layer and the clay in order to prevent the migration of fine particles. Beneath the sand layer is a collection system which contains the permeant which has passed through the soil barrier. Because the size of a lysimeter is typically larger than 50 cm (20 inches) in diameter, the engineer may have a sample that is more indicative of the actual soil conditions. It is suggested by Benson et al. (1993) that measurements for several construction conditions may be made using sample sizes with an area as small as 0.07 m^2 (110 in^2) and thickness of 0.15 m (6 in). This sample size, which has a diameter of 0.3 m (11.8 inches), is large enough to provide accurate indication of macropores which may be present in actual barriers. The larger size also improves the ability to see the effects that drying cycles have on the clay barrier. Daniel (1989) suggests that some problems with measuring hydraulic conductivity with a lysimeter are the lack of ability to apply overburden and the length of time to obtain measurements. Lack of overburden may result in the hydraulic conductivity of laboratory tests using lysimeters being higher than values determined in the field. It is difficult to apply overburden even in field tests because the particular layer must be tested before overburden soil may be applied. Overburden applied to the soil barrier is important in preventing the swelling of the clay and in obtaining an accurate value of hydraulic conductivity of the soil.

Liner Thickness

Elsbury, et al. (1990) suggests that hydraulic conductivity can be related to barrier thickness. Several factors are important, such as lack of overburden, length of flow path and number of defects in the layer. The larger the overburden on the clay, the lower the conductivity will be because the consolidation will be greater. Voids are removed from the clay as consolidation increases and interclod flow decreases. Also, overburden can help prevent swelling, which may lead to the enlargement of interclod pores. A thick layer also causes preferential flow paths to travel a greater distance, thus, the permeant must go further in order to penetrate the barrier. As the thickness of a barrier increases, the number of lifts used to place the barrier must increase. The probability of connecting defects in the lifts decreases as more lifts are used. Shear, et al. (1992), support the idea that swelling increases the size of macropores. It was shown using electron microscopy and mercury intrusion that the voids within a cluster of clods do not increase significantly when high void ratios are recorded, and as the void ratio decreases the intracluster pores remain at a constant volume and the macropores decrease in volume.

Benson and Daniel (1994), conclude that breakthrough time is directly related to the number of lifts or increasing thickness of the barrier. They also found that the hydraulic conductivity of the entire barrier is dependent in the average hydraulic conductivity of each lift. Variability within the lift will occur. However, if concentration is placed on keeping the mean hydraulic conductivity of each lift low during construction the variability of hydraulic conductivity within the lift will decline. Daniel and Benson (1994) contend that four to six lifts will provide sufficient redundancy to prevent preferential flows paths from interconnecting and providing a continuous path through the barrier.

Sample Size

The size of the sample tested should be considered if the hydraulic conductivity is going to be accurately measured. The hydraulic defects found in large scale tests are less likely in smaller samples. Benson, et al. (1993), explain that poorly built liners can result when tests on small samples yield values of hydraulic conductivity that are many orders of magnitude lower than measurements obtained by field tests with larger samples. Defects which are produced in the field and in field size samples are difficult to reproduce in small samples and can be the controlling parameter of flow in clay liners. Field tests however, can prove to be difficult to perform due to time constraints and expense. Hydraulic gradient and stress state of the sample is also difficult to control due to changing field conditions. Benson, et al. (1993), state that

> "A logical alterative to field tests is to conduct standard laboratory conductivity tests on specimens large enough to simulate field conditions. Laboratory tests can be performed rapidly with accurate control of the state of stress and gradient."

Benson, et al. (1993), performed flexible-wall permeameter tests on samples taken by pushing a trimming ring, 0.58 meters (22.83 in) in diameter and 0.30 meters (11.81 in) in height, into the ground and digging away the excess soil. The sample was then placed in large scale flexible-wall permeameter and run according to The Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (ASTM D 5084). The results of this experiment showed that hydraulic conductivity was related to sample size for specimens with less than 0.07 m^2 (108.5 in^2) in cross-sectional flow area or 0.3 m (11.81 in) in diameter. These large samples yielded hydraulic conductivities at or near their measured field hydraulic conductivities.

The large scale testing by Benson, et al. (1993), concluded that the large samples are representative of the field-scale hydraulic conductivity, especially with poorly built clay liners. The minimum size of the large samples to assure field-scale measurements of hydraulic conductivity was a cross-sectional flow area of 0.7 m^2 (108.5 in^2), which corresponds to a diameter of 0.3 m (11.81 in) and a thickness of 0.15 m (6 in). This sample size is found to be adequate to represent the development of defects within a full-scale clay liner.

CRACKING OF SOIL BARRIERS

Desiccation cracking may occur when soils are exposed to atmospheric conditions. Evaporation of water causes negative pore pressure in the soil which consequentially causes an increase in effective stress. This effective stress increase produces a reduction of volume in all directions and cracking follows. These cracks may reseal as water reenters the soil. However, if the geometry of the crack is changed due to spalling or additional rock or sand flowing into the crack, the crack will be unable to properly reseal (Kleppe and Olsen, 1985). These open cracks will then contribute to the increase in hydraulic conductivity. Kleppe and Olsen (1985) suggest that desiccation cracking can "be prevented by avoiding evaporation by watering, sealing or burying the liner." These methods, with the exception of burying, may not be applicable to landfill use.

The following sections deal with factors that are applicable to this thesis which may contribute to increasing hydraulic conductivity of clay barriers.

Soil Properties

Cracking can also be attributed to soil properties such as, percentage of clay, plasticity and shrink/swell properties. The addition of sand to a clay or a reduction of the percentage of clay will decrease the tendency for the soil to shrink and swell, and thus reduce the likelihood or severity of cracking. However, conductivity may increase as the percentage of clay decreases (Kleppe and Olsen, 1985).

Desiccation

Bronswijk (1991), tested field-scale samples of clay that measured 27.6 cm (10.87 in) in diameter and 60 cm (23.62 in) thick. These samples indicated that cracking could occur in clay samples representative of clay barriers in as few as four days. Bronswijk classified the shrinkage of his samples into four categories. Shrinkage that occurred in days one through four was classified as "structural shrinkage". During "structural shrinkage" water content decreased rapidly yet shrinkage of the soil was very small. The second stage of shrinkage, occurred from day 5 to 35 was called "normal topsoil shrinkage". In this stage the shrinkage rate is equal to the decrease in water storage (i.e., volume of water retained in the sample). The third stage occurred from day 36 to approximately day 70. During this stage "residual shrinkage" of the topsoil occurs when the rate of loss of water storage becomes higher than the shrinkage rate of the clay. After 70 days the process repeated itself starting with normal shrinkage of the subsoil. The normal shrinkage of the subsoil becomes the dominant force in cracking of the soil while residual shrinkage of the topsoil continues.

The steps outlined by Bronswijk (1991) agreed with G. B. Stirk (1954). However, Stirk experimented with 14 different soils (nine of these soils were classified as clays) ranging in thickness from 10.2 cm (4 in) to 86.4 cm (34 in), and found that the length of time for the soil to pass from one stage to the next was dependent on the particle size of the soil. Also, in the clay soils used by Stirk, the "structural shrinkage" accounted for 0 - 7 percent of the total shrinkage, "normal shrinkage" accounted for 12 - 24 percent of the total shrinkage and "residual shrinkage" accounted for 3 - 10 percent of the total shrinkage. The total shrinkage was not accounted for because the sample was not dried back to 0% water content.

While frequent shrinking and swelling does produce cracking, it also improves soil structure (Bronswijk, 1989). The aggregate volume decreases and the density increases as the cycles of shrinking and swelling repeat. This is not good if the purpose of the clay barrier is to prevent the flow of water. However, if drainage is desired in the soil, altering the soil structure through cyclic shrinkage and swelling will lead to improved drainage.

Sibley and Williams (1993) used Deagon clay to measure strain as water content decreased in the samples. When placed in a mold that provided initial restraint on the samples, the clay displayed circumferential cracks. These circumferential cracks yielded an inner disk of clay which remained an intact soil aggregate. This soil aggregate when unrestrained did not display cracking. This would suggest that if a clay barrier could, in some manner, be placed and remain minimally restrained that desiccation may be minimized as the water content decreased.

Clod Size

Shackelford and Javed (1991), noted that in large scale permeability testing, the conductivity is related to precompaction clod size. The larger the precompaction clod size of the clay the higher the permeability. Clod size may not effect density when compacted in the Proctor mold due to the small volume and high confinement. However, when compacting large scale samples the volume is greater and the clods are more difficult to break down during compaction. Also, the lack of confinement can cause the void ratio to be increased. Large voids are more likely to form when the sample has large clods. Therefore, flow would occur between the clods (through the interclod voids) instead of through the clods.

DESIGN AND CONSTRUCTION OF CLAY BARRIERS

Daniel (1984) suggested the following points be considered for designing and constructing clay barriers that will help achieve the desired hydraulic conductivity and prevent leakage. Initially, the engineer should refrain from trying to design a barrier that will be susceptible to damage occurring because of its thickness during construction and postconstruction changes due to desiccation. Secondly, good construction inspection is essential with water content, clod size and quality of the clay should be as close to optimum as possible. Thirdly, the use of laboratory testing should be kept in perspective realizing that laboratory tests, especially with small samples, will often underestimate the hydraulic conductivity of the soil. These tests should be used as guidance for initial design, remembering that some type of geomembrane may be needed in the final design. In situ testing of the soil should be used to verify the hydraulic conductivity determined by laboratory testing and for assurance of quality construction.

Benson and Daniel (1994) suggested that increasing the thickness of the barrier does increase the breakthrough time for both well built and poorly built barriers. However, there is a reasonable number of lifts (4 to 6) that should provide sufficient thickness, if compacted properly, to prevent the interconnection of preferential flow paths that are inherently present in these clay barriers.

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PART II

FLEXIBLE-WALL PERMEAMETER TESTING

INTRODUCTION

The flexible-wall permeameter is used to measure hydraulic conductivity of soil samples, usually with condition of falling headwater, rising tailwater (Figure 2-1). The samples are placed in a latex membrane, or flexible-wall, which prevents sidewall flow when the sample is placed under a confining pressure while in a triaxial cell. The fluid is then allowed to flow from high pressure (headwater) to low pressure (tailwater) from the bottom of the sample through the top of the sample. By allowing the fluid to flow from bottom to top, air in the sample is more likely to be displaced. Hydraulic conductivity is determined when the amount of water displaced from the headwater pipet is equal to the amount of water gained in the tailwater pipet.

Soil samples measured in the flexible-wall permeameter represent an intact, continuous, homogenous clay barrier much like an intact or noncracked portion of a clay barrier. These samples are dimensionally similar to those taken by means of a Shelby Tube sampler, but were laboratory compacted in a Proctor mold and trimmed prior to testing. The samples are approximately 10.3 cm (4.06 in) in height and 7.2 cm (2.83 in) in diameter. The density and water content of these samples are more likely to be uniform than larger field-scale samples (Part III) because they were mixed in 2.72 kg (6 lb) batches where water content losses could be controlled. The samples were compacted according to ASTM D 698 standards, therefore they are consistent with industry methods.

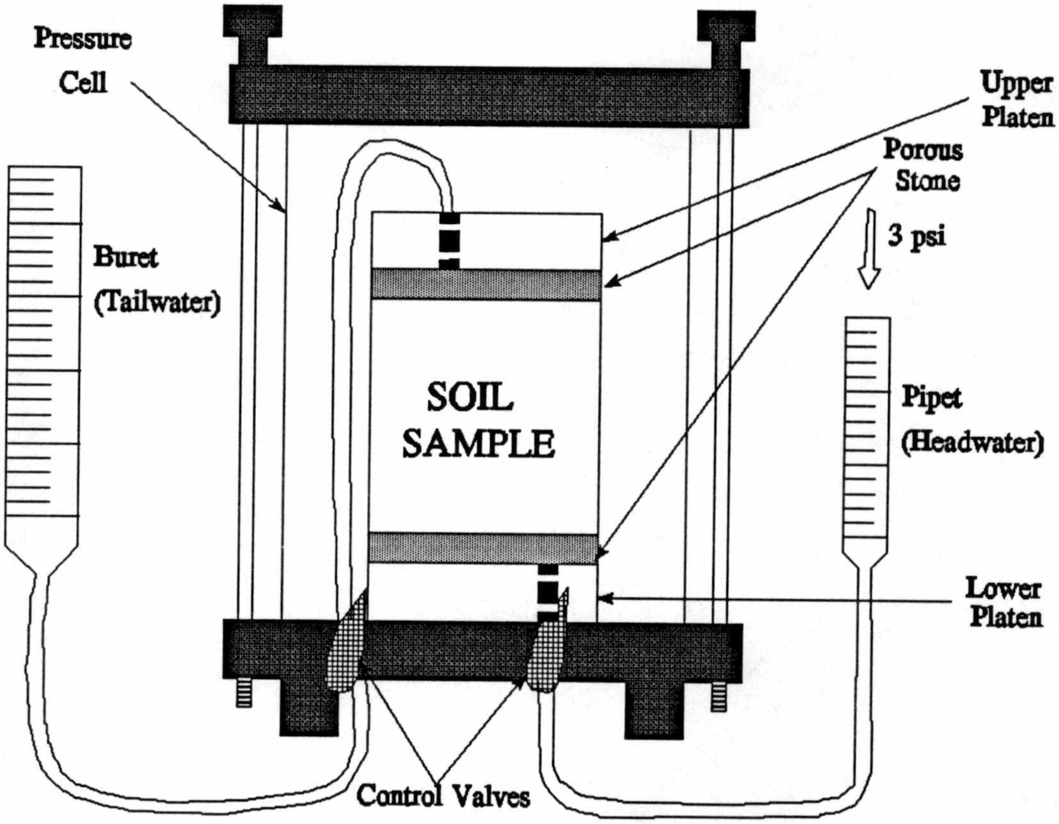

Figure 2-1 - Flexible Wall Permeamater schematic

EXPERIMENTAL METHOD

Materials

The clay tested in this portion of the project was obtained from the West Chestnut Ridge Borrow Area in Oak Ridge, Tennessee and has been used for capping purposes on the Oak Ridge Reservation. It was a reddish brown silty clay classified as CH according to the Unified Soil Classification System (USCS). Particles less than 2μm accounted for 50% of the soil (Figure 2-2) and the liquid limit and plastic limit were 61 and 31, respectively (Table 2-1). These soil properties are similar to those determined by Daniel and Benson (1990) who also studied clay from West Chestnut Ridge.

Test Procedure

The test procedure is similar to that used by Phifer (1993) in determining kaolinite barrier response. The samples where compacted at specified water content and trimmed to fit the flexible-wall permeameter. The hydraulic conductivity was determined by the ASTM Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (D 5084) Method C. The samples were then dried in atmospheric conditions before the hydraulic conductivity was measured again. Differences from Phifer's (1993) procedure will be noted in the next sections.

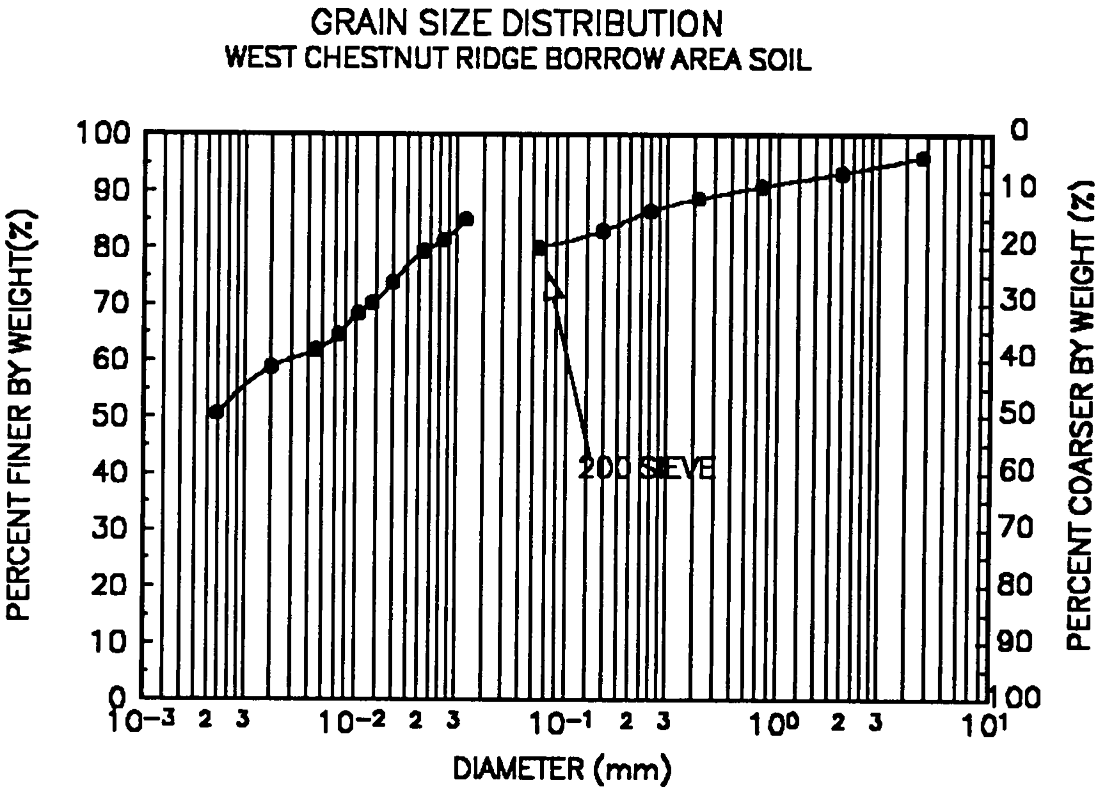

Figure 2-2 - Grain size analysis of West Chestnut Ridge clay

Table 2-1 - West Chestnut Ridge Borrow Area Clay (CH)

Mineral Composition[1]	Quartz	
	Kaolinite	
	10 A° Clay (Illite)	
Particle Size	Sand(<500μm)	15%
	Silt(<74μm)	32%
	Clay(<2μm)	50%
Atterberg Limits	Liquid Limit	61
	Plastic Limit	31
	Plasticity Index	30
Miscellaneous	Specific Gravity	2.63

[1]Phifer, 1992

Sample Preparation

Standard Proctor tests were performed according to ASTM Test Method for Moisture-Density Relations of Soil and Soil-Aggregate Mixtures Using 2.49-kg (5.5-lb) Rammer and 305-mm (12-in) Drop, (D 698) (Figure 2-3 and Table 2-2). In addition, the soil was passed through a number 4 sieve before it was remolded in the laboratory.

Two samples for hydraulic conductivity testing were prepared using standard Proctor energy. The first sample was prepared at optimum water content and the second sample at 3% above optimum water content. The samples were prepared in a 10.16 cm (4 in) Proctor mold, scarified on the ends and trimmed with a soil lathe in order to fit the flexible wall permeameter. The flexible-wall permeameter may fit a sample with maximum diameter of 7.20 cm (2.83 in) while the maximum height of samples tested was 10.28 cm (4.05 in). The initial dry density and water content conditions of the samples are shown in Figure 2-3. In Table 2-3 these conditions are listed along with initial dimensions.

Hydraulic Conductivity Test Procedure

Falling head water-rising tailwater hydraulic conductivity tests were performed in accordance with ASTM Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (D 5084) Method C. Equipment used, manner of saturation and confining pressure were identical to the hydraulic conductivity tests on kaolinite by Phifer (1993). As with Phifer's kaolinite testing, a 0.01 N calcium sulfate ($CaSO_4$) solution was used as the permeant. The

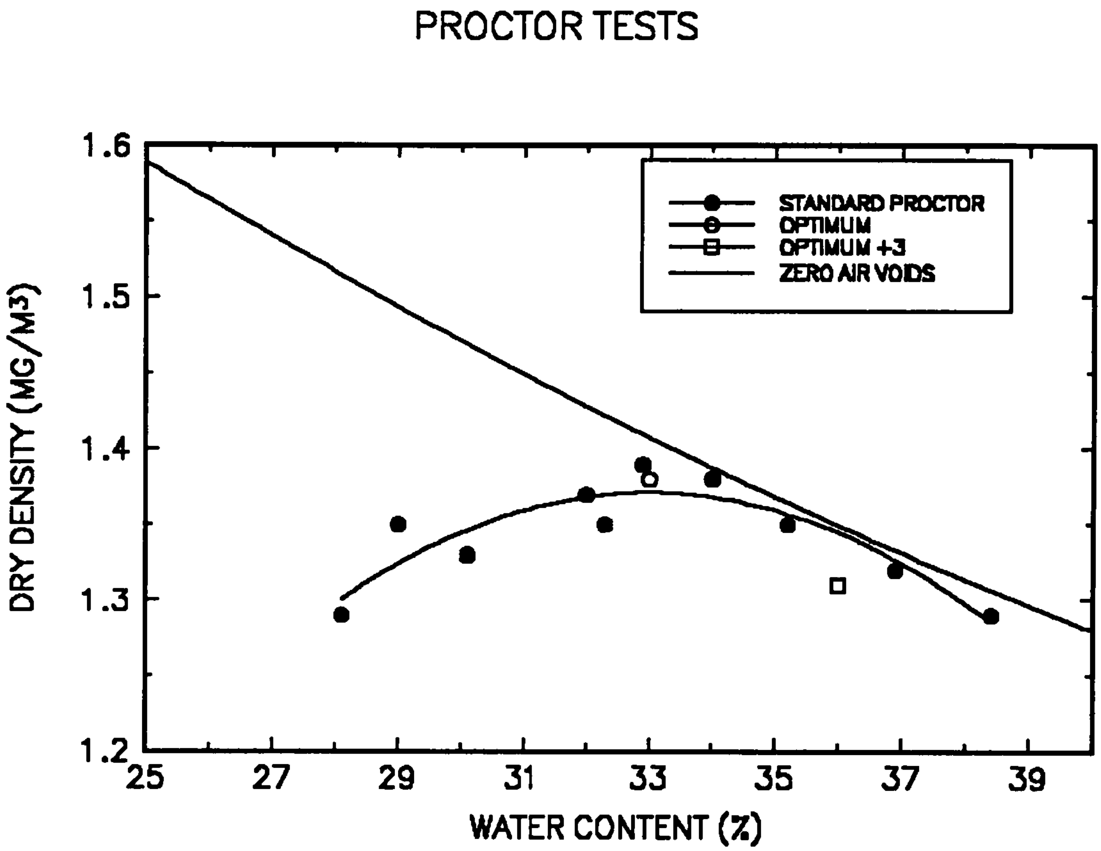

Figure 2-3 - Moisture density relationship and inital sample preparation

Table 2-2 - Results of Proctor Tests

Parameter	Standard
Optimum water content (%)	33.0
Maximum dry density (Mg/m^3)	1.37

Table 2-3 - Initial sample preparation

Sample	Dry Density (Mg/m^3)	Water Content (%)	Average Diameter (cm)	Average Length (cm)
Optimum	1.38	33.0	7.094	10.260
Optimum +3	1.31	36.0	7.030	10.280

hydraulic gradients (Table 2-4) were determined by dividing the change in head between the headwater and tailwater by the height of the sample. Temperatures during the test ranged between 21.0 and 27.0°C. Hydraulic conductivity was corrected to 20.0°C. The initial values of hydraulic conductivity were 3.6 x 10^{-7} cm/s for the optimum sample and 6.9 x 10^{-7} cm/s for the optimum +3 sample. These values were determined from the equation for conductivity for falling headwater-rising tailwater hydraulic conductivity tests (Daniel, 1989):

$$k = \frac{a_i \times a_o \times L}{(A \times t) \times (a_i + a_o)} \ln\left(\frac{h_1}{h_2}\right) \quad (2\text{-}1)$$

where,

k = hydraulic conductivity, cm/s
a_i = headwater pipet cross-sectional area, cm^2
a_o = tailwater pipet cross-sectional area, cm^2
L = sample length, cm
A = sample cross-sectional area, cm^2
t = time between readings, s
h_1 = initial sample head loss, cm
h_2 = final sample head loss, cm

Sample Dry-back Procedure

The samples were dried after the measurement of the initial saturated hydraulic conductivity. Dry-back of the samples was performed by placing them horizontally on a filter fabric, while remaining in the membrane in order to prevent any loss of soil due to contact with the filter fabric. Both ends of the samples were exposed to the air to ensure uniform drying of the samples. Temperature ranges were from 21.0 to 27.0°C and humidity ranges were from 32 to 86%. Each day the sample weight, room

Table 2-4 - Hydraulic conductivity test parameters

Sample	Headwater hydraulic head range (m)	Talwater hydraulic head range (m)	Hydraulic gradient range
Optimum	2.32 - 2.06	0.65 - 0.72	16.28 - 13.06
Optimum +3	2.30 - 2.05	0.71 - 0.83	15.47 - 11.87

temperature, and humidity were recorded until the desired water content was reached. The samples were then resaturated in the flexible-wall permeameter and the dry-back hydraulic conductivity determined. Each of the samples was subjected to 5 drying cycles.

RESULTS

The flexible-wall permeameter samples are representative of an uncracked portions of clay barriers. The behavior and changes in hydraulic conductivity, with the changes in water content and volumetric strain, of these samples are discussed in the following sections.

Hydraulic Conductivity Versus Time

Figures 2-4 and 2-5 represent the optimum and optimum +3 sample changes in hydraulic conductivity over time. Measurements of conductivity were erratic and unpredictable during each saturation period until the flow became steady. As the sample became fully saturated the reading of hydraulic conductivity became steady.

Both samples showed a decrease in hydraulic conductivity with each successive dry-back period. Although small cracks could be seen developing during the dry-back periods, these cracks did not seem to affect the conductivity of the samples because the cracks formed at lift boundaries which were perpendicular to flow. After four dry-back periods the conductivities of the samples were 1.7×10^{-8} cm/s and 2.0×10^{-8} cm/s for

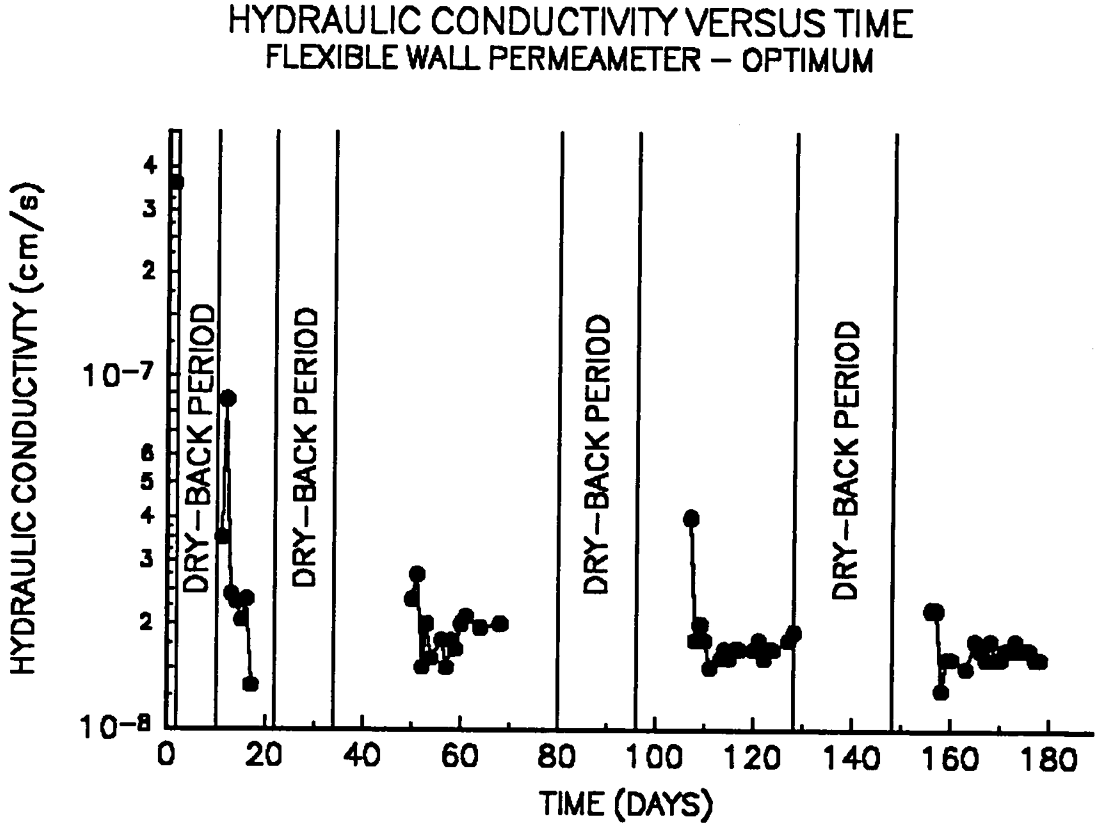

Figure 2-4 - Hydraulic Conductivity Versus Time - FWP Opt.

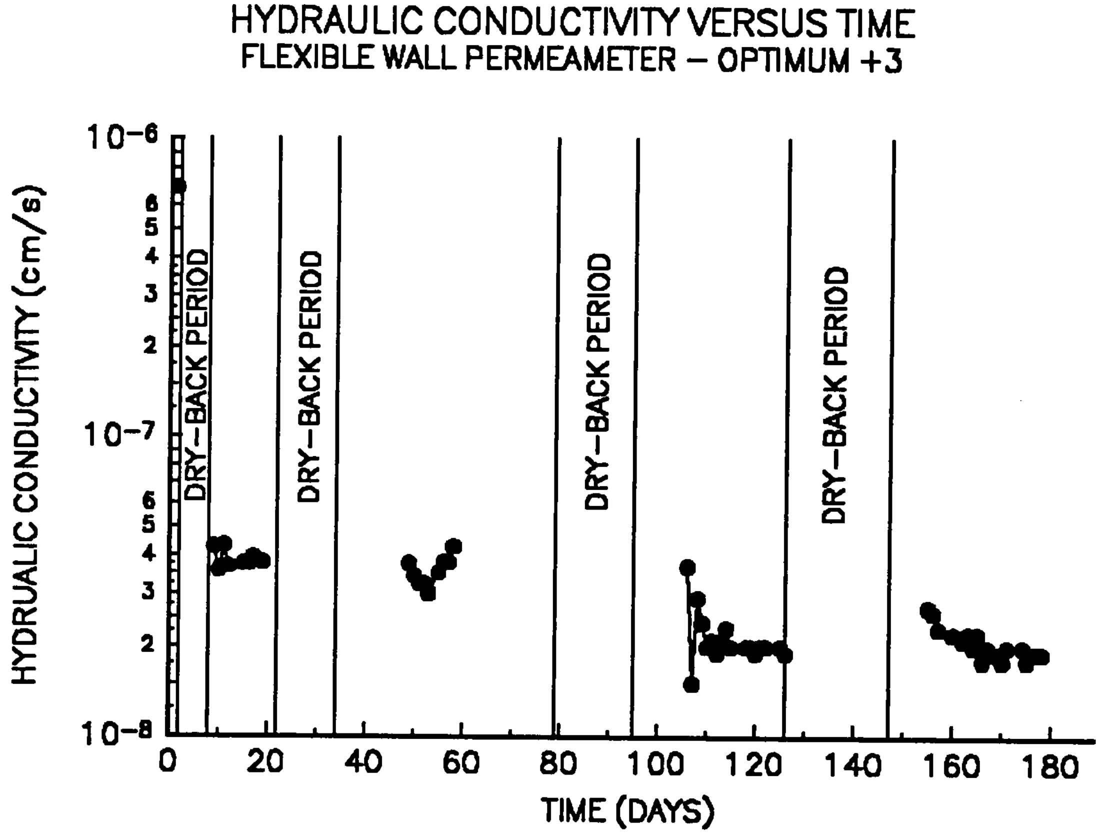

Figure 2-5 - Hydraulic Conductivity Versus Time - FWP Opt.+3

the optimum and optimum +3 samples, respectively. This is a decrease of just over one order of magnitude.

Dry-Back Paths

The optimum and optimum +3 samples were subjected to several cycles of drying and saturation (Figure 2-6 and 2-7). Observation number 1 indicates the initial conditions of the sample. Odd numbered points represent conditions at the end of the dry-back cycle and even numbered points represent conditions at the end of the permeation or saturation cycle. The zero air voids curve is compared with the saturated points (Figure 2-6 and 2-7). Deviations in the measurement of the specific gravity and/or the dry density explain why these points were slightly above the zero air voids curve.

Initially, the optimum sample shrank slightly (density increased) with the first permeation (Figure 2-6, Point 2). It continued to shrink with each succeeding dry-back cycle. During the permeation cycles (rebound cycles) the sample approached the initial water content conditions but did not duplicate this condition. Point 4, for both samples, was calculated from density measurements because an error occurred when measuring the weight of the samples when determining the gravimetric water content. The dry density remained greater than the initial density and continued to increase with each successive cycle. The final rebound water content by weight was observed to be 30.4%. The final observed dry-back density was 1.59 Mg/m^3 and the limiting rebound density was 1.49 Mg/m^3. The difference between the last observed dry-back and rebound densities was 0.10 Mg/m^3. A similar response was observed by Phifer (1993) for kaolin

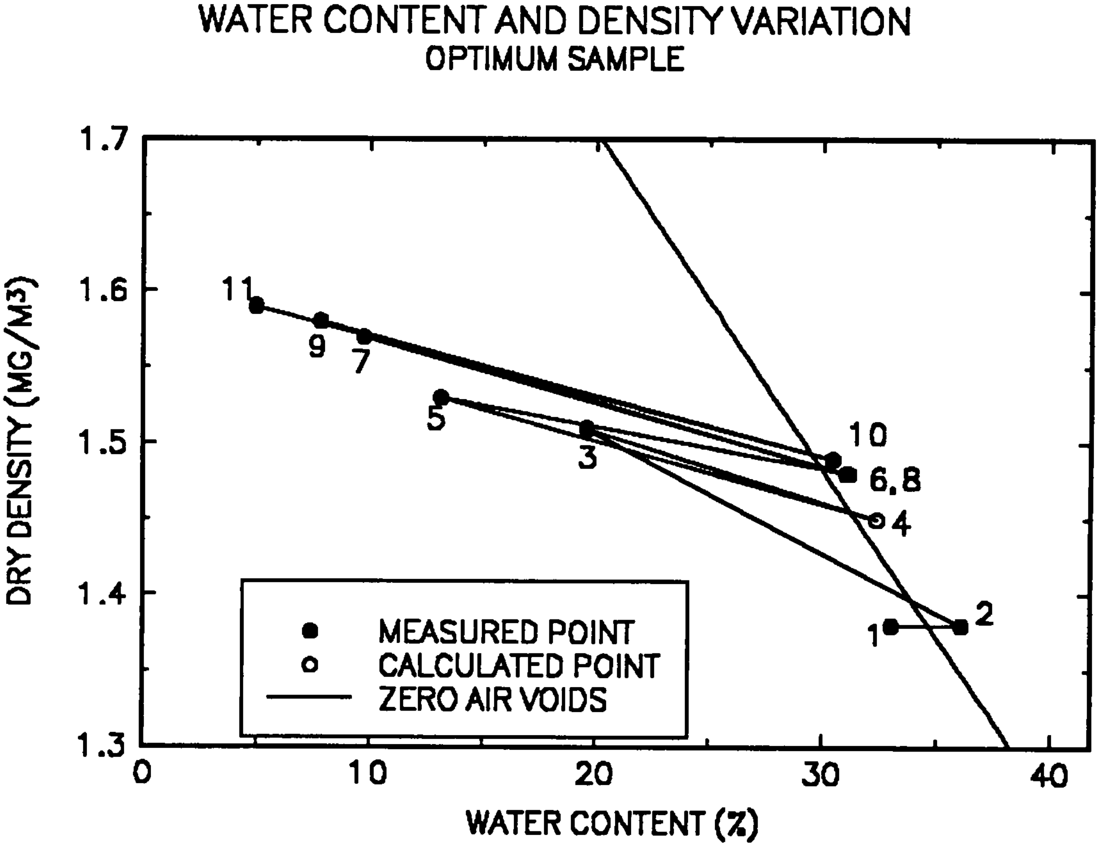

Figure 2-6 - Optimum cyclic dry-back path

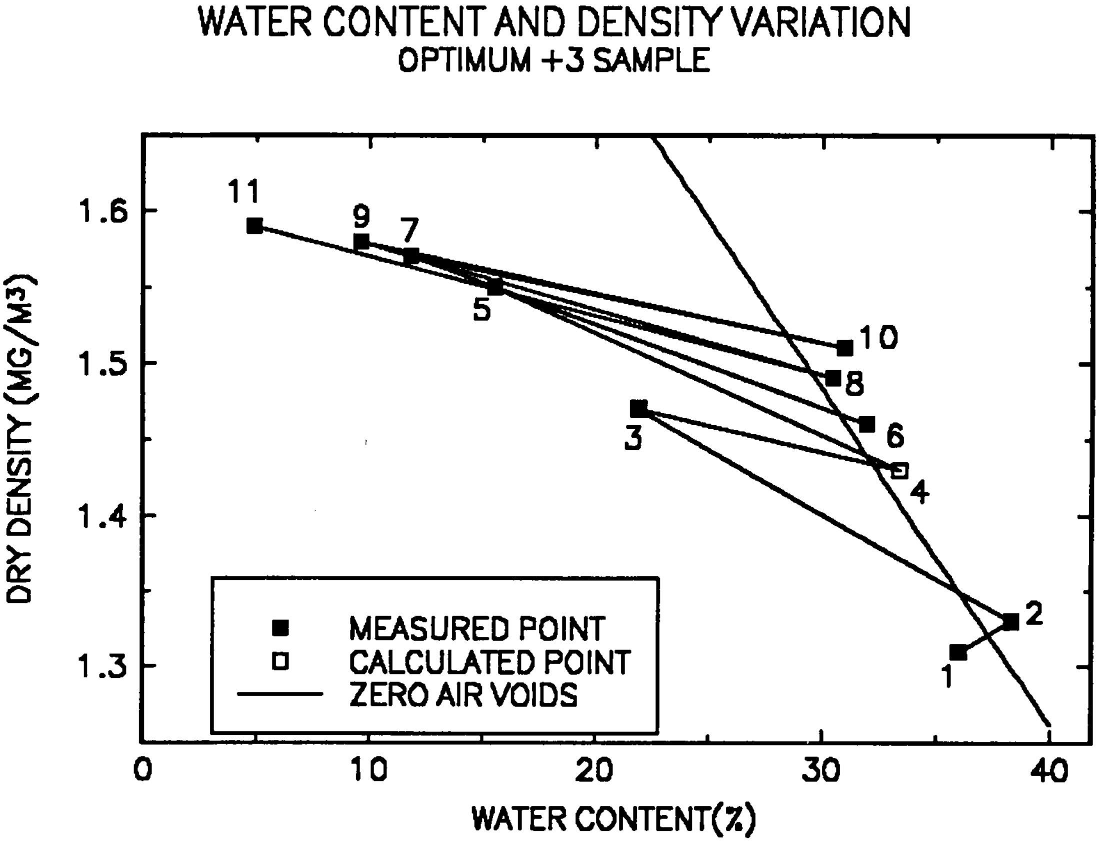

Figure 2-7 - Optimum +3 cyclic dry-back path

clay. The density continued to increase as the dry-back water content decreased. The initial magnitude of water content change in the dry-back cycle was greater than the initial dry-back of the kaolinite samples since the determination of the limiting conditions was the goal of the testing. The dry-back density decreased with subsequent drying cycles.This change indicated that the limiting values of density were being approached.

The optimum +3 sample also experienced slight shrinkage in the initial permeation cycle (Figure 2-7, Point 2). Successive dry-back cycles displayed an increase in density. Rebound cycles, once again, did not approach the initial density of the sample. Again, point 4 was calculated due to an error in determining the water content of the sample. The initial water content conditions were approached but not duplicated. As with the optimum sample, the final observed dry-back density was 1.59 Mg/m^3 and the limiting rebound density was 1.49 Mg/m^3. The difference between the final observed dry-back and rebound densities is 0.10 Mg/m^3, just as the optimum sample. The final observed rebound gravimetric water content is 30.4% which is identical to the optimum sample. This suggests that the clay has a limiting rebound water content at or near 30.4% after repeated drying and saturating cycles. Also, when the soil is at 100 percent saturation, the water content will not exceed 30.4%. This characteristic is also independent of initial water content. As in the case of the optimum sample, these values of density also increased with additional cycles of drying and saturation. The optimum +3 sample results corroborated the findings in the optimum sample. The samples were dried-back with large initial losses in water content in order to determine the limiting conditions quicker. These water content losses were decreased as the sample became drier.

These data points obtained showed that the initial water content does not have a significant effect on the limiting rebound densities, the final dry-back densities or the rate of density change. In Figure 2-8 it can be seen that the final observed rebound densities of each sample were closer to the final dry-back densities than they were to the initial densities of each sample. Both the final rebound densities and the final dry-back densities converged to almost the same point regardless of the initial water content. The rate of density change in the soil depended on the initial water content because the sample approached the same maximum dry-back density (Table 2-5). The overall density increase shows that the higher the initial water content, the greater the magnitude of potential density change upon dry-back. This density increase was greater for the optimum +3 sample because the initial density was lower. It may be seen in Figure 2-8 and Table 2-5 that the final dry-back density and limiting rebound density was independent of the initial water content.

Hydraulic Conductivity Variations

Initial hydraulic conductivities, of 3.6×10^{-7} and 6.9×10^{-7} cm/s, were measured for the optimum and optimum +3 samples, respectively. Daniel and Benson (1990) tested several samples of clay from the same location and reported measurements which were between 1.0×10^{-7} and 1.0×10^{-8} cm/s. The soil used in this project is similar to the West Chestnut Ridge Soil Type A reported by Daniel and Benson (1990). The

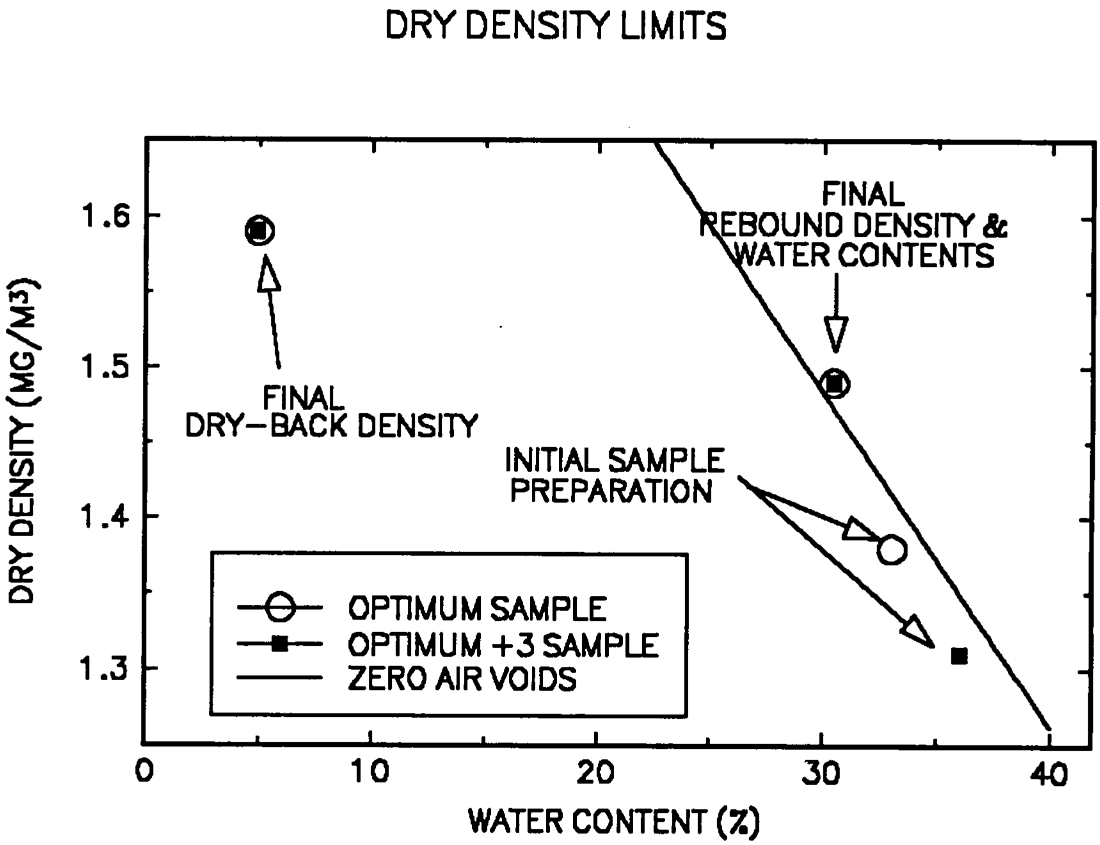

Figure 2-8 - Dry-back and rebound density and water content limits

Table 2-5 - Dry-back effects on water content and density

Sample	Overall sat. w.c. decrease[1]	Overall reb. ρ increase[2]	Overall D-B ρ increase[3]	Reb. ρ rate of change[4]
Optmimum	-28.06	.115	.215	0.0041
Optimum +3	-31.11	.179	.277	0.0007

[1]saturated water content (%); [2]rebound density (Mg/m^3); [3]dry-back density (Mg/m^3); [4]rebound density (Mg/m^3) increase per 1% dry-back

Atterberg Limits of the clay in this project were six to eight percentage points higher then type A soil used by Daniel and Benson (1990). Also, the optimum gravimetric water content of this project's soil was 33% versus 23% which was reported by Daniel and Benson (1990). This could reflect the slight differences in the hydraulic conductivity of the two soils collected from West Chestnut Ridge. In spite of these differences, similar values were obtained from both test programs.

Density Effect

Since the soil for both samples was passed through a number 4 sieve prior to compaction, the hydraulic conductivity should be dependent on density and not clod size (Benson and Daniel 1990). The log of hydraulic conductivity was linearly related to density (Figure 2-9). The numbers on the figure refer to the cycle number in Figures 2-6 and 2-7. The density was determined after saturation. For both samples the largest decrease in hydraulic conductivity was noted after the first dry-back cycle (Cycle #2). The hydraulic conductivity decrease between cycles became smaller and more consistent after this initial dry-back. Both samples converged to limiting values of hydraulic conductivity and density as summarized in Table 2-6. It should be noted that the initial dry-back cycles for both samples exceeded a ten percent loss of water content, and the second cycles were approximately seven percent. This contributed to the large differences in the hydraulic conductivity over a change in density of 0.15 Mg/m^3.

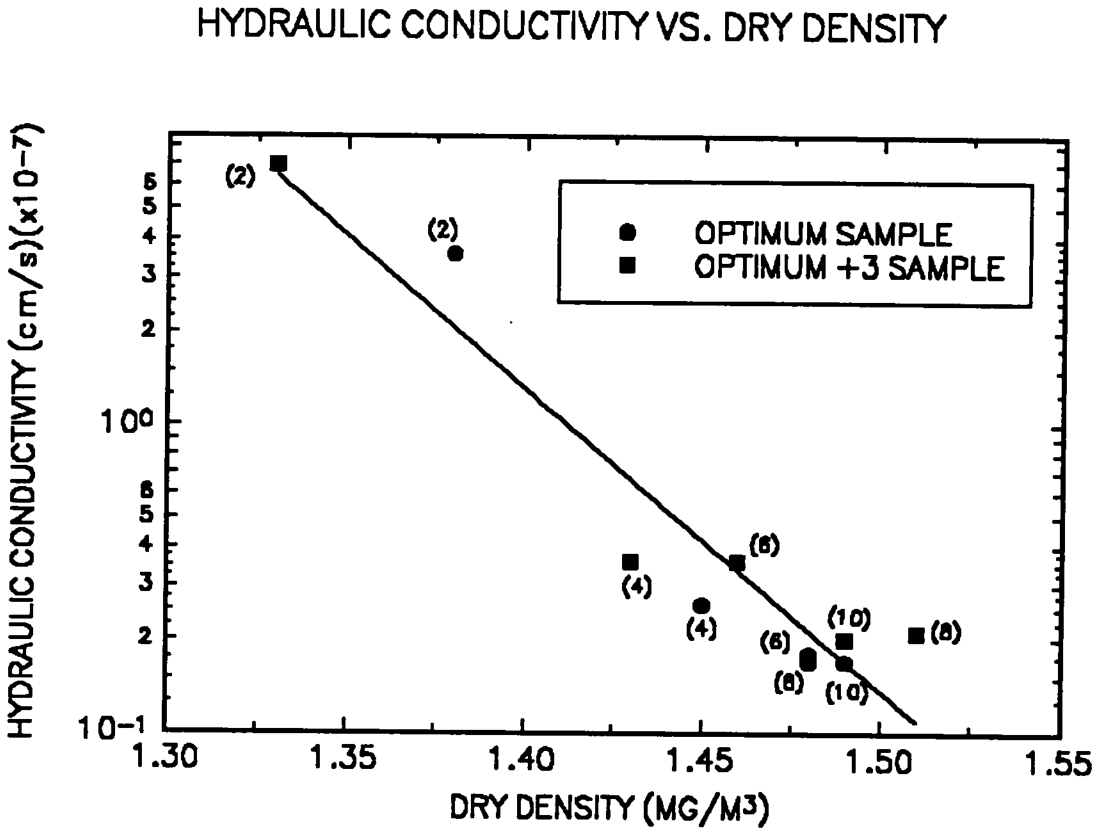

Figure 2-9 - Rebound density effects on hydraulic conductivity variation

Table 2-6 - Hydraulic conductivity

Sample	Initial hyd. cond.[1] (cm/s)	Final hyd. cond.[2] (cm/s)	Final obs. reb. density[3] (Mg/m^3)	Final obs. sat. wat. content[4] (%)
Optimum	3.6×10^{-7}	1.7×10^{-8}	1.49	30.43
Optimum +3	6.9×10^{-7}	2.0×10^{-8}	1.49	30.43

[1]Initial hydraulic conductivity; [2]Final hydraulic conductivity; [3]Final observed rebound density; [4]Final observed saturated water content

Saturated Water Content Effect

The saturated water content (rebound cycle) was linearly related to the log of the hydraulic conductivity (Figure 2-10). The numbers on the figure indicate the cycle corresponding to Figures 2-6 and 2-7. As mentioned previously, point number 4 (for both samples) in Figure 2-6 and 2-7 was back calculated from the density measurement due to an error in determining the water content. The hydraulic conductivity decreased with each decrease in saturated water content. The greatest decrease, again, came after the first dry-back cycle. However, when the samples were resaturated for the permeability test, the ability of the sample to return to its original saturated water content was hampered by the increasing density. Therefore, the saturated water content decreases with each dry-back cycle. While the resaturation does not affect the change in saturated hydraulic conductivity, the change in density does. A certain percentage of the density increase is unrecoverable. This percentage depends on the initial water content of each sample because the samples approached the same water contents as dry-back cycles increased.

Volumetric Strain Effect

The volumetric strain represents the change in volume during the drying and wetting cycles divided by the volume measured after the initial compaction. The hydraulic conductivity was weakly related to the dry-back volumetric strain (Figure 2-11) and rebound volumetric strain (Figure 2-12) during the cyclic water variation. The

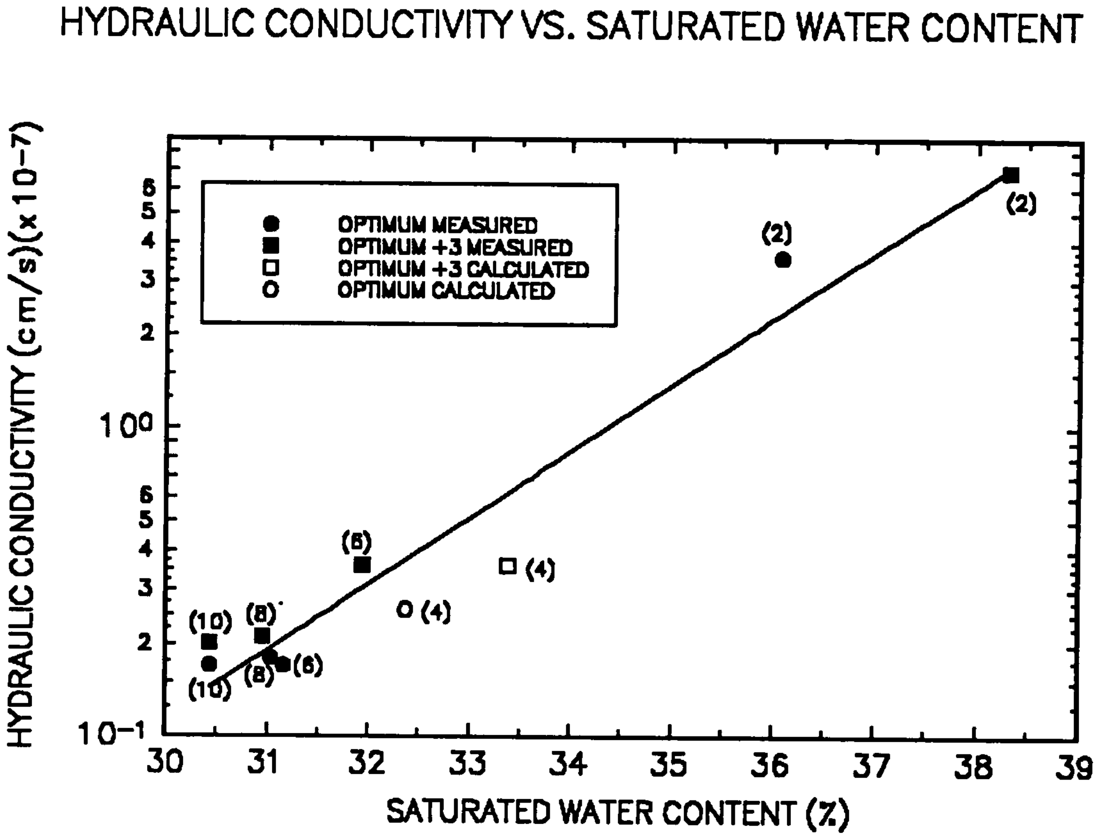

Figure 2-10 - Saturated water content effects on hydraulic conductivity variation

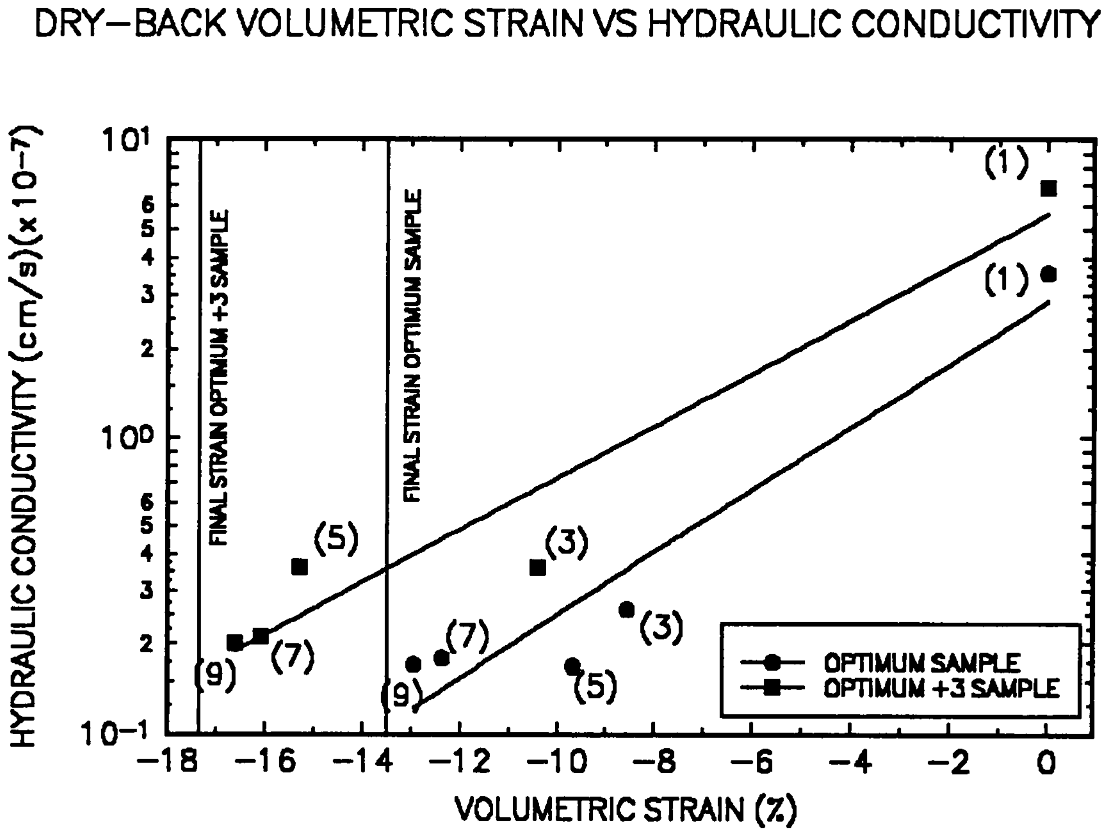

Figure 2-11 - Hydraulic conductivity versus volumetric strain of dry-back cycles

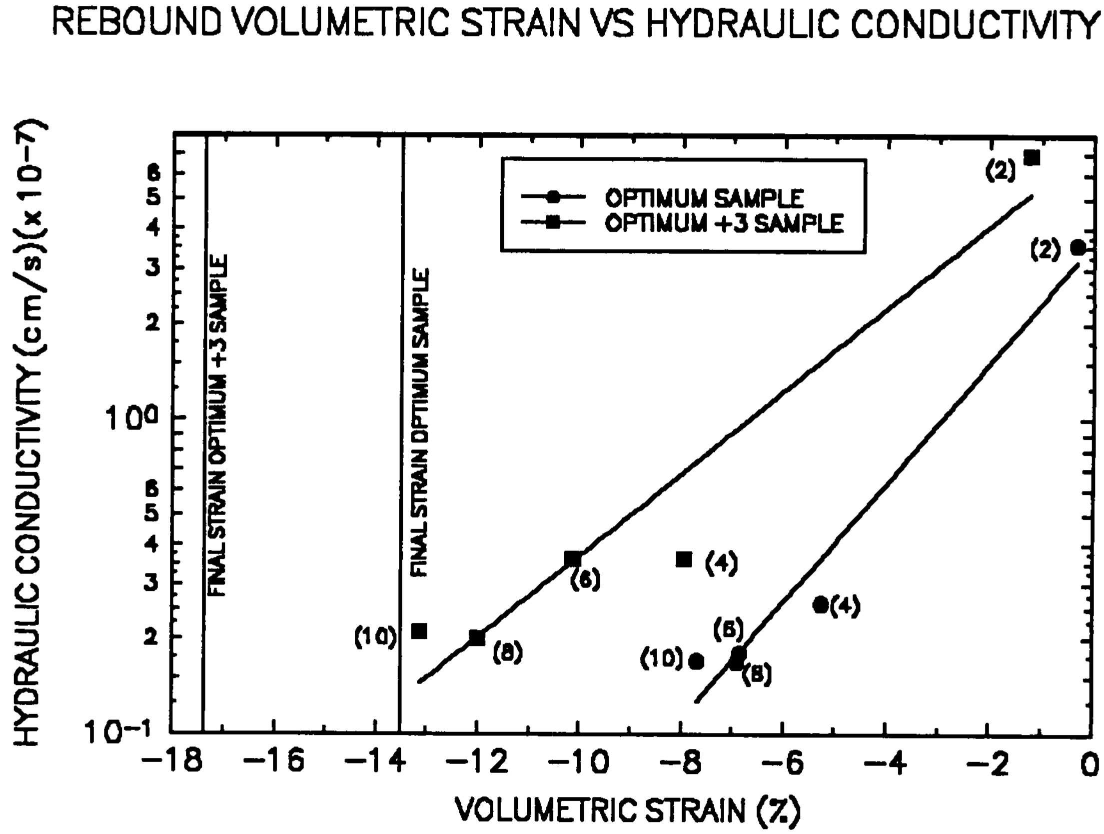

Figure 2-12 - Hydraulic conductivity versus volumetric strain for rebound cycles

numbers on both figures represent the corresponding cycles in Figures 2-6 and 2-7. Both samples display increased strain during both dry-back and rebound cycles. This shows that both the saturated water content and saturated density cannot return to the initial conditions and are approaching a limiting value. Unlike the relationships shown with the different samples using hydraulic conductivity versus saturated water content are dry density, these relationships are independent due to the difference of the initial saturated water content. The greater the initial water content the greater the strain upon dry-back. In the current log relationship, at equal strains, the optimum sample shows a lower hydraulic conductivity due to its initial higher density and current higher density than the optimum +3 sample. The difference in the strain values between the samples tends to increase. This indicates that the optimum +3 sample will not reach the same hydraulic conductivity as the optimum sample under identical compaction energy and different initial water content. Equal hydraulic conductivity can only be achieved by expansion of the samples. Table 2-7 shows that while the final strains for both cycles are different the strain rates are similar. The different initial water contents of the samples will not allow the final strains to be the same because one sample will have to experience greater strain in order to reach the same dry density.

SUMMARY

The flexible-wall permeameter sample is representative of the uncracked portions of a clay barrier, or the intact clay matrix. These data provide information on the effects of post compaction water content variation on the saturated hydraulic conductivity of

Table 2-7 - Volumetric Strains

Sample	Rebound vol. strain rate[1]	Last obs. reb. vol. strain[2]	Last obs. D-B vol. strain[3]
Optimum	-2.87	-6.872	-9.647
Optimum +3	-2.02	-10.095	-15.275

[1]Rebound volumetric strain (%) per 1% dry-back; [2]Last observed rebound volumetric strain (%); [3]Last observed dry-back volumetric strain (%)

compacted clay from the West Chestnut Ridge Borrow Area in Oak Ridge, Tennessee. The samples were permeated and dried to increasingly lower water contents in a cyclic manner. The information observed from the data collected can be summarized as follows:

1) The initial shrinkage and density increase in the samples was greater than that of subsequent cycles because the initial dry-back cycle had a larger decrease in water content than subsequent cycles. As the water content decreases became smaller, the density increases became smaller as well. There appears to be a limiting value of dry density.

2) Upon resaturation, the initial saturated water content conditions of the samples were approached but not duplicated. With each successive dry-back cycle the rebound water content was progressively less than the initial water content. The density conditions were not replicated in any cycle but increases in the density became smaller as cycles increased. The final limiting densities were observed to be nearly identical for both the dry-back and rebound cycles, regardless of the initial water content.

3) The sample with the higher initial water content and lower initial dry density experienced the greatest volumetric change. When constructing clay barrier the

water content should be kept at or near optimum in order to prevent volume change which leads to cracking in the barrier.

The extent of water content variation had a direct bearing on the variation of dry density and volumetric strain. The strain and density variations were not fully recoverable. As the density of the samples increased, hydraulic conductivity decreased. This is because the flexible-wall sample behaved essentially as a singular, intact soil aggregate with no cracks. This is unlike the behavior of an entire clay barrier. Only the impacts on the aggregates between cracks due to desiccation was studied. Thus, the flexible-wall samples represent the portions of the clay barrier which dry-back but do not crack by behaving in this manner. When hydraulic conductivity of a soil is determined for a clay barrier, these intact, homogenous samples are often used for the measurements. Clay barriers will inevitably degrade and form cracks and these measurements may not reflect the actual conductivity of the entire barrier.

In the next part of this research these cracked portions of a clay barrier will be explored using a field-scale laboratory sample to determine hydraulic conductivity. The procedure of cyclic wetting and drying will be similar in order to reproduce those same cycles which occur both in the atmosphere and the vadose zone.

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Part III

LYSIMETER TESTING

INTRODUCTION

Lysimeters are used to measure water movement through soil, e.g. hydraulic conductivity of field-scale samples, typically one to two meters in diameter either in the field or in the laboratory. Lysimeters may be used either in the field or in the laboratory. When in the field the lysimeter may be placed directly beneath the soil which is to be tested or the sample may be built directly in the lysimeter with field sized equipment if the lysimeter is large enough. When using field lysimeters the head applied on the sample is difficult to control and the hydraulic gradient cannot be measured directly. The lysimeters in this portion of the research were used in the laboratory and placed in a room were the water content of the samples could be controlled. Because these lysimeters are in the laboratory the sample had to be reconstructed with equipment that was able to be handled in the confined space where the lysimeters were kept. The advantages to keeping the lysimeters in the laboratory were the wetting and drying cycles could be controlled, time and labor used to construct the lysimeter was kept localized and unwanted intruders were not allowed to disrupt the test. Additionally, the hydraulic gradient on the sample could be measured accurately. By being able to control the water content of the sample, wetting and drying cycles that occur naturally (periods of rain and heat) were controlled in the lab. Also, the conditions of saturation and drying which occur in the vadose zone may be easily modeled.

Unlike the flexible-wall samples discussed previously, the samples which were used in the lab lysimeters are more representative of actual clay barriers because they may represent a heterogeneous structure. The density of the lysimeter samples are not as consistent as the flexible-wall samples due to the volume differences and because they were compacted by a different means. The density of the lysimeter was also determined differently than the flexible-wall samples. Instead of measuring and weighing the entire sample as with the flexible-wall samples, a small portion of the field-scale sample was removed in order to determine the density, and assumed to represent the entire sample. The variation of density and water content throughout the sample was not investigated. However, desiccation induced volume changes in the lysimeter sample may result in cracking which may cause the density of the entire sample to increase. These discontinuities in the sample are a contributor to the significant increases in hydraulic conductivity of the entire the sample while the hydraulic conductivity of the soil matrix decreases.

PROCEDURE

In order to test the hydraulic conductivity of the West Chestnut Ridge clay as a heterogeneous clay barrier, the following steps in construction of the lysimeter and preparation of the sample were performed. The purpose of the lysimeter samples was to simulate the conditions present in a field scale clay barrier which is also a heterogeneous soil mass.

Lysimeter Construction

The lysimeters used in this research are basins used for measuring hydraulic conductivity of soil by placement of soil in the interior of the vessel. Water is then applied to soil sample and allowed to permeate the soil. The bottom of the lysimeter has a water collection device to obtain measurements of the volume of water passing through the soil. In this case, erlenmeyer flasks were used to collect the water exiting the bottom of the lysimeter.

These lysimeters were made entirely of welded polyvinyl chloride (PVC). They were circular in shape with a diameter of 75 cm (29.5 in) and depth of 62 cm (24.4 in). The bottom of the lysimeters were divided into 14 chambers from which water is collected (Figure 3-1). The two outer chambers (#13 and #14) prevented readings from being influenced by sidewall leakage from draining water that passed between the sample and the lysimeter wall. The twelve other chambers were created by two concentric circles, with four chambers in the inner circle and eight chambers in the outer circle. The height of the dividing section of the collection chambers was 8 cm (3.15 in). The outside of the lysimeter and the walls of each chamber were sealed with silicon caulk.

The entire lysimeter was elevated 15.9 cm (6.25 in) so collection bottles may be placed underneath the chambers. The lysimeter was drained through a nozzle which emptied into a 1.6 cm (5/8 in) hose. The fluid then passed into a compression chamber and entered the bottle through a 0.64 cm (1/4 in) hose. The 0.64 cm (1/4 in) hose was kept in place by a two hole stopper which was connected to the collection bottle. The hydraulic conductivity was measured using a constant head test. In order to keep the water level at a constant height, a drain spout was placed approximately 30.5 cm (1 ft) above the projected top of the soil sample. Since the bottom of the soil sample is at atmospheric pressure, the head on the sample could be kept constant at 33.0 cm (13 in).

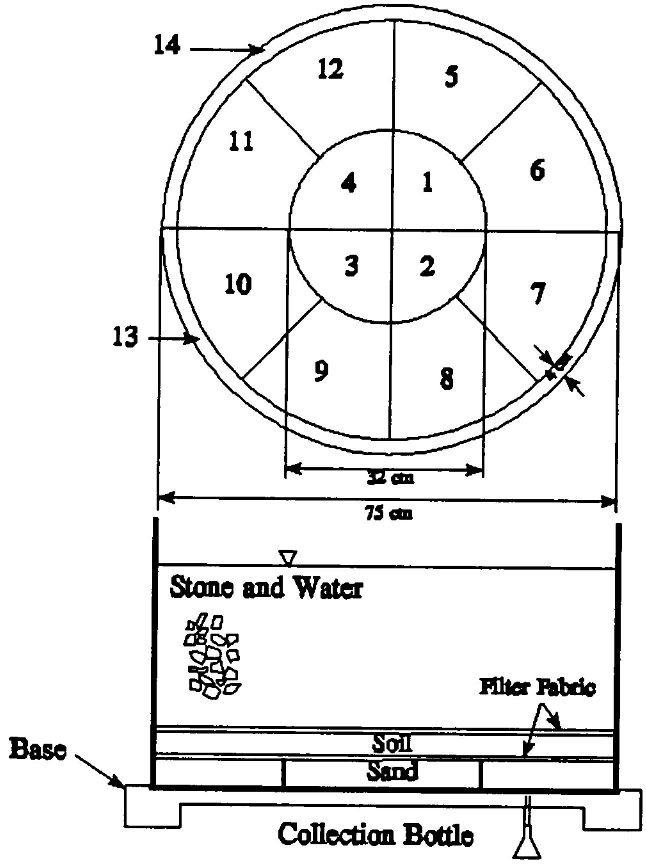


Figure 3-1 - Plan view of individual chambers of lysimeters (Top)
Cross-section of lysimeter (Bottom)

Lysimeter Preparation

Soil Preparation

After being passed through a number 4 sieve, the soil was mixed to the desired water content in a 0.5 or 1.5 cubic yard concrete mixer by adding the appropriate amount of water with a sprinkler bottle while the soil was being stirred. The soil was compacted in two lifts, with the soil for each lift mixed separately. The soil was double bagged, placed in small, metal cans and placed in a humidity room for a minimum of 24 hours prior to compaction to ensure full saturation of the soil.

Drainage Layer Preparation

Ottawa sand was placed in the bottom of the lysimeter in each chamber, to promote drainage below the soil sample. This layer was approximately 8 cm (3.15 in) high and compacted using a 2.49 kg (5.5 lb) rammer and by draining with water. A 0.64 cm (1/4 in) thick geotextile (Supac• 16NP-L17800) was placed over the sand layer and sealed around the circumference with silicon caulk to prevent leakage. The geotextile and sand both have a hydraulic conductivity much greater than that of the soil and are assured to have negligible effect on the hydraulic conductivity measurements.

Compaction

Initially, the bottom portion of the lysimeter wall was scarified with sandpaper and prepared with a two-part epoxy in order to bond the PVC and the soil to reduce sidewall leakage. IPS Weld-On 810™ Two-Part Adhesive was used on Lysimeter A and PC-7 Multi-purpose Waterproof Epoxy was used on Lysimeter B. The PC-7 Multi-purpose Waterproof Epoxy was easier to work with in the confined space of the lysimeter.

Two methods where used to compact the samples in the lysimeters. A 2.49 kg (5.5 lb) Proctor rammer and a 1.6 cm (5/8 in) thick by 15.2 cm (6 in) diameter metal plate were used to compact the sample. The soil was placed in two lifts and compacted to 3.8 cm (1.5 in) thickness for each lift for a total height of approximately 7.6 cm (3 in).

In the first method, the sample was compacted to a specified height to ensure the desired density was achieved. The rammer was dropped on a metal plate to compact the soil. The larger surface area used to compact the soil was thought to save time in compaction without sacrificing density. However, the desired density of sample A was not met with this method.

The second method was similar to the first but the metal plate was not used and the soil was not compacted to a specified height. The rammer was used to directly compact the sample. A layer of wax paper was placed over the sample during compaction to prevent the soil from sticking to the rammer. The number of drops to compact the lysimeter to the proper density was determined by the ratio of drops of the rammer to the area of the mold when compared to the Standard Proctor test. To compact each lift of the sample 1360 drops of the rammer were required . The sample prepared in this manner is referred to as Lysimeter B.

Overburden

To prevent swelling of the soil and simulate overburden of topsoil, thirteen to fourteen inches of gravel was placed on the soil. The load was equivalent to approximately 6.34 kPa (0.92 lbs/in^2). This surcharge was enough to keep the soil firm enough to sample and prevented any noticeable swelling. The gravel was separated from the soil by a layer of Supac® 16NP-L17800 geotextile in order to prevent the stone from lodging into the clay sample and keep fine particles from migrating into the clay sample. This geotextile was not caulked into place so it could be easily removed when the sample was being dried-back. After reaching steady state flow through the soil sample, the overburden was removed along with the geotextile in order for the clay to dry. Swelling of the clay due to the removal of the overburden was assumed to be negligible.

Water Collection

As the water flowed through the soil barrier and into the divided chamber below it was collected in flasks. The water traveled through a nozzle, which was welded in place underneath the lysimeter, and into vinyl tubing which emptied into a flask. The tubing was connected to the flask by inserting it into a double holed rubber stopper. The second hole was left open to the atmosphere. A flask containing water was kept exposed to the atmosphere in order to determine if any water was lost due to evaporation. Adjustments to the final weight collected in each flask were made according to the weight lost in the evaporation flask. The volume of water collected was corrected for 20.0°C after the selected time interval for data collection (which varied from 20 minutes to five days) was finished, the flasks were collected and weighed. Water collected on the outside of the flask was wiped off prior to weighing the flasks. The hydraulic conductivity of the soil sample was calculated by Darcy's Law based on the hydraulic gradient of the sample, change in time over the collection period, the area of the collection chamber and the weight of the water collected.

Hydraulic Conductivity Calculation

The hydraulic conductivity was determined from Darcy's law. The temperature of the water was recorded at the collection time and the density was determined. Flow was then calculated by the following equation.

$$Q = \frac{Wt.\ H_2O - Evap.\ Loss}{\rho \times \Delta T} \quad \textbf{(3-1)}$$

where,

Q = Flow of water through soil sample, (cm^3/s)
Wt. H_2O = Mass of water collected in flask, (g)
Evap. Loss = Water loss in evaporation flask, (g)
ρ = Density of water, (g/cm^3)
ΔT = Change in time, (s)

The hydraulic gradient was determined by dividing the thickness of the clay sample by the height of the water. It was assumed that the energy or head loss through the geotextile, sand and piping to the collection bottle was negligible and the lysimeter exit was at atmospheric pressure. After flow was determined, the hydraulic conductivity was calculated knowing the hydraulic gradient of the sample and the area of the collection chamber.

$$k = \frac{Q}{A \times i} \quad (3\text{-}2)$$

where,

$\boldsymbol{k}$ = Hydraulic conductivity of individual chamber, (cm/s)
$\boldsymbol{Q}$ = Flow, (cm^3/s)
$\boldsymbol{A}$ = Area of chamber, (cm^2)
$\boldsymbol{i}$ = Hydraulic gradient, (cm/cm)

The hydraulic conductivity for each individual chamber was determined. Then the hydraulic conductivity of the entire lysimeter was determined by summing the flows determined in each chamber and dividing by the total area and the hydraulic gradient.

$$k_T = \frac{\Sigma Q}{A_T \times i} \quad (3\text{-}3)$$

where,

$\boldsymbol{k_T}$ = Total hydraulic conductivity of soil sample, (cm/s)
$\boldsymbol{\Sigma Q}$ = Sum of flows in each chamber, (cm^3/s)
$\boldsymbol{A_T}$ = Entire area of lysimeter collection chambers, (cm^2)
$\boldsymbol{i}$ = Hydraulic gradient, (cm/cm)

In this manner, the overall or total hydraulic conductivity was determined, as well as the hydraulic conductivity for each individual chamber.

RESULTS

The dry density of the lysimeter sample was determined by pushing a soil sampling tube into a solid soil region of the barrier. This sampling tube had an inside diameter of 1.85 cm (0.73 in) and an outside diameter of 2.5 cm (0.98 in). The volume of the sample which was extruded was measured for width. The height was measured from the void left in the barrier. The extruded sample was dried and weighed in order to determine the dry density. This measurement was reported as the dry density of the entire lysimeter sample. When cracks occurred these could not be measured or taken into account when determining the dry density. While the dry density of the soil which was actually measured was accurate, the dry density of the areas which displayed cracking could not be measured. These samples were taken as close the outer sections (#13 and 14) as allowed in the event that the may have caused leakage. The hole left by the sampling method was repaired by compacting clay of similar water content in the hole to form a plug. No leakage was observed from these clay plugs and no cracks were observed to propagate from the plugs.

The smallest detectable hydraulic conductivity is at or near 1×10^{-9} cm/s. Measurements below this rate are questionable due the water storage capacity of the Ottawa Sand used in the drainage layer. While some sections of the lysimeters had non-detectable flow or flow that was measured in the 10^{-10} cm/s range, these flows could possibly be higher since a portionof the water that passed through the clay barrier must recharge the sand. Flow that was greater than 1 x 10^{-9} cm/s was not influenced by the storage capacity of the sand because the amount of water that passed through the barrier was greater than that which was capable of being stored in the sand.

Lysimeter A Results

Lysimeter A was compacted with a Standard Proctor rammer and a metal plate in order to reduce the number of blows required to compact the entire sample. Approximately 220 blows were required per layer. When the soil met the required height it was assumed that the sample had met the required density. As a result of this method, this clay barrier did not become as dense as desired. The initial density of Lysimeter A was 1.20 Mg/m^3 with a water content of 35.8 %. The density, water content and resulting hydraulic conductivity were measured for each cycle (Table 3-1). For reference, the optimum water content of the soil was 33.0% and the maximum dry density was 1.37 Mg/m^3. After day ten of the initial saturation cycle, the overburden was added to the sample.

Hydraulic Conductivity Over Time

In contrast to the flexible-wall tests, which tested only the clay matrix, the hydraulic conductivity of the entire lysimeter tended to increase throughout the length of the testing period (Figure 3-2). During each cycle however, the sample showed a temporal decrease in hydraulic conductivity. No significant changes were seen after the

Table 3-1 Lysimeter A Parameters

Run	Dry-Back	W(%)	$\rho(Mg/m^3)$	K(cm/s)
-	Initial	35.8	1.20	-
1	-	-	-	$1.3x10^{-6}$
-	1	31.2	1.32	-
2	-	-	-	$7.0x10^{-6}$
-	2	27.0	1.43	-
3	-	-	-	$> 1.4x10^{-4}$

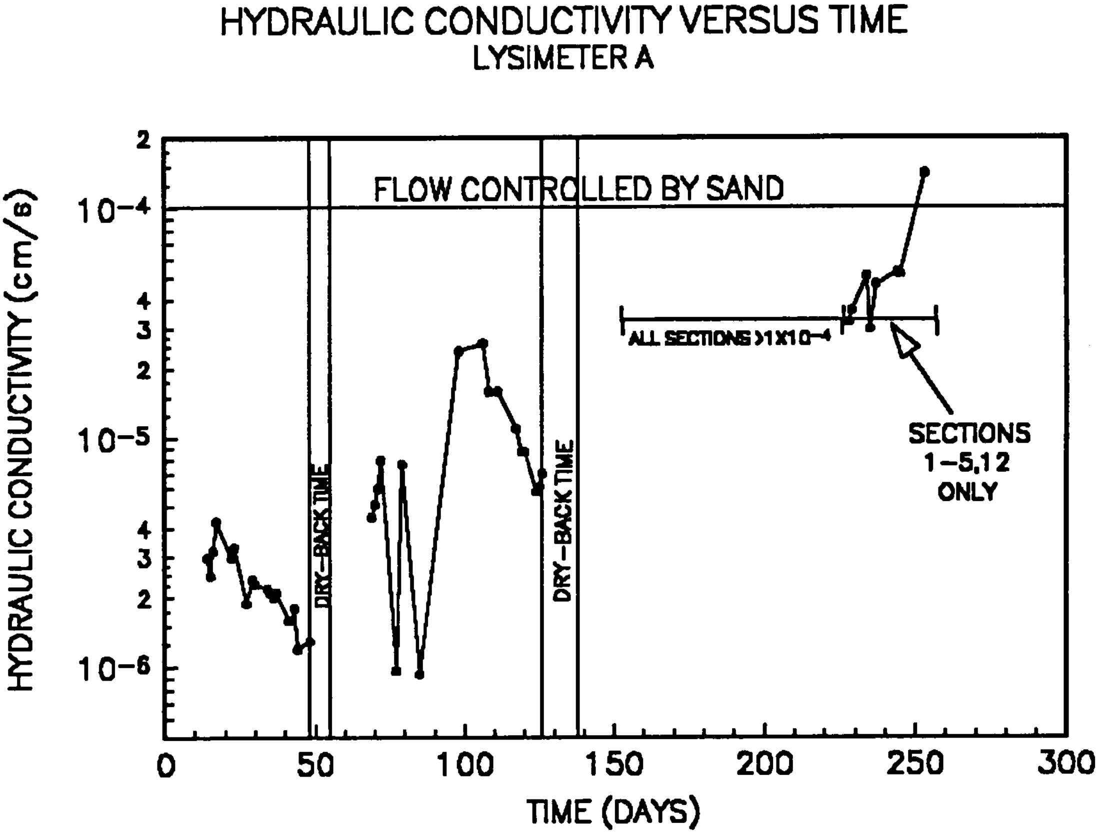


Figure 3-2 - Hydraulic conductivity over time - Lysimeter A

overburden of 6.34 kPa (0.92 lb/in^2) was added after the tenth day. The dry-back cycles caused increases in overall hydraulic conductivity because of cracks that developed in the sample. Early measurements within each cycle exhibited large variations that were attributed to incomplete saturation. Upon complete saturation, the sample experienced a peak hydraulic conductivity value and then proceeded to decrease in value. The third cycle showed increases that were difficult to measure because of the extent of the cracking within the sample and yielded values of hydraulic conductivity greater than 1 x10^{-4} cm/s.

Sectional Hydraulic Conductivity

The lysimeter was divided into 14 subsections as shown in Figure 3-1. The hydraulic conductivity of each section was compared to the hydraulic conductivity of the entire lysimeter for each cycle over time. Examples are shown in Figure 3-3, 3-4 and 3-5 from Lysimeter A, section 7 for runs one, two and three. The entire set of graphs for Lysimeters A can be seen in Appendix A. The total hydraulic conductivity over time is represented by the triangle and the hydraulic conductivity of the particular section is represented by the circle. While the hydraulic conductivity of the individual sections did vary greatly (as much as two orders of magnitude) in the first cycle, the general trend was for the flow to decrease over time within the saturation cycle. Some sections displayed minimal flow (less than 1 x 10^{-9} cm/s), while others had flow which would be greater than 1 x 10^{-10} cm/s. The breakthrough time, which is the initial time for the fluid to pass through the soil, also varied between sections. The number of readings taken

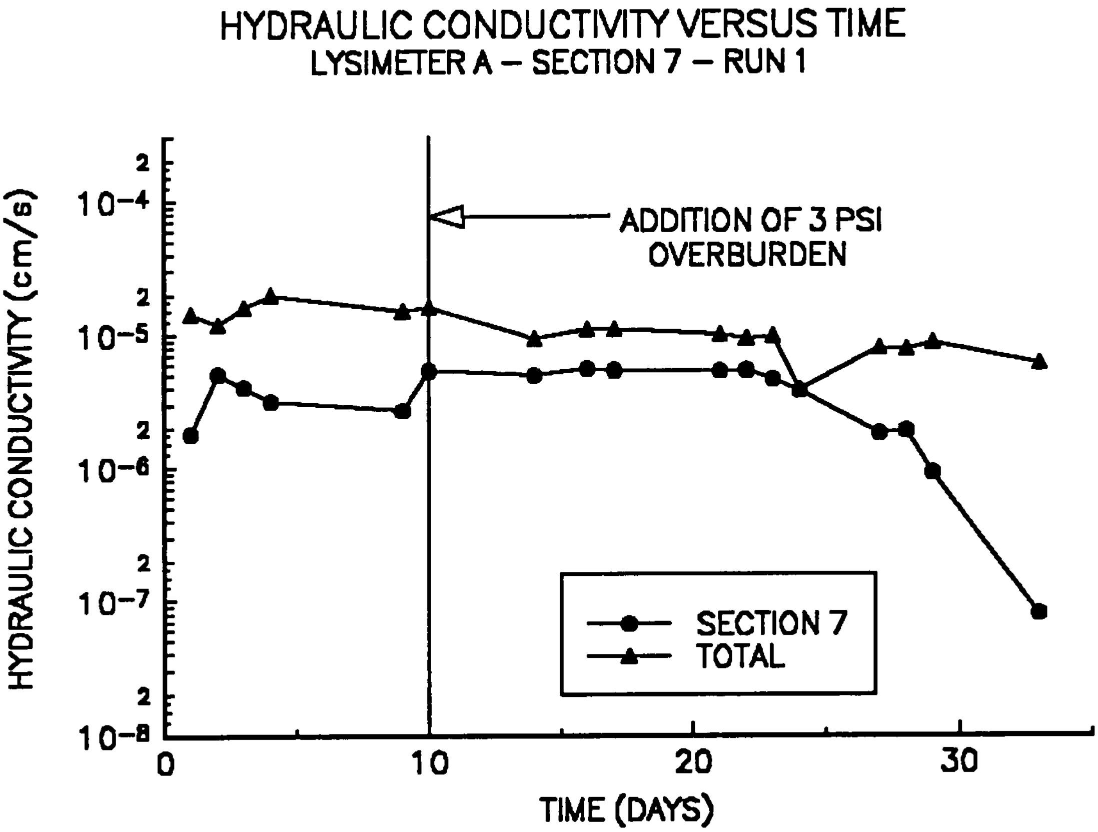


Figure 3-3 - Hydrualic conductivity versus time - Lysimeter A, Section 7, Run 1

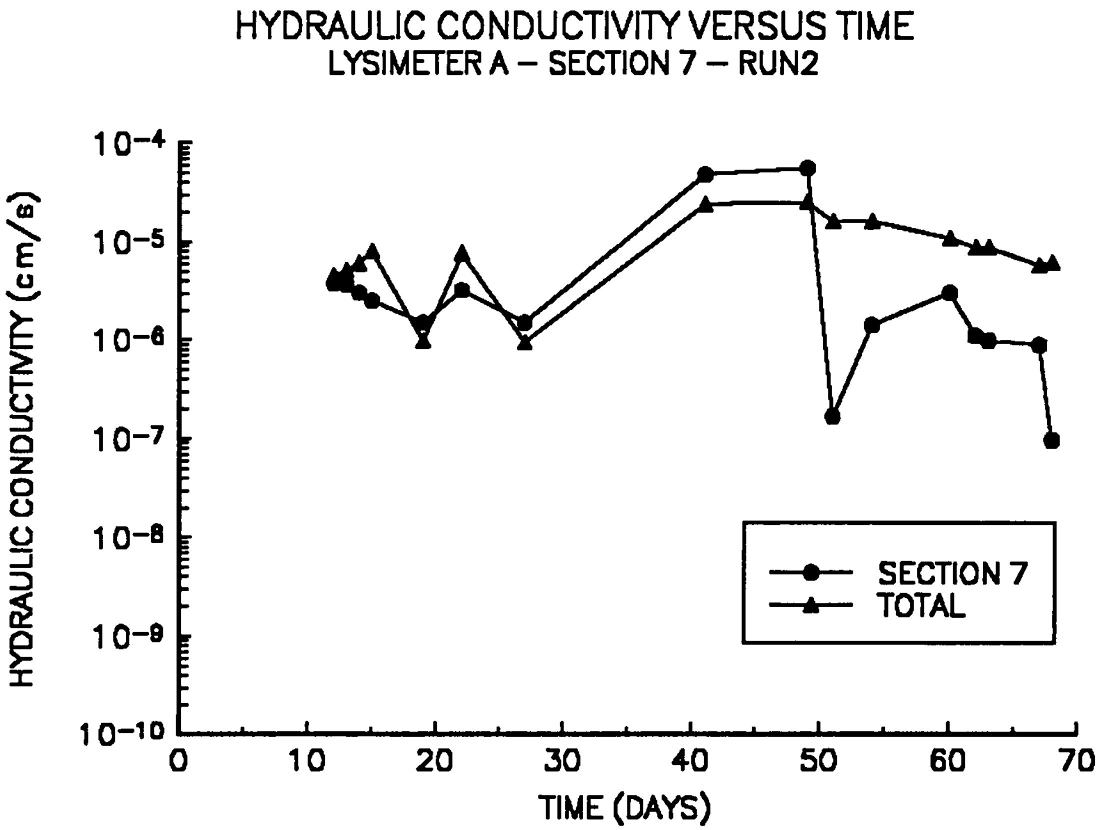


Figure 3-4 - Hydraulic conductivity versus time - Lysimeter A, Section 7, Run 2

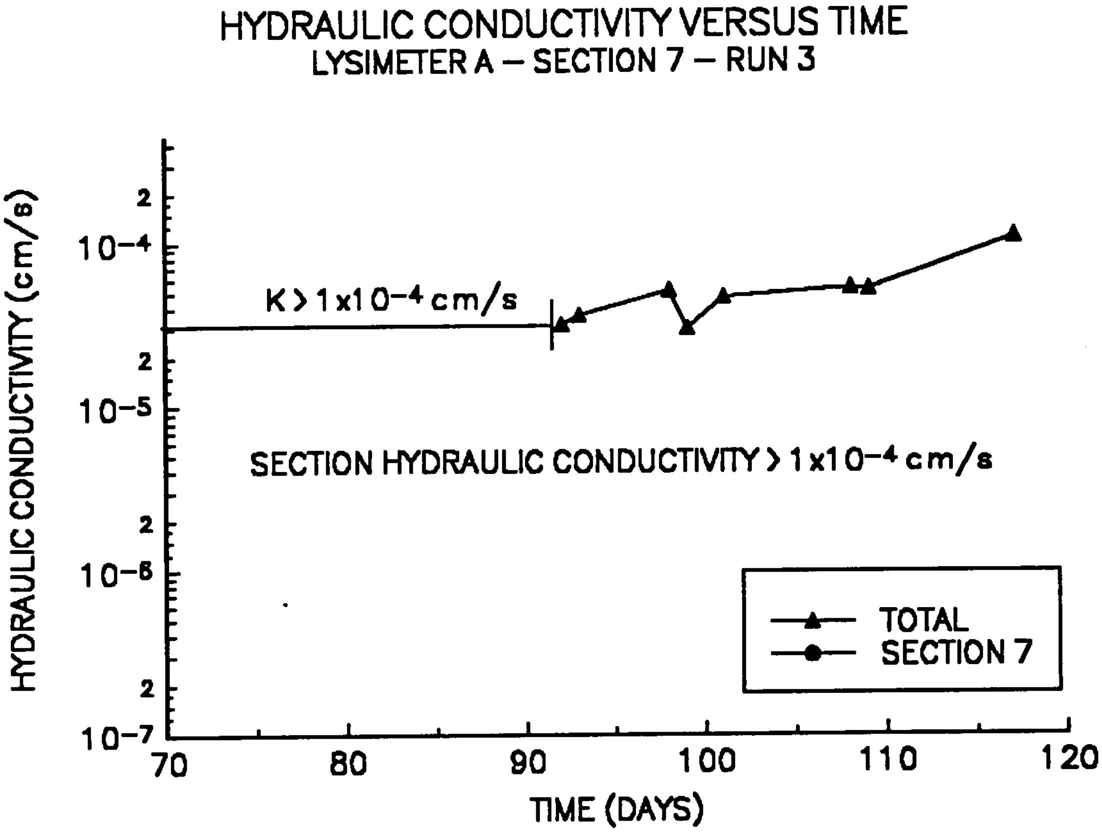


Figure 3-5 - Hydraulic conductivity versus time - Lysimeter A, Section 7, Run 3

during the test was equal to that represented by the values on the total hydraulic conductivity line. In Appendix A, when a corresponding point within the sectional hydraulic conductivity data is missing, it represents a period of nondetectable flow. The hydraulic conductivity of each chamber during each run may be seen in Table 3-2.

The second cycle showed less detectable flow through many sections. However, the hydraulic conductivity increased significantly in other sections. This increase in conductivity may be attributed to the development of cracks. The sections which displayed cracking (Figure 3-6) must also have a decrease in density because the volume of voids increased. Also, the same sections of increased hydraulic conductivity often mimic the path taken by the line that represents the total hydraulic conductivity of the sample. This is because these sections controlled the hydraulic conductivity of the entire sample. In Figures 3-7, 3-8 and 3-9 the variation of hydraulic conductivity throughout the sections may be seen for each saturation cycle. Similar results were experienced by Rogowski (1990) over a 13 month period on a grid of lysimeters measuring 9 m (29.5 ft) by 23 m (75.5 ft). Each lysimeter within this grid measured 0.9 m by 0.9 m (3 ft by 3 ft) and showed variations similar to the lysimeters used in this research.

The third run caused an increase in hydraulic conductivity so great that the drainage layer become the controlling factor for the flow of water. The cracking in the sample was so extensive that the clay barrier could no longer serve its purpose to impede the flow of water through the clay.

Table 3-2 - Hydraulic conductivity of each section for each run - Lysimeter A

Section	Run 1	Run 2	Run 3
1	2×10^{-6} cm/s	0.0 cm/s[1]	3×10^{-5} cm/s
2	1×10^{-7} cm/s	0.0 cm/s[1]	> 1×10^{-4} cm/s
3	2×10^{-7} cm/s	0.0 cm/s[1]	> 1×10^{-4} cm/s
4	8×10^{-8} cm/s	6×10^{-7} cm/s	2×10^{-7} cm/s
5	2×10^{-5} cm/s	1×10^{-6} cm/s	5×10^{-6} cm/s
6	0.0 cm/s[1]	3×10^{-5} cm/s	> 1×10^{-4} cm/s
7	1×10^{-6} cm/s	2×10^{-6} cm/s	> 1×10^{-4} cm/s
8	6×10^{-6} cm/s	5×10^{-6} cm/s	> 1×10^{-4} cm/s
9	0.0 cm/s[1]	7×10^{-6} cm/s	> 1×10^{-4} cm/s
10	6×10^{-7}cm/s	7×10^{-5} cm/s	> 1×10^{-4} cm/s
11	3×10^{-6} cm/s	1×10^{-7} cm/s	> 1×10^{-4} cm/s
12	3×10^{-5} cm/s	2×10^{-7} cm/s	2×10^{-5} cm/s

[1]Although some sections had no detectable flow, this does not neccessarily mean that no flow occured. The drainage layer of sand could store water which passed through the clay barrier. A minimum amount of water must initially pass into the sand before flow is detected in the collection bottle. This storage capacity was determined without the barrier in place, by finding the minimum amount of water that could be stored in the sand before it was detectable in the collection bottle. This test was performed over a two hour period. The minimum calculated hydraulic conductivity detectable from the lysimeters with the clay barrier in place is 1×10^{-9} cm/s. However, hydraulic conductivity was measured below 1×10^{-9} cm/s (from 0.0 to 9×10^{-10} cm/s). Measurements below 1×10^{-9} cm/s do indicate very low hydraulic conductivity but may not be accurate.

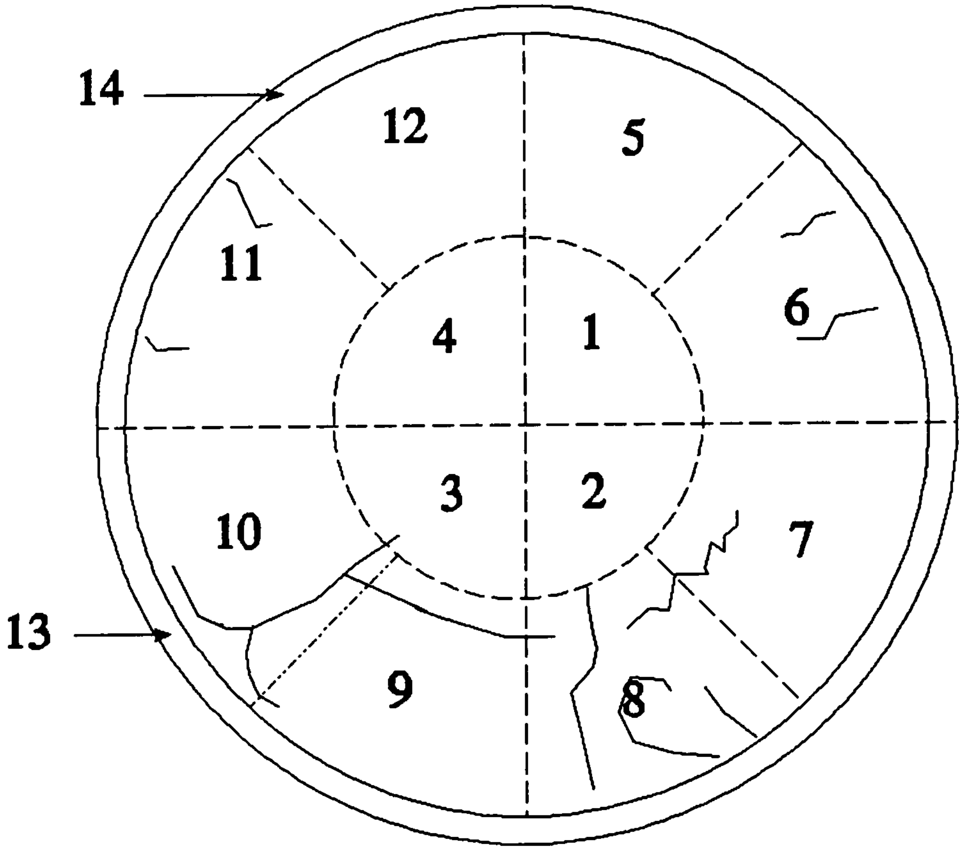


Figure 3-6 - Crack map - Lysimeter A

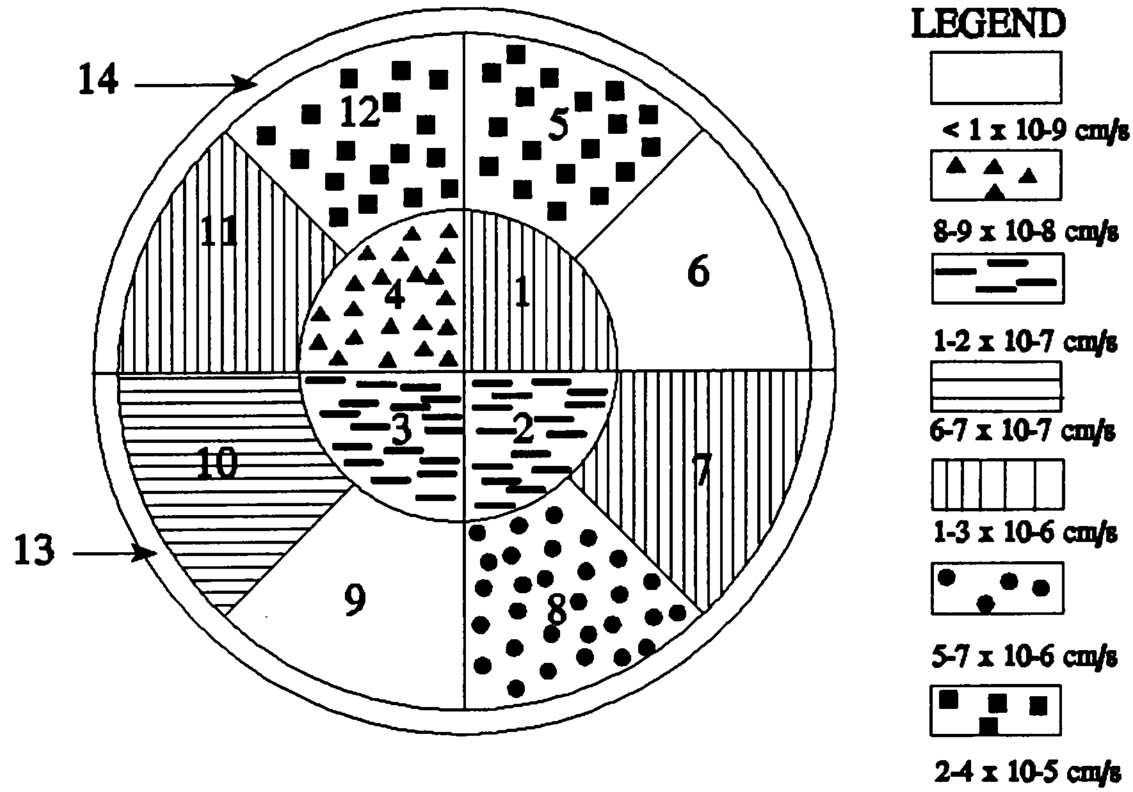


Figure 3-7 - Hydraulic conductivity variation - Lysimeter A, Run 1

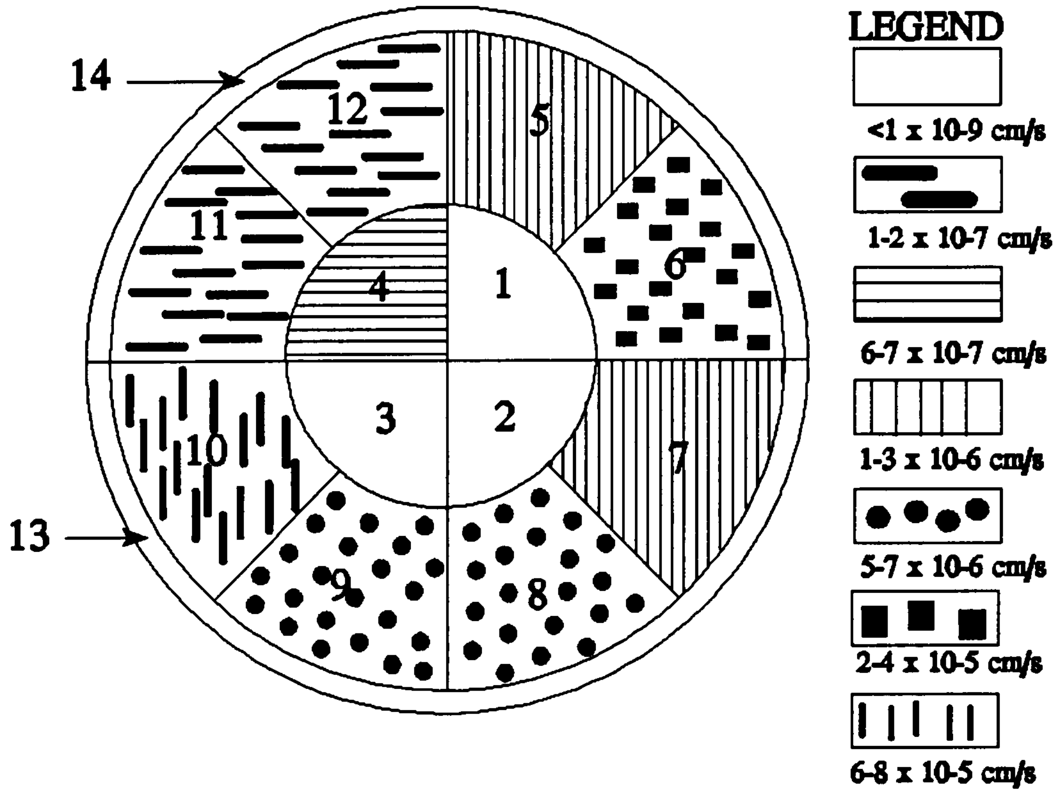


Figure 3-8 - Hydraulic conductivity variation - Lysimeter A, Run 2

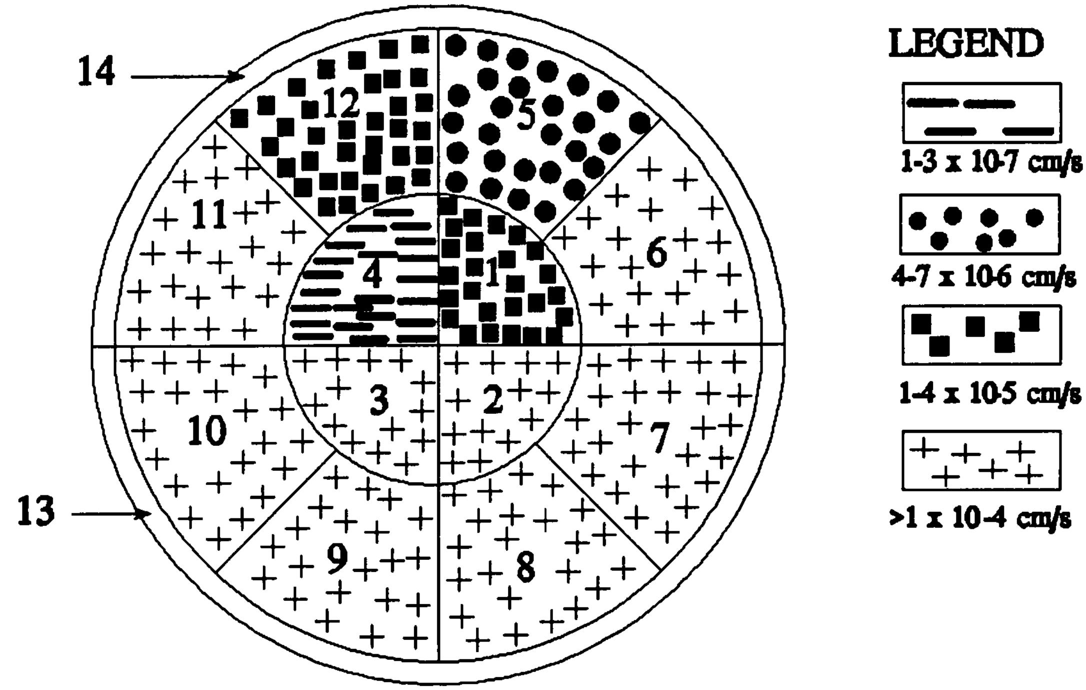


Figure 3-9 - Hydraulic conductivity variation - Lysimeter A, Run 3

Hydraulic Conductivity of the Entire Sample

In Figure 3-10, the path of dry density and water content of the sample in Lysimeter A is shown with its relation to the zero air voids curve. As the water content decreased the dry density is increased. This reflects the shrinkage or decrease in void volume of the intact portion. The relation of these two parameters relate to the change in hydraulic conductivity will be discussed in the next two sections.

Dry Density Effects -- The hydraulic conductivity was observed (Figure 3-11) to change with changes in dry density of the entire sample. As the sample was subjected to drying conditions, the dry density increased and the hydraulic conductivity also increased. In contrast, when the soil in the flexible-wall samples became more dense the hydraulic conductivity of the intact portion decreased because the volume of voids decreased. The increase in hydraulic conductivity in the lysimeter sample can be attributed to cracking that occurred in the sample which was not represented by the flexible-wall samples. The center sections of the sample displayed minimal cracking, and as expected, the center sections of the sample showed a decrease in hydraulic conductivity. On the outside of the sample, where the majority of the cracks occurred, the hydraulic conductivity increased. The increase from the outside of the sample was great enough to show an overall increase in the hydraulic conductivity of the entire sample.

Water Content Effects -- Hydraulic conductivity was affected by water content as shown in Figure 3-12. This water content corresponds with the measurement taken at the end

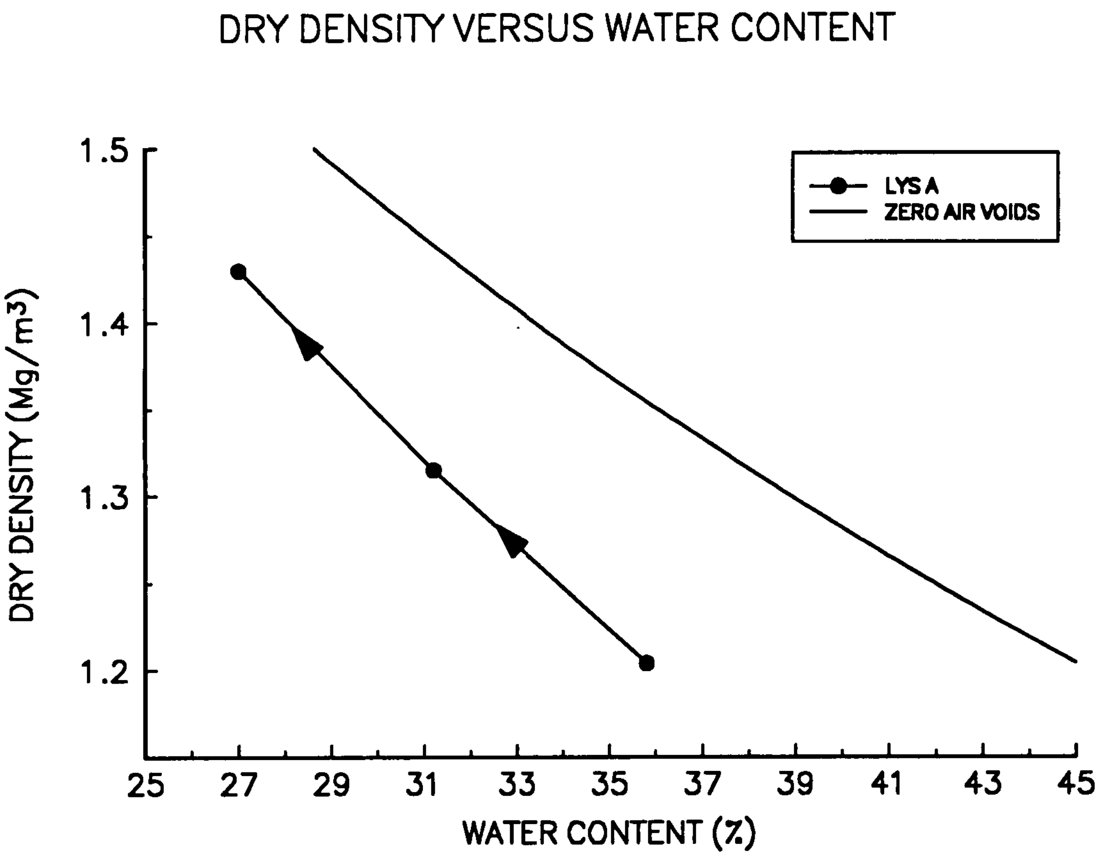


Figure 3-10 - Dry density versus water content - Lysimeter A

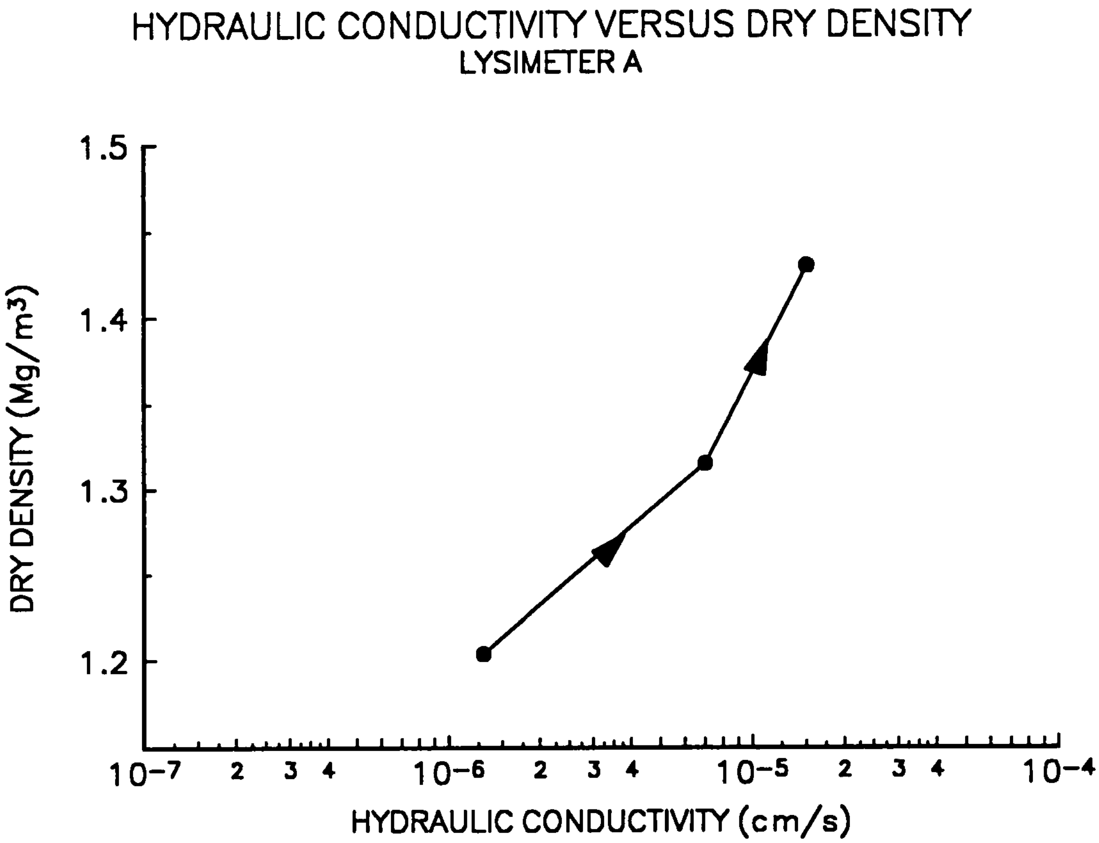


Figure 3-11 - Hydraulic conductivity versus dry density-Lysimeter A

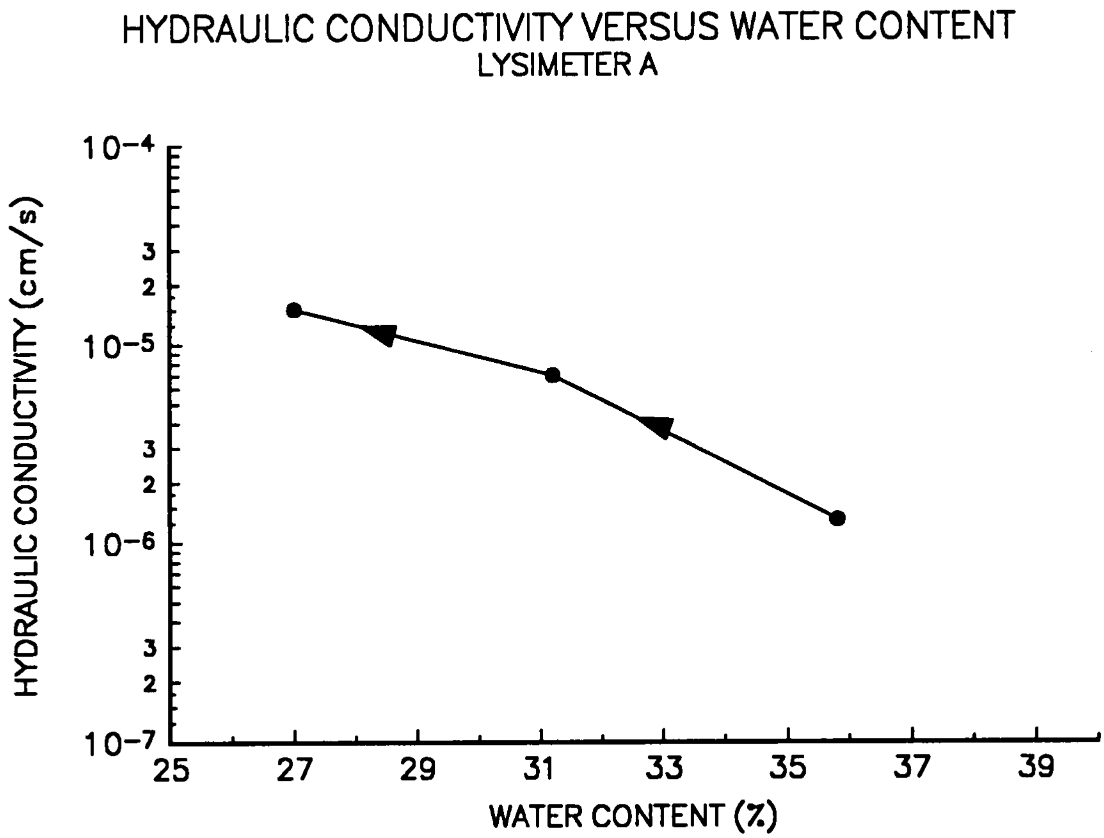


Figure 3-12 - Hydraulic conductivity versus water content - Lysimeter A

of a dry-back cycle. The measurement was taken by pushing a soil sampling tool into an uncracked clay zone. The volume of this sample was measured and the water content was determined in order to calculate the dry density. The water content is a factor that can controlled easier in the laboratory than in the field. During each cycle the water content was taken lower than the previous cycle. As the water content decreased, the hydraulic conductivity increased because cracks formed allowing water to flow through the sample at a faster rate. These cracks did not occur because of the dry density sampling method. All cracks which did occur were not in the region that was sampled. The water content and the initial compaction effort were the two factors that controlled the dry density in this experiment.

Effects of Overburden on the Sample

Overburden was initially added to help control the swelling of the sample. It was believed, based on past experience with similar samples, that without the overburden the thin barrier of clay would have swelled and become too soft for performing density measurements. Additionally, to simulate actual conditions, the overburden also acted similar to topsoil placed on clay barriers to support vegetation. Based on the dry density measurements, which always increased, the samples did not experience any measurable swelling. However, one of the contributing factors to the continual decrease of hydraulic conductivity during each cycle was the small amount of consolidation that occurred due the overburden.

Lysimeter B Results

Lysimeter B was compacted with a Standard Proctor rammer in the same manner as Lysimeter A, however the metal plate was not used in order to obtain a more dense sample. The number of blows required was determined by the ratio of surface area of a Proctor mold to the surface area of the lysimeter. Each layer required 1360 blows of the rammer. The initial density of the sample was 1.28 Mg/m^3 with a corresponding water content of 33.5%. The density and water content values from each cycle and their corresponding hydraulic conductivities. Values (Table 3-3) can be compared with the initial density and water content values of Lysimeter A which were 1.20 Mg/m^3 and 35.8%, respectively. For reference, the optimum values for the soil were 1.37 Mg/m^3 and 33.0%.

Hydraulic Conductivity Over Time

The hydraulic conductivity (Figure 3-13) exhibited significant temporal variation. The conductivity of this entire sample showed an overall increase over the three cycles as did the measurements in Lysimeter A. The hydraulic conductivity of the sample in Lysimeter B had a lower initial value than that of Lysimeter A, which was compacted with a lower density. However, Lysimeter A had a lower compaction water content. Within each cycle, as with Lysimeter A, the sample showed a decrease in hydraulic conductivity once the sample became fully saturated. Again, the addition of overburden did not show an immediate affect on the hydraulic conductivity of the sample. In thefirst cycle, of Lysimeter B the initial readings of hydraulic conductivity were much lower

Table 3-3 - Lysimeter B Parameters

Run	Dry-Back	W(%)	ρ(Mg/m^3)	K(cm/s)
-	Initial	33.5	1.28	-
1	-	-	-	3.8×10^{-8}
-	1	32.3	1.33	-
2	-	-	-	1.2×10^{-7}
-	2	32.6	1.41	-
3	-	-	-	1.9×10^{-7}

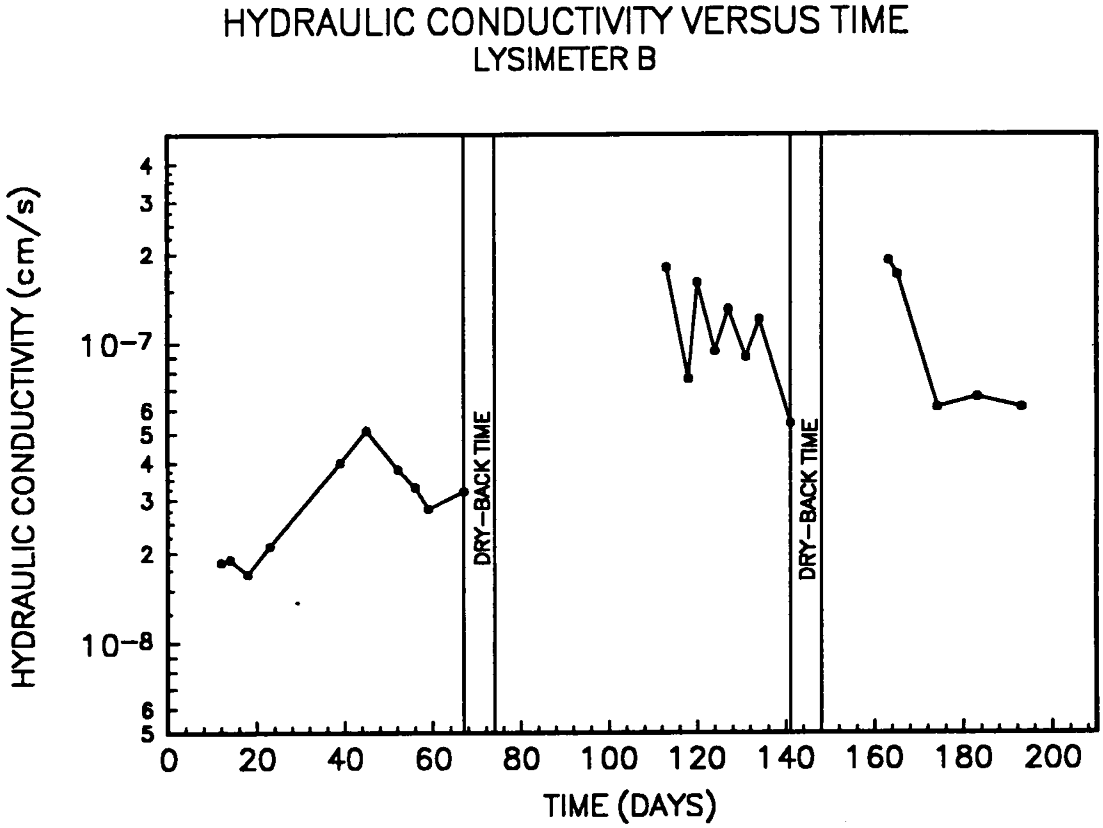


Figure 3-13 - Hydraulic conductivity over time - Lysimeter B

than the final readings. This was due to the incomplete saturation of the sample. When the sample became fully saturated the conductivity measurements declined and became steady.

Sectional Hydraulic Conductivity

Figures 3-14, 3-15 and 3-16 displays hydraulic conductivity of Lysimeter B, section 5 versus time, compared with the hydraulic conductivity of the entire sample, for the first, second and third cycles. The entire set of graphs can be seen in Appendix B for each lysimeter section. These graphs are set up in the same manner as those in Appendix A. Again, in the first cycle, the hydraulic conductivity of the individual sections varied over two orders of magnitude while some sections had no measurable flow. Breakthrough time, as defined previously, was the time for fluid to begin to pass out of the soil barrier. Some sections in the first cycle of Lysimeter B displayed longer breakthrough times than measured in Lysimeter A. This was also a contributor to the lower conductivity measurements in the first cycle.

During the second cycle, all sections had measurable flow at some point during the test. Breakthrough times for this cycle were longer than that of the first cycle and the conductivity measurements, in eight of twelve sections, were lower than the measurement of the entire sample (Table 3-4). The four sections which had higher conductivities than that of the entire sample had been affected by the decreased density which occurred during the dry-back cycle. This is shown in Figure 3-17 by the increase n cracking in these sections. Figures 3-18, 3-19 and 3-20 display the variation of

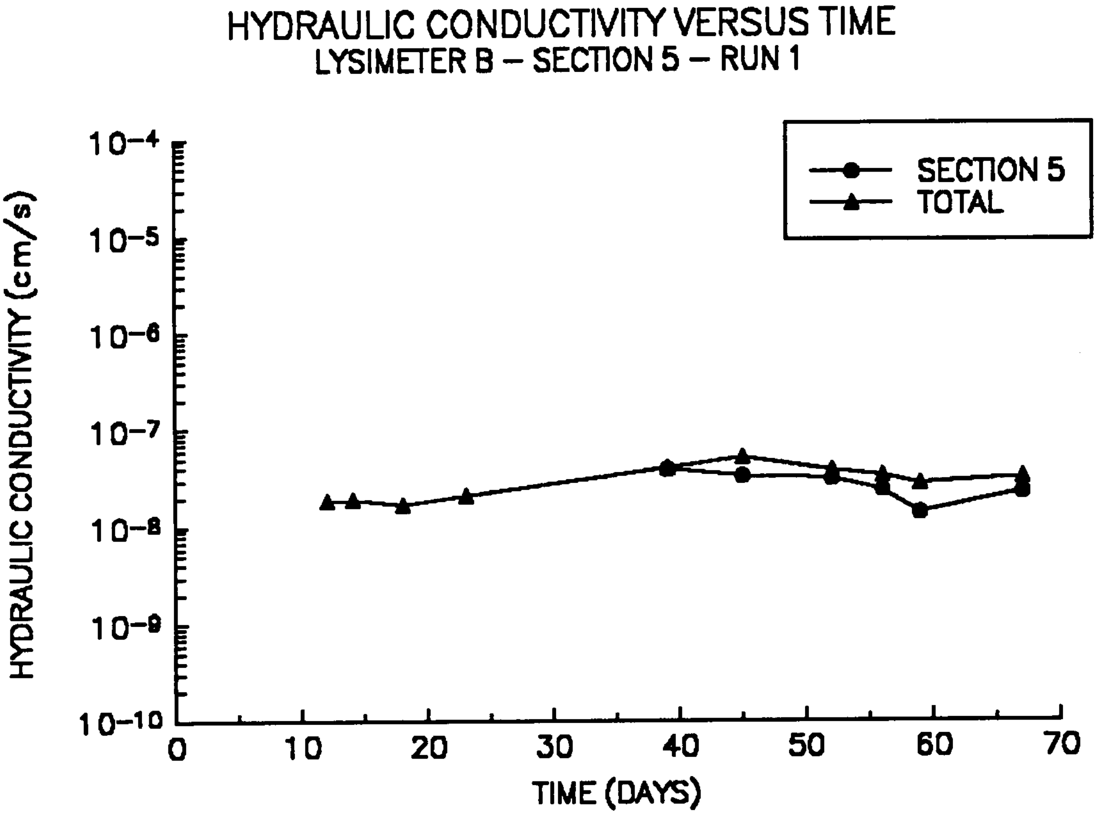


Figure 3-14 - Hydraulic conductivity versus time - Lysimeter B, Section 5, Run 1

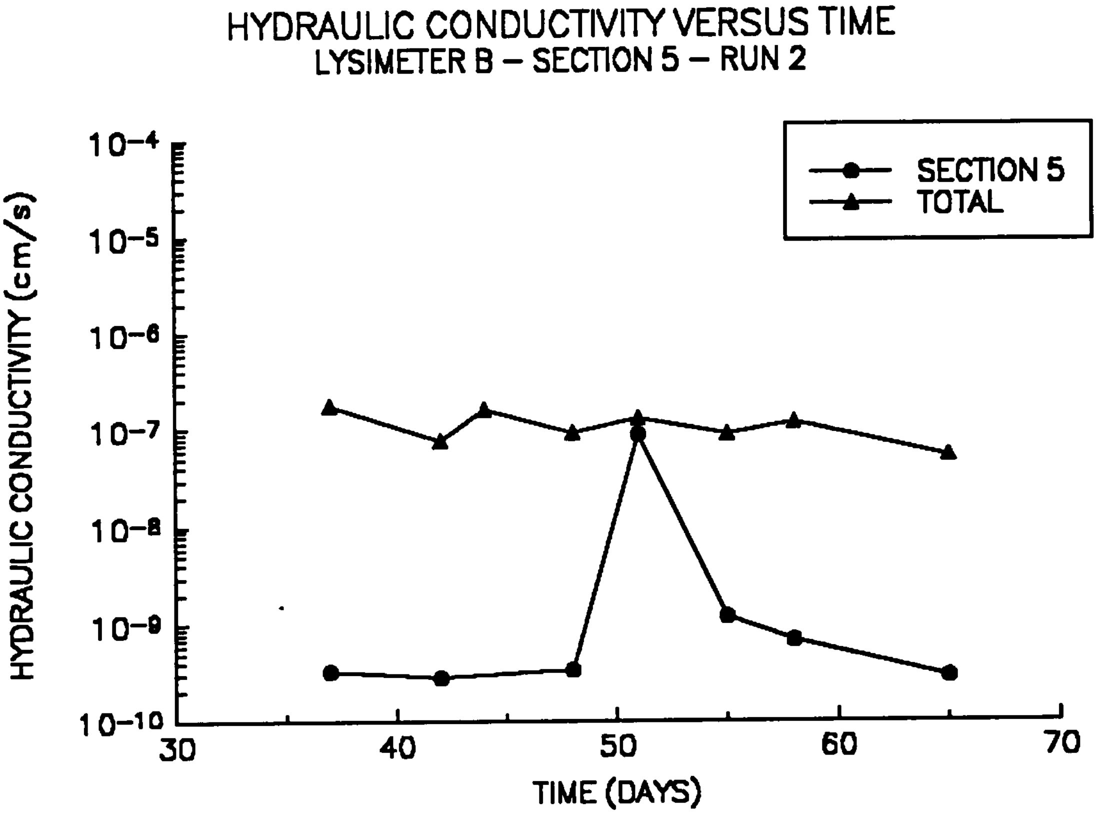


Figure 3-15 - Hydraulic conductivity versus time - Lysimeter B, Section 5, Run 2

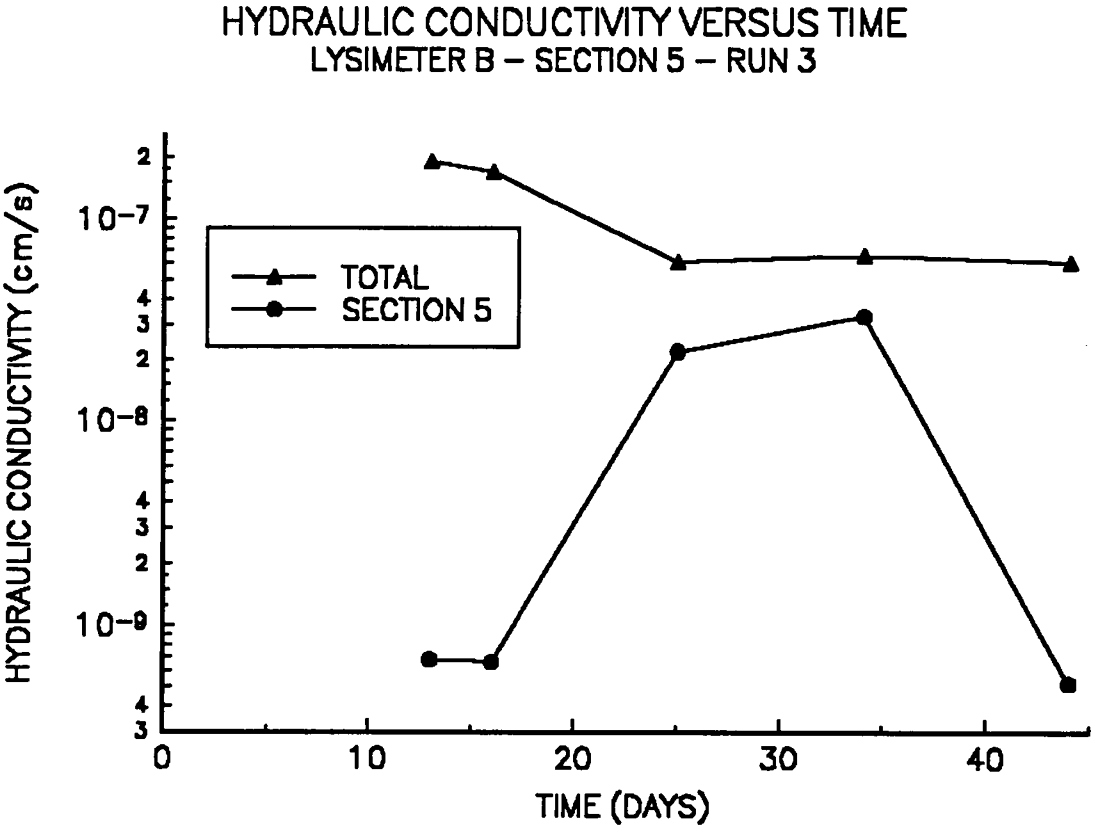


Figure 3-16 - Hydraulic conductivity versus time - Lysimeter B, Section 5, Run 3

Table 3-4 - Hydraulic conductivity of each section for each run - Lysimeter B

Section	Run 1	Run 2	Run 3
1	0.0 cm/s[z]	3×10^{-10} cm/s	0.0 cm/s[z]
2	4×10^{-8} cm/s	4×10^{-10} cm/s	2×10^{-10} cm/s
3	1×10^{-8} cm/s	0.0 cm/s[z]	0.0 cm/s[z]
4	0.0 cm/s[z]	4×10^{-10} cm/s	3×10^{-10} cm/s
5	3×10^{-8} cm/s	3×10^{-10} cm/s	6×10^{-10} cm/s
6	0.0 cm/s[z]	7×10^{-10} cm/s	2×10^{-7} cm/s
7	0.0 cm/s[z]	2×10^{-10} cm/s	5×10^{-10} cm/s
8	6×10^{-8} cm/s	8×10^{-9} cm/s	8×10^{-9} cm/s
9	8×10^{-9} cm/s	2×10^{-8} cm/s	3×10^{-7} cm/s
10	1×10^{-7}cm/s	1×10^{-8} cm/s	4×10^{-7} cm/s
11	2×10^{-7} cm/s	5×10^{-8} cm/s	3×10^{-7} cm/s
12	0.0 cm/s[z]	2×10^{-7} cm/s	2×10^{-10} cm/s

[z]Although some sections had no detectable flow, this does not necessarily mean that no flow occured. The drainage layer of sand could store water which passed through the clay barrier. A minimum amount of water must initially pass into the sand before flow is detected in the collection bottle. This storage capacity was determined without the barrier in place, by finding the minimum amount of water that could be stored in the sand before it was detectable in the collection bottle. This test was performed over a two hour period. The minimum calculated hydraulic conductivity detectable from the lysimeters with the clay barrier in place is 1×10^{-9} cm/s. However, hydraulic conductivity was measured below 1×10^{-9} cm/s (from 0.0 to 9×10^{-10} cm/s). Measurements below 1×10^{-9} cm/s do indicate very low hydraulic conductivity but may not be accurate.

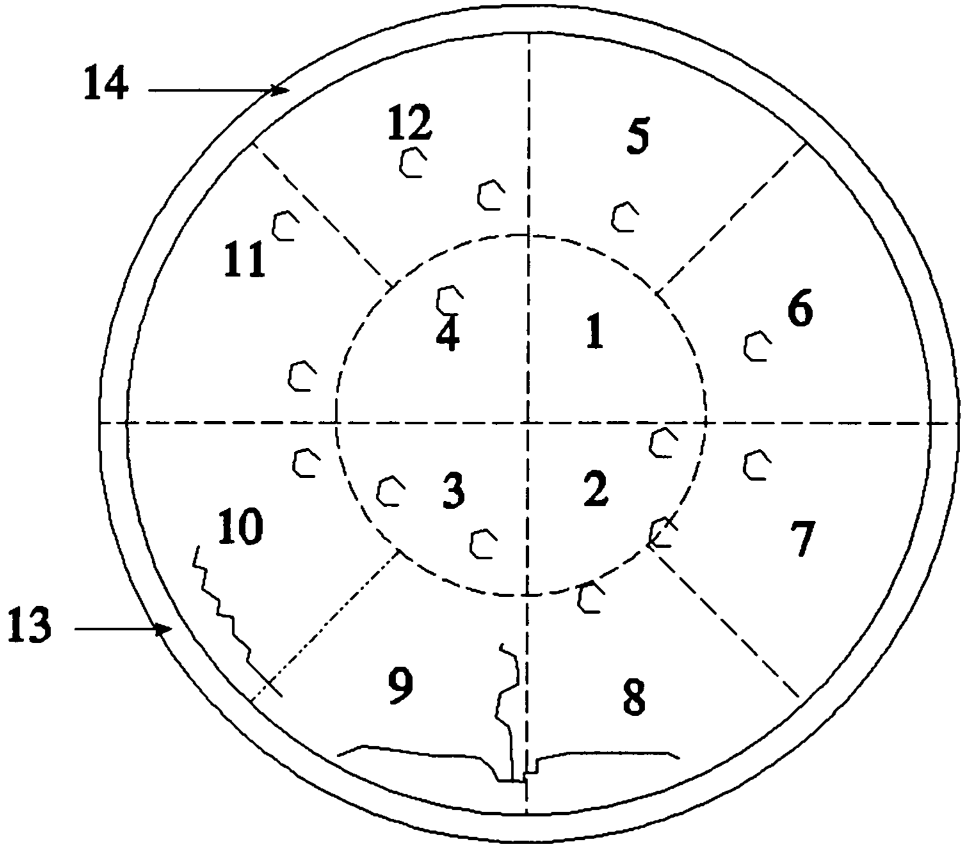


Figure 3-17 - Crack map - Lysimeter B

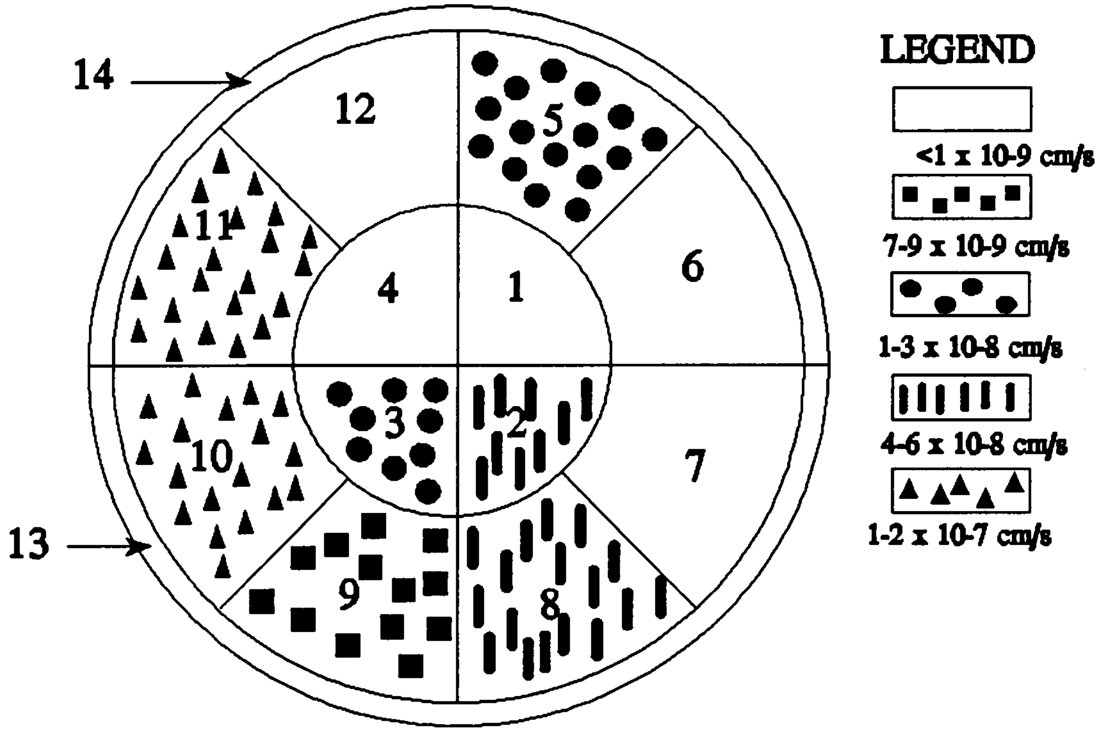


Figure 3-18 - Hydraulic conductivity variation - Lysimeter B, Run 1

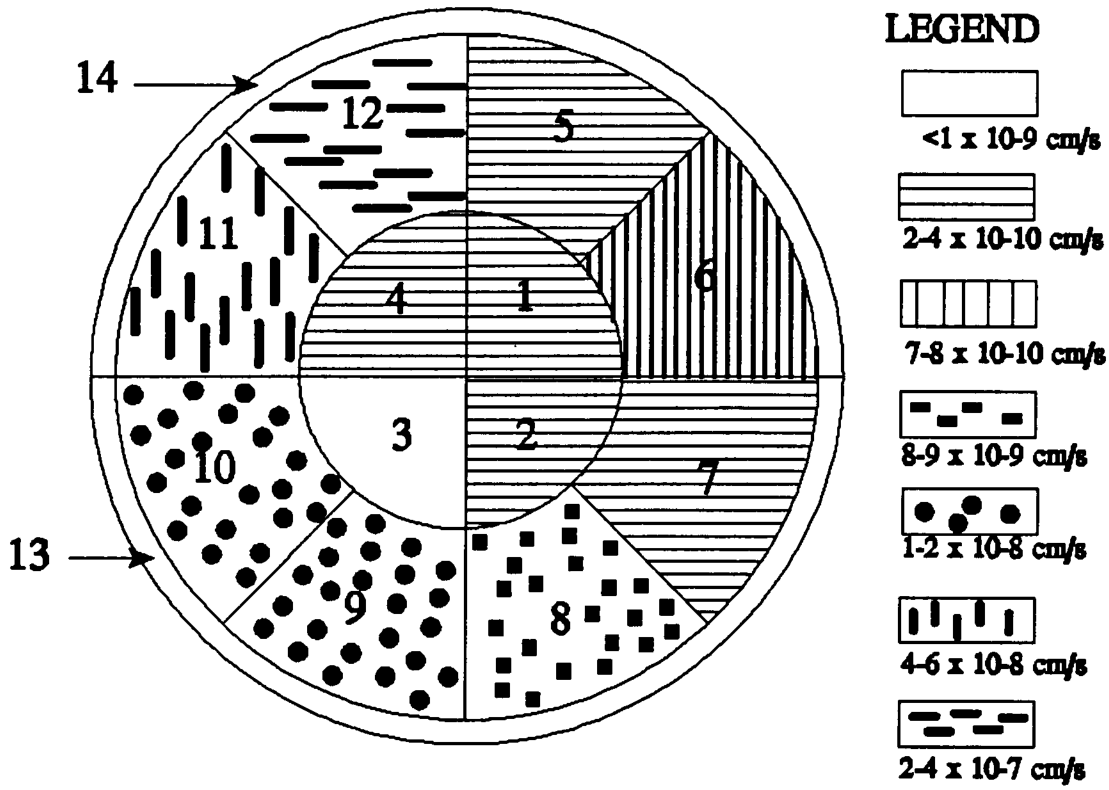


Figure 3-19 - Hydraulic conductivity variation - Lysimeter B, Run 2

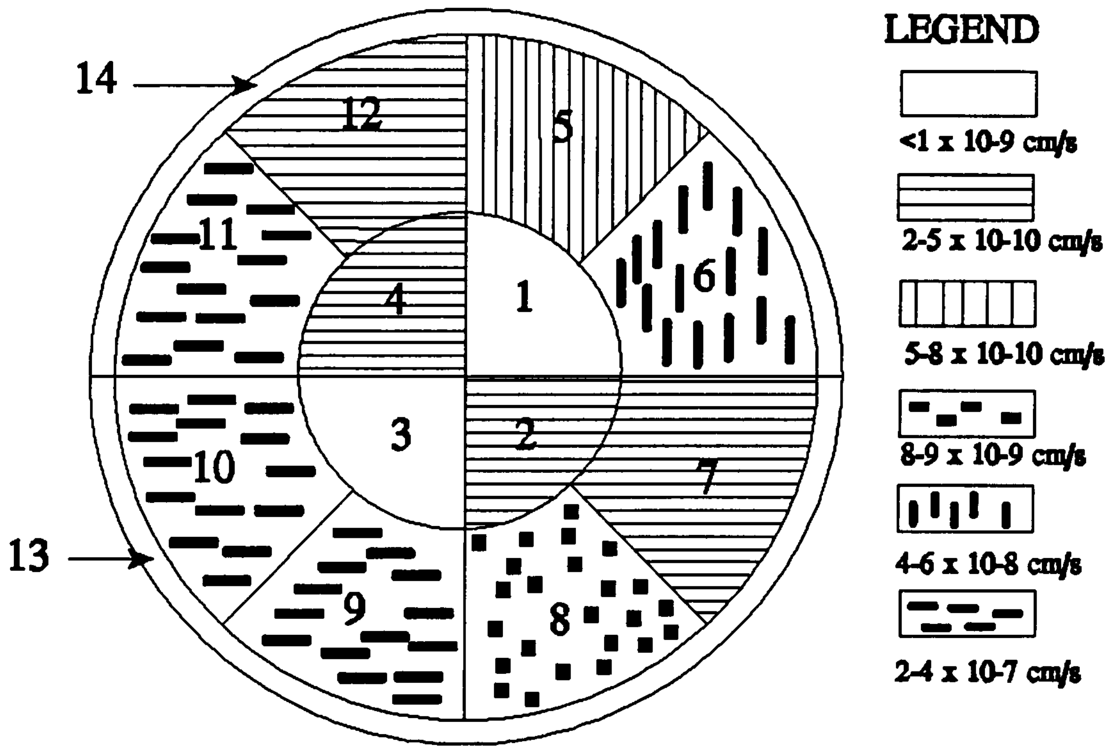


Figure 3-20 - Hydraulic conductivity variation - Lysimeter B, Run 3

conductivity throughout the sections of the lysimeter samples for each saturation cycle. The decrease in density is a result of an increase in voids which can be attributed to the visible cracks seen in the sections with higher conductivities. As in Lysimeter A, the sections which had cracks, mimicked the path of conductivity taken by the entire sample. These sections were the ones which controlled the conductivity of the entire sample.

The third cycle showed an increase in hydraulic conductivity in the outer sections and a continued decrease in hydraulic conductivity in the inner sections. The sections which had a measurable increase in hydraulic conductivity corresponded to the sections which produced cracks.

Hydraulic Conductivity of Entire Sample

The temporal variation in density and water content for the drying and wetting cycles with respect to the zero air voids curve is displayed in Figure 3-21. In the first cycle the water content decreased as the dry density became greater. However, in the second cycle the water content did not become lower than it did in the first cycle. This suggested that the water content variation must not become significantly lower to obtain an increase in dry density. It should be kept in mind, however, that this data is based on a single measurement. The next two sections will discuss the relation of dry density and water content to hydraulic conductivity.

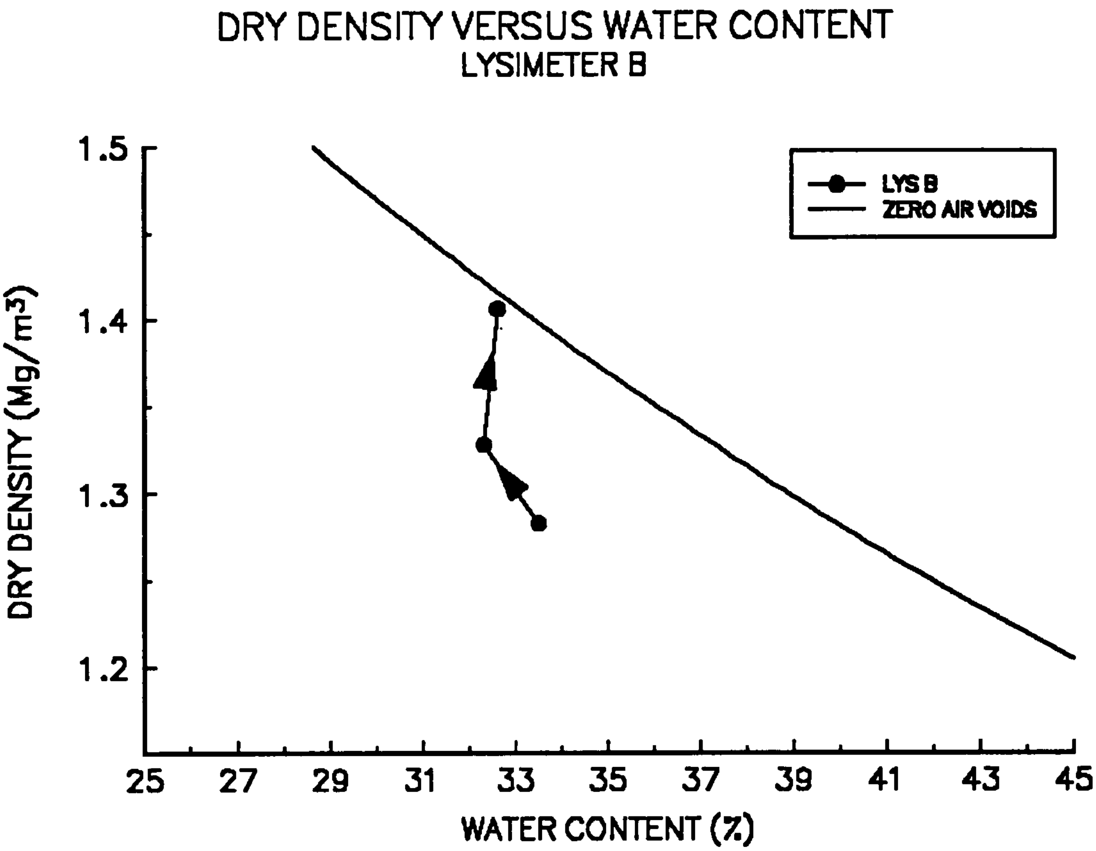


Figure 3-21 - Dry density versus water content - Lysimeter B

Dry Density Effects -- It is evident in Figure 3-22 that as dry density increased, the hydraulic conductivity increased. This is the opposite of what happened with the samples measured by the flexible-wall permeameters which represented the matrix only, i.e. a homogenous barrier. The lysimeters represent a heterogeneous barrier, so while the density increased in the intact areas, it decreased in the areas which were not continuous. Discontinuities or cracks in the sample cause the increase in hydraulic conductivity. The dry density increase was attributed to the drying cycles of the sample. The hydraulic conductivity would be expected to decrease if void space was decreased during the drying process. As with Lysimeter A, the increase in conductivity was caused by cracking in the sample. Once the sample formed cracks, the hydraulic conductivity was controlled by the size of the cracks and the amount of flow allowed by those cracks. Typically, the cracks increased the conductivity at the outside of the sample and kept the conductivity of the inside sections very low. This trend was also observed in Lysimeter B.

Water Content Effects -- Hydraulic conductivity was strongly related to water content as shown in Figure 3-23. The water content was measured at the end of the dry-back cycle. Although the water content did not decrease as much as in the first cycle, the hydraulic conductivity still increased. This increase in conductivity was attributed to the cracks that developed in the sample during the dry-back cycles. The cracks that developed continued to propagate during the second cycle even though the water content did not decrease as much as in the first cycle. Because water content was controlled in the

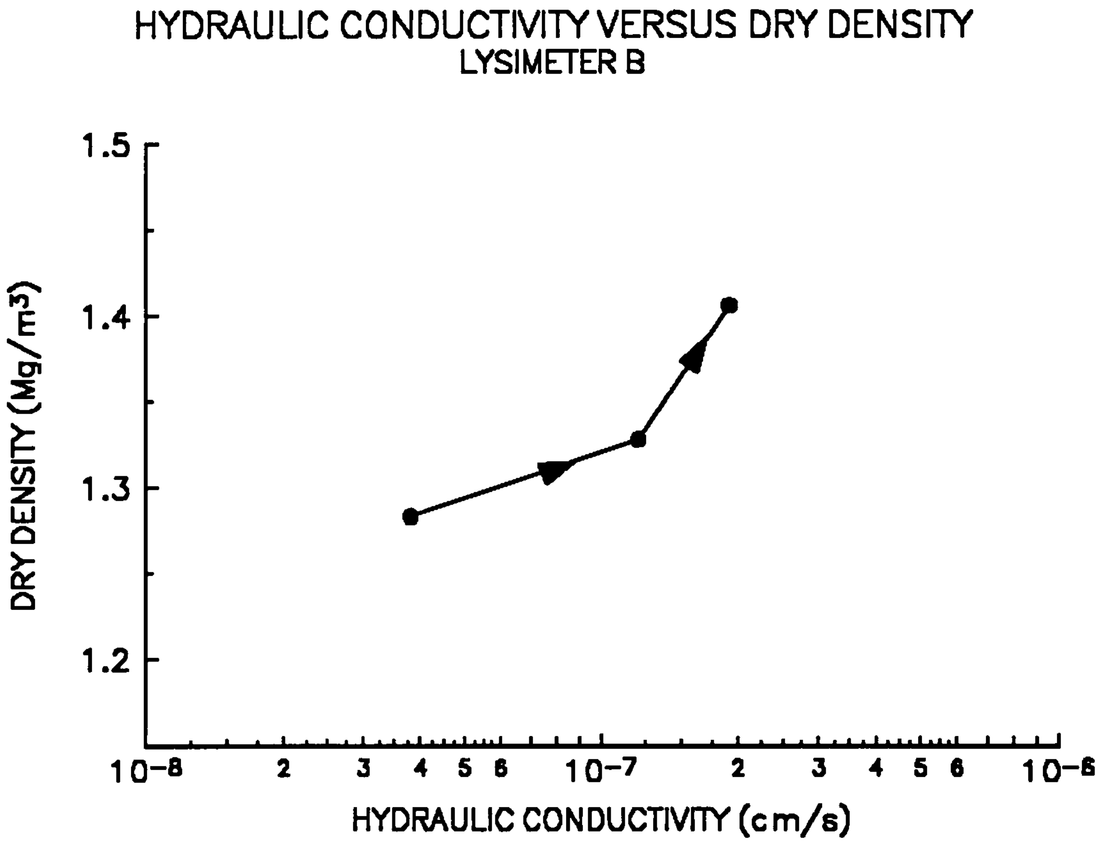


Figure 3-22 - Hydraulic conductivity versus dry density - Lysimeter B

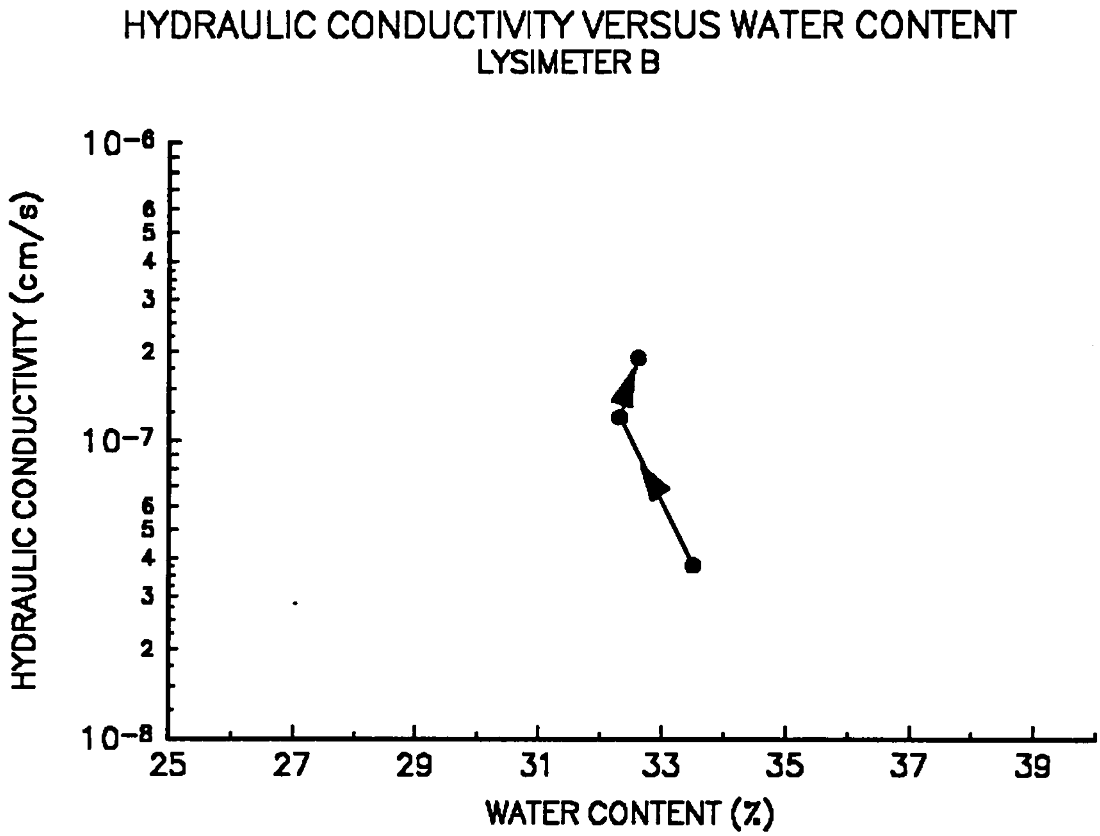


Figure 3-23 - Hydrualic conductivity versus water content - Lysimeter B

laboratory, the wetting and drying cycles varied as they might actually occur in the field. This allowed the sample to crack at different rates and showed that once a crack has begun, small changes in water content increase the conductivity by orders of magnitude due to crack growth.

Effects of Overburden on the Sample

As with Lysimeter A, the overburden was added to prevent the sample from swelling. The resulting stress from this overburden did prevent damage to the sample which may have been caused by swelling, but it also may have consolidated the sample. The decrease in hydraulic conductivity of the sample within the wetting cycle was caused by the replacement of the overburden after the drying cycle. If the cycles were extended for longer periods of time, the conductivity would likely continue to drop and eventually stabilize at a lower rate.

REFERENCES

Rogowski, A. S. (1990). "Relationship of Laboratory- and Field- Determined Hydraulic Conductivity in Compacted Clay Layer." *Report No. EPA/600/2-90/025*, United States Environmental Protection Agency, Cinncinnati, Ohio.

PART IV

DISCUSSION OF RESULTS

HYDRAULIC CONDUCTIVITY CHANGES

The lysimeter testing showed that while the overall hydraulic conductivity of a clay barrier may be at an acceptable value, there are portions of the barrier that have conductivities that are very low, while other sections have conductivities which are very high. Upon desiccation, these differences in conductivity are magnified. These differences became very evident by using a lysimeter with twelve different collection chambers. Hydraulic conductivity was measured as low as 3×10^{-10} cm/s on Lysimeter B and as high as 1×10^{-4} cm/s on Lysimeter A. As flow through the soil samples was collected, there were differences larger than an order of magnitude in chambers which were adjacent to one another. Thus, preferential flow through a clay barrier constructed to be as homogenous as possible was significant. Preferential flow results in a barrier that may appear sufficiently low in hydraulic conductivity to meet the standards of 1×10^{-7} cm/s, but may still be unsafe in regard to leakage since localized areas may exceed this value.

The lysimeter samples were dried in a cyclic manner by means of a dehumidifier. The resulting hydraulic conductivity conditions due to the drying and wetting of the samples caused post construction changes in the clay barrier's hydraulic and physical properties. During the initial saturation, the hydraulic conductivity of each section differed as much as one order of magnitude or less. The comparison of hydraulic conductivity of the lysimeter sections to the hydraulic conductivity of the entire lysimeter sample showed similar paths of hydraulic conductivity versus time, but variances in magnitude did occur. After desiccation and during the second saturation, these differences in conductivity became more distinct. On the other hand, the flexible-wall samples displayed a consistent decline in hydraulic conductivity upon each successive dry-back cycle.

The drying of the soil increased the density in some places in the lysimeter samples and reduced the hydraulic conductivity in those regions. However, the stress that accompanied the density increase resulted in cracks in the lysimeter samples which increased the hydraulic conductivity in the region of the cracking. The flexible-wall samples had a consistent drying that proceeded from the outer portion of the samples toward the center of the sample. In the flexible-wall samples, this density increase did not result in cracks because the sample was able to remain a singular soil matrix. The homogenous soil matrix controlled the flexible-wall sample's hydraulic conductivity. Instead of having similar hydraulic conductivity measurements throughout the lysimeter sample, cracks or preferential flow paths controlled the hydraulic conductivity. The noncracked, dense regions within the lysimeter sample decreased the overall hydraulic conductivity of these areas. The similarity between the overall hydraulic conductivity and that displayed by some sections of the lysimeters (Appendix A and B), indicate which regions of the soil sample control the hydraulic conductivity of the entire clay barrier. Thus, sampling in an uncracked area can give a biased measurement of the hydraulic conductivity of a larger area.

The use of small laboratory samples may also give a distorted indication of hydraulic conductivity of a large area. The samples used in the flexible wall permeameter are indicative of a well compacted single aggregate of a large clay barrier.

Preferential flow paths are not able to form in such a small sample, especially when it is kept under pressure during testing. The flexible-wall samples show how drying cycles continue to reduce the hydraulic conductivity of the soil matrix and the lysimeter samples show how drying cycles increase the conductivity of the entire samples. This is because the dry density increased as the water content decreased which results in the volume of voids becoming smaller. In the lysimeter sample, the voids volume was displaced to form cracks.

Representative Sample Size and Hydraulic Conductivity Measuring

The larger the sample tested, the more representative the sample should be of a field-scale barrier and the more susceptible it is to have defects. The flexible wall samples were less representative than the lysimeter samples because there was less possibility of defects developing when the samples were made. The small samples were compacted with a mechanical rammer which covered all areas of the Proctor mold with the same number of blows. The lysimeter samples were compacted by hand. This allowed the possibility of unevenly compacted regions within the samples. This is similar to field conditions in which compaction conditions will vary location to location and day to day due to differences in water content, lift thickness and compactive effort. The smaller the sample, the easier each of these factors are to control.

The flexible wall samples displayed initial hydraulic conductivity values of 3.6 x 10^{-7} cm/s and 6.9 x 10^{-7} cm/s while the lysimeters displayed initial hydraulic conductivity values of 1.3 x 10^{-6} cm/s and 3.8 x 10^{-8} cm/s. The flexible wall samples were similar (same order of magnitude) in conductivity due to their uniformity in compaction effort. The small differences in the two flexible wall samples was due to these initial water content.

On the other hand, the initial conductivity of the lysimeter samples varied by two orders of magnitude. This was primarily due to the variation in compaction effort. Because of the size of the samples, the compaction effort was more difficult to control. The soil for the lysimeter samples was prepared at 35.8 and 33.5% and the flexible wall samples were prepared at 33.0 and 36.0%. Thus, water content for both samples was approximately the same. However, the greater the volume of soil the more difficult it was to control uniformity of the water content.

All factors which contribute to the measurement of hydraulic conductivity become more difficult to control as the sample size become larger. Therefore, when many acres of clay are compacted in order to act as a water barrier these factors become even less controllable. Variations in hydraulic conductivity in the lysimeter samples, which were from less than 1×10^{-9} cm/s to greater than 1×10^{-4} cm/s may be exceeded in an actual clay barrier. Granted, extremely low hydraulic conductivities can and have been achieved in the field but the variation of the hydraulic conductivity of one barrier is difficult to measure because of expense, and the fact that these studies are only of interest when a barrier has failed. When hydraulic conductivity is measured for a barrier, it is presented as a range of values. A study that could measure the hydraulic conductivity of different regions of a barrier after compaction may show how factors such as weather, equipment operators, slight changes in soil characteristics, and ability to sample affect the conductivity of a barrier.

The flexible-wall samples represent a homogenous, continuous clay matrix with minor hydraulic defects. Conversely, the lysimeter sample represent a heterogeneous, noncontinuous clay matrix with visible postcompaction hydraulic defects. Because the lysimeter samples indicate the hydraulic conductivity is controlled by the flow through these preferential flow paths, it is suggested that the flexible-wall samples are not representative of the conductivity of an entire clay barrier. However, the flexible-wall samples do provide a good control for the experiment because of their homogeneity. They also provide a standard by which strain may be measured.

Cyclic Drying Effects on Hydraulic Conductivity

The volume of the flexible-wall samples decreased throughout the drying cycles, but cracks which allowed flow through the sample to increase did not form. The volume of the lysimeter samples decreased as well, but the results were much different because the sample did not remain as one unit. The lysimeter samples showed cracking throughout the sample causing an increase in void space allowing preferential flow paths to develop, thus increasing the overall hydraulic conductivity and heterogeneity in hydraulic conductivity.

This increase was caused by the drying cycles. While there may have been preferential flow paths after the original compaction, they were accentuated by the drying of the soil. The repetitive process of wetting and drying the soil, especially in the large samples, caused the soil to contract and form cracks. This cyclic procedure imitates the wetting and drying events that occur in the field which may cause clay barriers to fail through desiccation. The longer the wetting and drying occurs the longer and deeper the cracks will become. These cracks, which may partially reseal during a wetting event, allow more water to exit the barrier than would be able to pass through the clay matrix after the soil swells. This was evident in the lysimeter samples at the beginning of each wetting cycle. Cracking may be prevented by keeping the differences in the wetting and drying cycle at a minimum.

As the water content of each sample decreases the dry density increases (Figure 4-1). The rates of dry density increase to water content decrease may be compared between the flexible wall samples and the lysimeter samples. From Figure 4-1, it can be seen that the dry density of the lysimeter samples increase with smaller changes in water content than the flexible wall samples. This faster rate is due to the differences in thickness of the samples and the location and method of measurement in the noncracked region. The rate of increase of dry density for the lysimeter samples and flexible wall samples was 0.027 and 0.00062, respectively. While the initial compactive effort was important to the rate at which dry density increased, the sample size could also play a role.

The flexible wall samples had a ratio of diameter to thickness of 0.68 while the lysimeter samples ratio ranged from 10.73 to 11.81. This ratio may be referred to as the shape factor. These data suggests that the temporal path which the sample will take

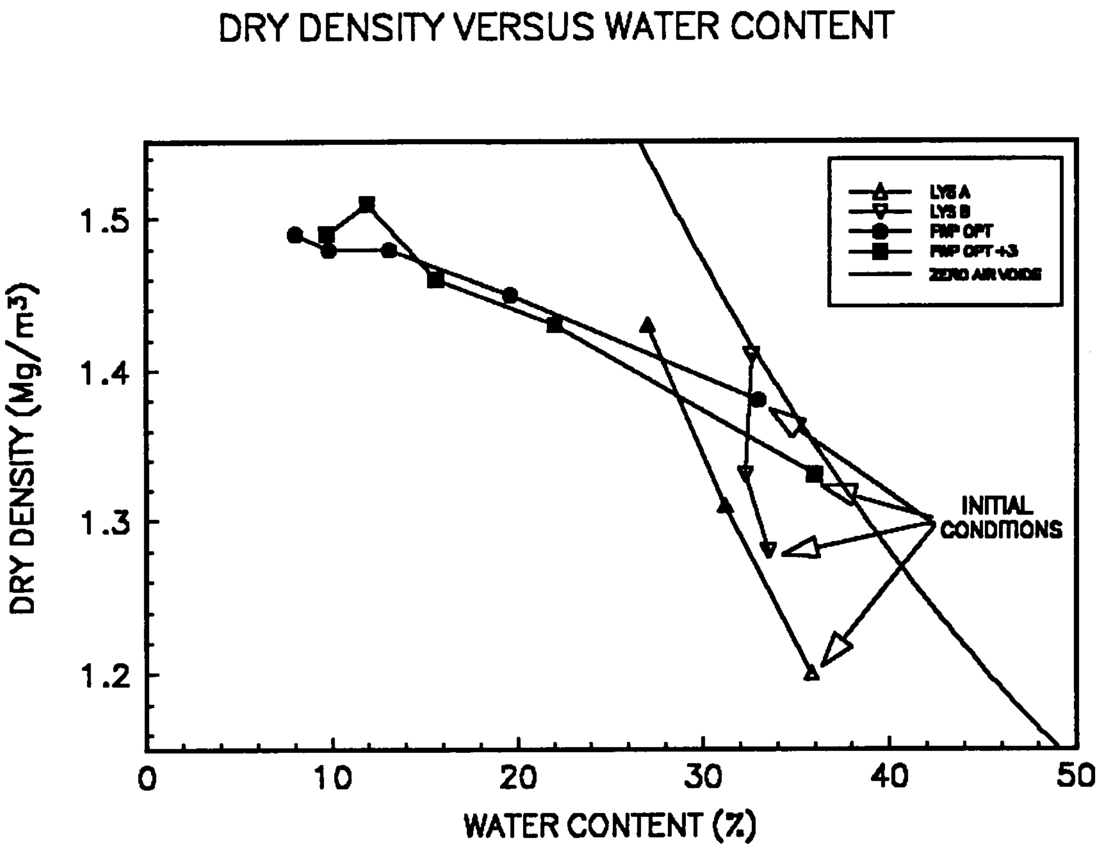


Figure 4-1 - Dry density versus water content - All samples

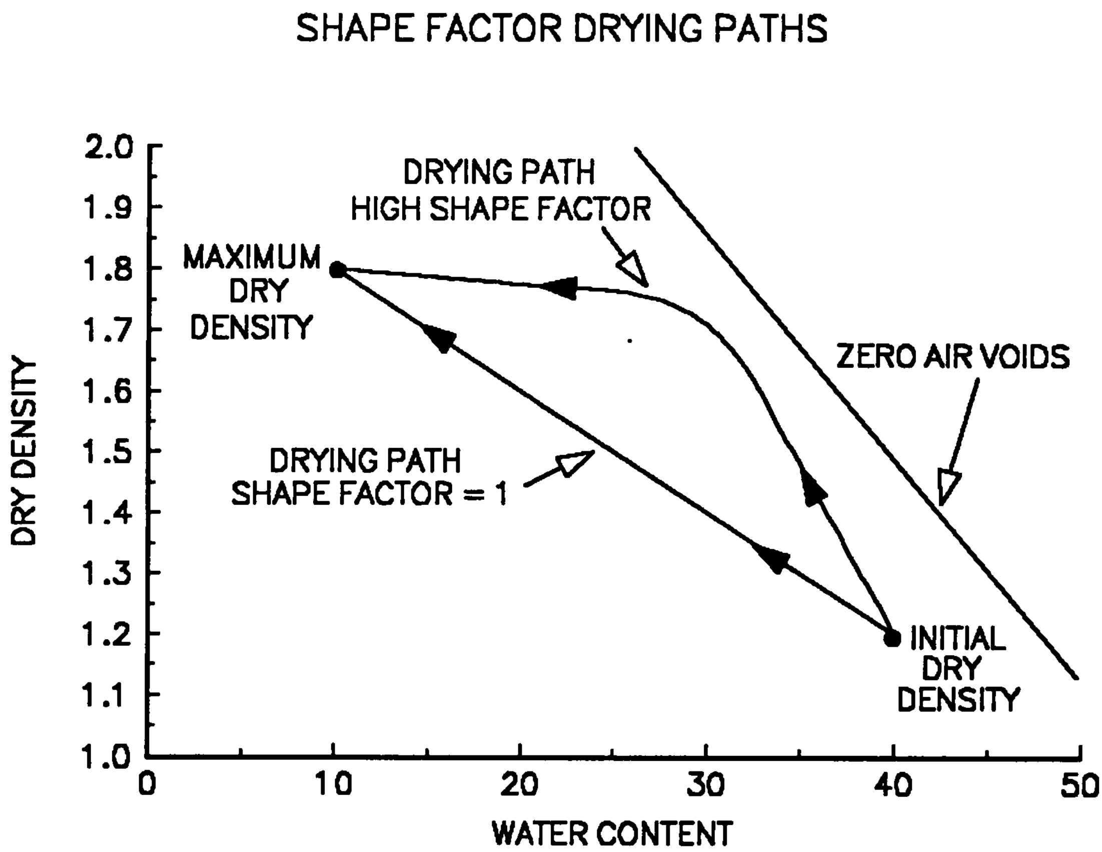


Figure 4-2 - Drying paths for high and low shape factors

to reach the maximum dry density achievable depends on the shape factor (Figure 4-2). Accordingly, the following hypothesis has been formed.

> The closer shape factor is to 1.0, the more direct the path will be toward the maximum dry density from the initial dry density.

Therefore, as the shape factor became larger, the path toward the maximum dry density would be initially steep and become more flat as the maximum dry density is approached. This path would hold true for samples with higher shape factors if and only if a dry density measurement was taken from an intact portion of the barrier. Because the barrier was thin compared to its diameter the dry density approached the maximum faster with smaller changes in water content. As the barrier became closer to its maximum dry density, larger changes in water content did not affect the dry density as greatly.

If this dry density measurement was taken in a cracked region, the dry density would be very low or reflect a dry density that is not accurate. The soil collected in the sampling tool will decrease as the barrier approaches maximum dry density because the crack will continue to grow in aperture and length. When the barrier has reached maximum dry density, the volume of voids will be much larger than the volume of soil. This small soil mass in comparison to the large total volume will not be representative of the true maximum dry density.

WATER CONTENT CHANGES

The change in water content affected the two sets of samples differently just as the change in dry density affected the samples in different ways. The water content in all four samples decreased throughout the testing period. The flexible wall samples displayed a decrease in hydraulic conductivity and the lysimeter samples showed an increase in hydraulic conductivity (Figure 4-3). Lysimeter B had a large water content decrease for the first cycle with a subsequent hydraulic conductivity increase. On the second cycle the water content decrease was not as great as the first cycle but the hydraulic conductivity continued to increase. This suggests that the hydraulic conductivity may increase even if the repetitive drying cycles do not exceed previous water content conditions. The hydraulic conductivity of a clay barrier may be subject to continued degradation, no matter how great the subsequent drying cycles may be, once initial damage has begun.

Dry Density Changes Due To Sample Size

The dry density of both the flexible-wall and lysimeter samples increased throughout the drying cycles. However, the changes reported for the lysimeter samples did not take into account the cracked volume. These samples had the dry density determined by the small tube samples in an area which was uncracked.

The dry density of the lysimeter sample was determined by measuring a sample extruded from the barrier with a soil sampling tube. This measurement was assumed to be the dry density of the entire lysimeter sample. When cracks occurred, they could not

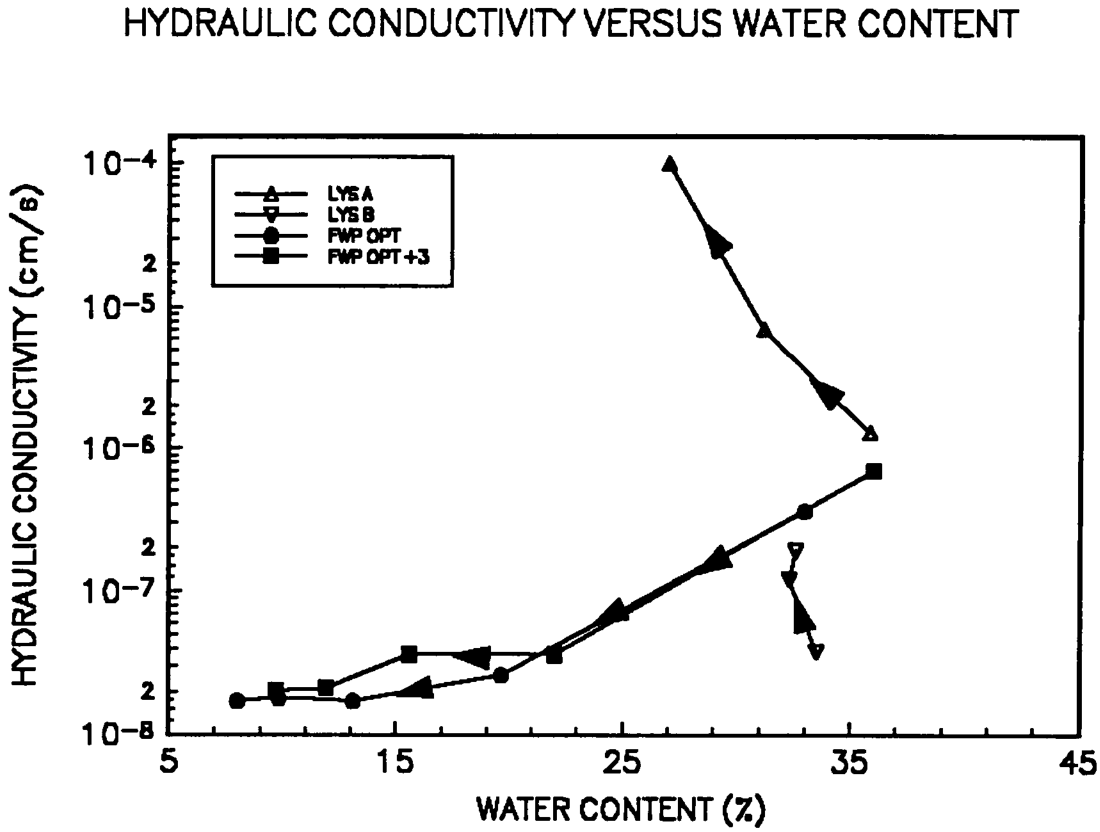


Figure 4-3 - Hydraulic conductivity versus water content - All samples

be measured or taken into account when determining the dry density. While the dry density of the soil which was actually measured was accurate, the dry density of the areas which displayed cracking were not taken into account.

The dry density of the flexible-wall sample was determined by weighing the sample when dried and dividing the weight by the measured volume of the entire sample. Cracks which occurred in the sample which were internal were automatically taken into account during the measurement of volume.

The size of the lysimeter sample prevented density from being measured directly. Although it would have been preferable to weigh the lysimeter for density measurements, movement of the sample could affect its integrity. As with the lysimeter sample, the density of a field size barrier must be determined from an area assumed to be representative. Thus, when characterizing the hydraulic conductivity of a clay barrier according to its dry density, the sample size must be taken into consideration.

Effects of Dry Density Change on Hydraulic Conductivity

With small samples, such as the flexible wall samples the hydraulic conductivity will decrease as the dry density increases (Figure 4-4). This is because the small sample is more likely to remain an entire structure than crack into separate pieces of soil which have their own density, hydraulic conductivity and water content.

The hydraulic conductivity of the lysimeter sample increased as the dry density increased (Figure 4-4) because the size and shape of the sample tended to produce cracks. When the cracks developed, individual soil aggregates were formed and acted

HYDRAULIC CONDUCTIVITY VERSUS DRY DENSITY

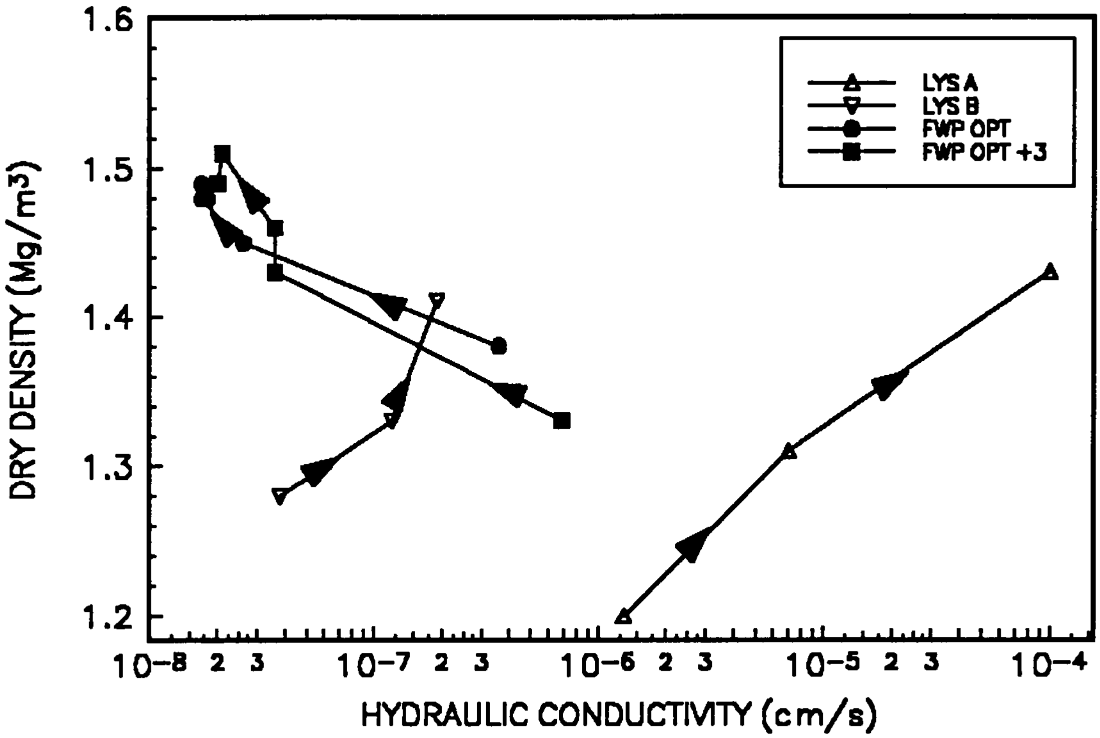


Figure 4-4 - Hydraulic conductivity versus dry density - All samples

independently of each other. Each of these individual units may have characteristics of a low hydraulic conductivity soil, but when they act as a whole, their inability to remain intact provided the path of least resistance for the flow of water through the barrier. This was evident by the variation of conductivity measurements taken from the lysimeters (Figure 3-7, 3-8,3-9, 3-18, 3-19 and 3-20). Prior to cracking, the lysimeter sample's initial hydraulic conductivity varied by two orders of magnitude from adjacent chambers. After cracking, these chambers displayed an increase in hydraulic conductivity by an order of magnitude in the cracked areas and no measurable conductivity in adjacent areas. Once again, the prevention of cracking or minimization of the cyclic wetting and drying periods was the key maintaining the integrity of the barrier.

Water Content Effects on Cracking Characteristics

The cyclic wetting and drying periods used in each of these tests reflected the variation of water content that can occur in the vadose zone. This can especially be a problem in the spring and summer in the southeast. As with actual clay barriers and layers, when the cyclic drying and wetting periods occur in the clay samples, cracks form as the dry density increases. These cracks formed differently in both samples.

The flexible wall samples had cracks which developed between lifts. These cracks did not begin until the fourth drying period, and since flow was directed across the fractures, appeared to have no detrimental effect on the hydraulic conductivity of these samples. When the samples dried to 8.0 percent water content or less, small hair sized cracks appeared within the sample. By looking at the side of these samples, the cracks could be seen to extend as far as 1.0 cm in depth. Whether or not these cracks were interconnected or how torturous the paths were could not be determined. Regardless, they did not allow the hydraulic conductivity to increase.

The lysimeter samples displayed cracking after the first dry-back period. It should be noted the first dry-back for the flexible wall samples decreased the water content 14 and 15%, while the lysimeter samples were dried-back only 4 and 5%. The cracks which developed were radial in orientation extending from the outside of the lysimeter to the inside of the sample. The chambers directly below these cracks showed an increase in hydraulic conductivity as expected. These cracks grew with each subsequent drying period even when the water content decrease was not as large in the next cycle (Figure 4-1, LYS B). This indicates that when the barrier is subjected to repeated drying and wetting cycles cracks will continue to propagate even when water content changes are small. If the water content can be kept constant, the integrity of the liner may be maintained. This may be achieved by keeping a thick layer of topsoil over the liner so the water will be evaporated from the topsoil and not the clay barrier. Another method to prevent the liner from cracking would be to keep it wet in the dry season by applying water to the clay to keep it from drying. As long as the clay is kept near optimum, the dry density of the clay may be maintained and the hydraulic conductivity will remain constant.

PART V

CONCLUSIONS AND RECOMMENDATIONS

FOR FURTHER RESEARCH

CONCLUSIONS

The flexible-wall and lysimeter samples were representative of two different portions of a clay barrier. The flexible-wall samples, after being subjected to several drying cycles, represented the intact portion of the barrier that remains after the dry density increases. These intact soil aggregates have a dry density near maximum and a hydraulic conductivity that has decreased since initial conditions.

The lysimeter samples, even prior to being subjected to drying cycles, showed heterogeneity in hydraulic conductivity within the same sample. These preferential flow paths within the samples became more evident as the samples were subjected to drying cycles. The lysimeter samples were representative of an entire clay barrier because of the heterogeneous nature of both soil structures.

Both lysimeters had a lower initial dry density than each of the flexible-wall samples. However, Lysimeter B had a lower initial hydraulic conductivity than the flexible-wall samples and Lysimeter B had a higher hydraulic conductivity than the flexible-wall samples. The initial hydraulic conductivity differences in these two lysimeters could due to the compaction method. Lysimeter A used an equal weight over a wider area with less blows. This factor could contribute to the formation of preferential flow paths. The lower energy used for compaction in Lysimeter A may not have been to close as many intraclod pores as the higher energy compaction thus yielding higher initial hydraulic conductivity.

Increases in dry density, which were due to the changes in water content, were the controlling factor for both the flexible-wall and lysimeter samples. The single unit samples of the flexible-wall displayed an increase in dry density that caused the hydraulic conductivity to decrease. This was due to the homogeneous nature of these units. The lysimeter samples also displayed an increase in dry density. However, this measurement was based on the intact portions of the lysimeter samples. This dry density increase, however, caused the formation of preferential flow paths which allowed the hydraulic conductivity to increase.

When the hydraulic conductivity of a clay is determined, the homogeneity of the structure must be taken into consideration. The flexible-wall samples or any sample which acts as a singular clay matrix will more likely yield conductivities that are lower than the entire clay barrier which is heterogeneous. Large lysimeter samples are more representative of a clay barrier because of the inclusion of preferential flow paths. This was evident by the variable hydraulic conductivities measured among sections within the lysimeter sample.

Additionally, when the drying cycles for the lysimeter samples do not allow the soil to reach water contents as low as previously measured, the dry density may continue to increase. This caused the preferential flow to increase while the flow through intact portions of the clay matrix to decrease. Therefore, once the dry density increase initiates a hydraulic conductivity increase, continued cyclic water content changes will ensure the enhancement of this increase in hydraulic conductivity. In order to prevent the dry density from increasing quickly, care must be taken to keep the drying and wetting cycles at a minimum or the barrier must be kept near optimum water content.

The flexible-wall samples do provide a better method for measuring the strain of the clay after successive drying cycles because of ease of handling the specimen. The strain developed in the lysimeter samples is difficult to measure because the specimen may not be disturbed. Also, the development of cracks adds to this difficulty in measuring because the depth of the crack was difficult to determine.

The shape of the sample tested also had an effect on how the dry density increased. Samples which had a larger width than height tended to have greater dry density increases with small changes in water content than samples with similar width and height. This quick increase in dry density was a contributor to the development of preferential flow paths. Therefore, if the barrier can be made thicker, the dry density would not increase as fast and preferential flow paths would not develop as quickly.

The variability of the hydraulic conductivity in the initial measurement is significant because the it places the validity of the sample size in question. While a portion of the barrier may meet regulatory requirements, other portions may not meet these requirements. Larger sample sizes may be needed to ensure both compaction and hydraulic conductivity requirements have been met throughout the clay barrier which is being tested.

RECOMMENDATIONS FOR FURTHER RESEARCH

In order to develop methods to better determine actual field hydraulic conductivity, the following recommendations are made for future research.

- Determination of minimum or critical water content loss which cause increases in dry density large enough to develop preferential flow paths.

- Determination of critical development of preferential flow paths. Find how long it takes for these flows paths to become instrumental in the increase of the hydraulic conductivity.

- Methods to determine the location of development of preferential flow paths should be developed.

- The concept of how the drying cycles affect breakthrough time in clay barriers should be investigated.

- Exploration of preferential flow path development through dye tracing and dissection of clay barrier or samples should be performed.

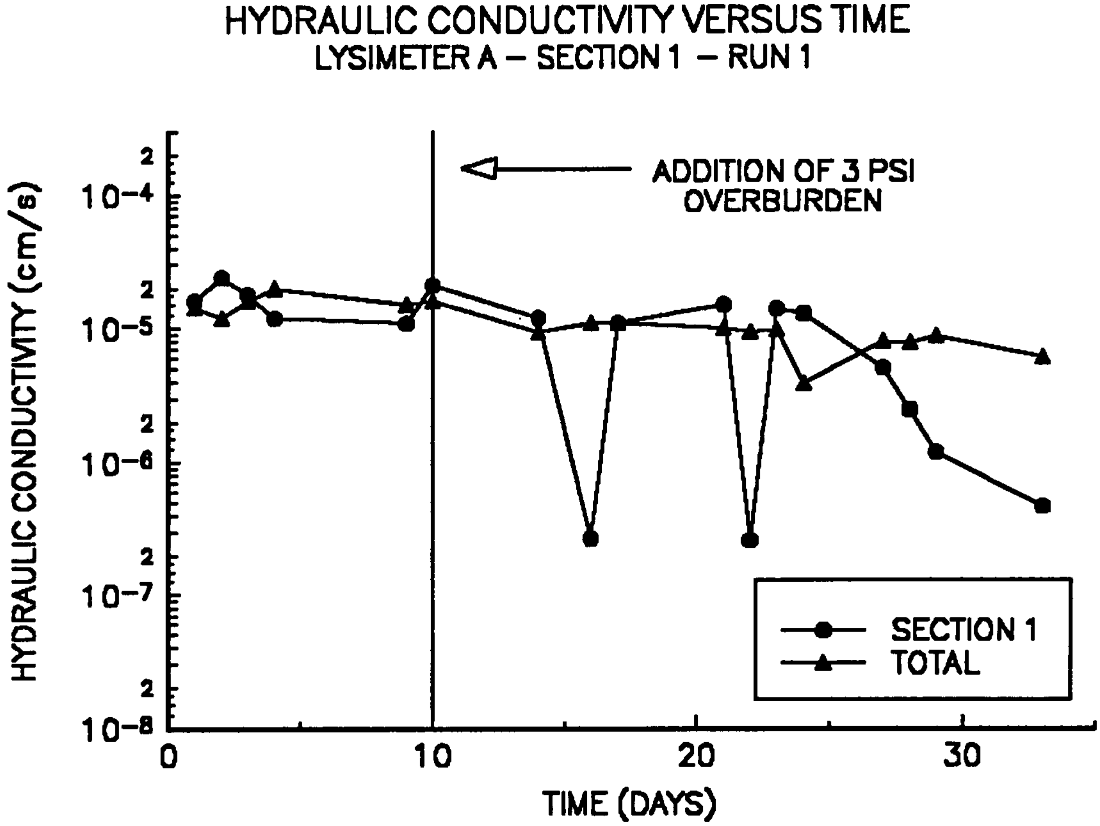
- Determination of methods to repair preferential flow paths before they become detrimental to the ability of the clay barrier to perform its function.

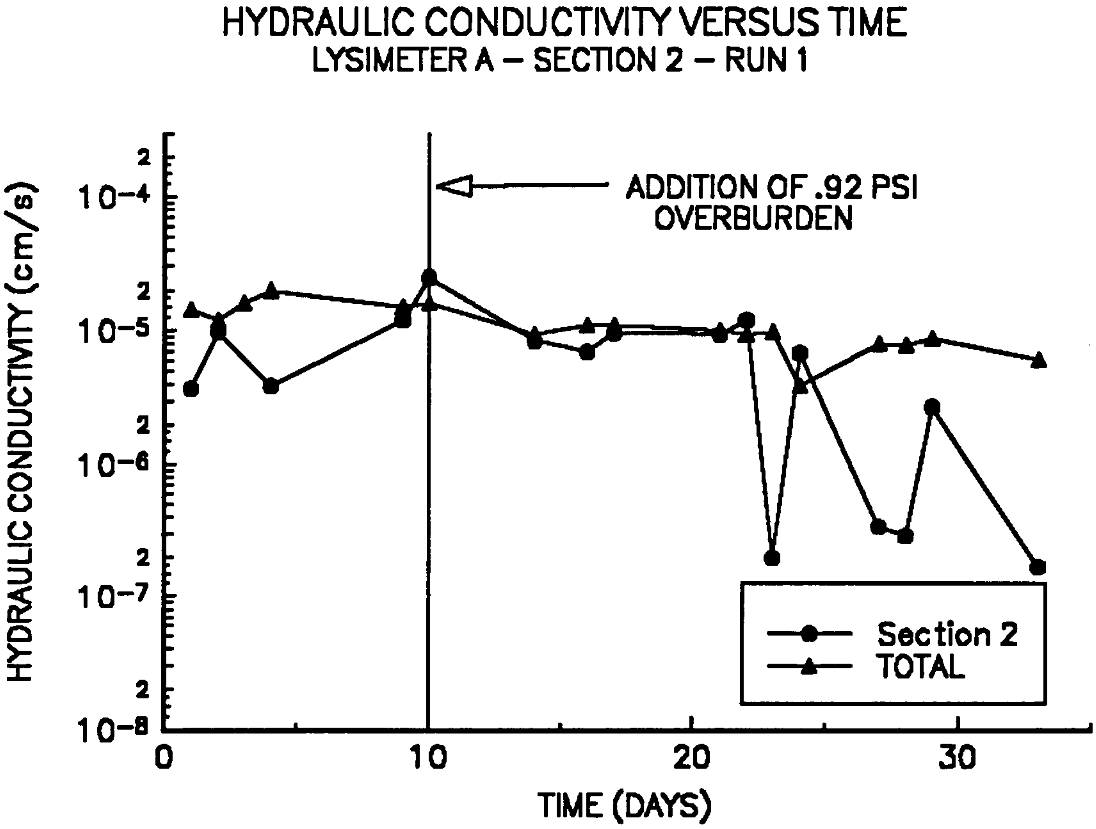
- Development of methods to prevent the evaporation of water from landfill caps or continue replenishing the water to the cap.

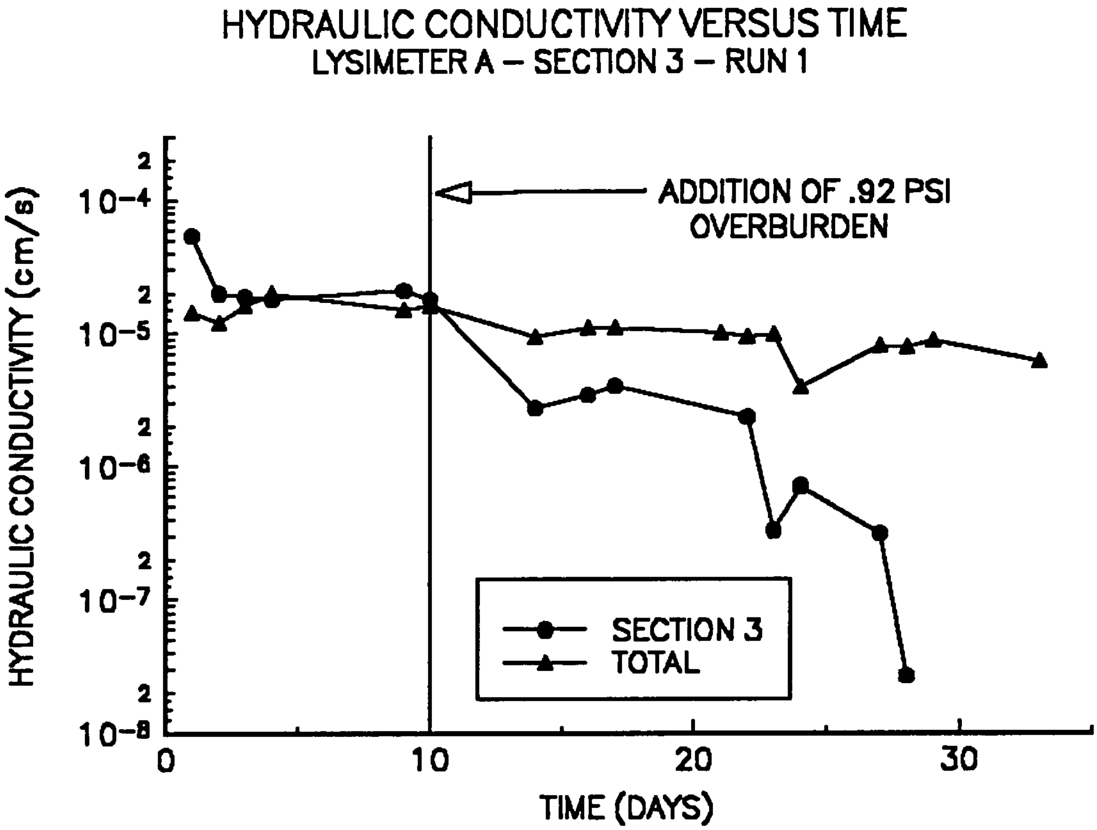
- Development of methods to strengthen the clay so preferential flow paths will have a more difficult time developing.

APPENDICES

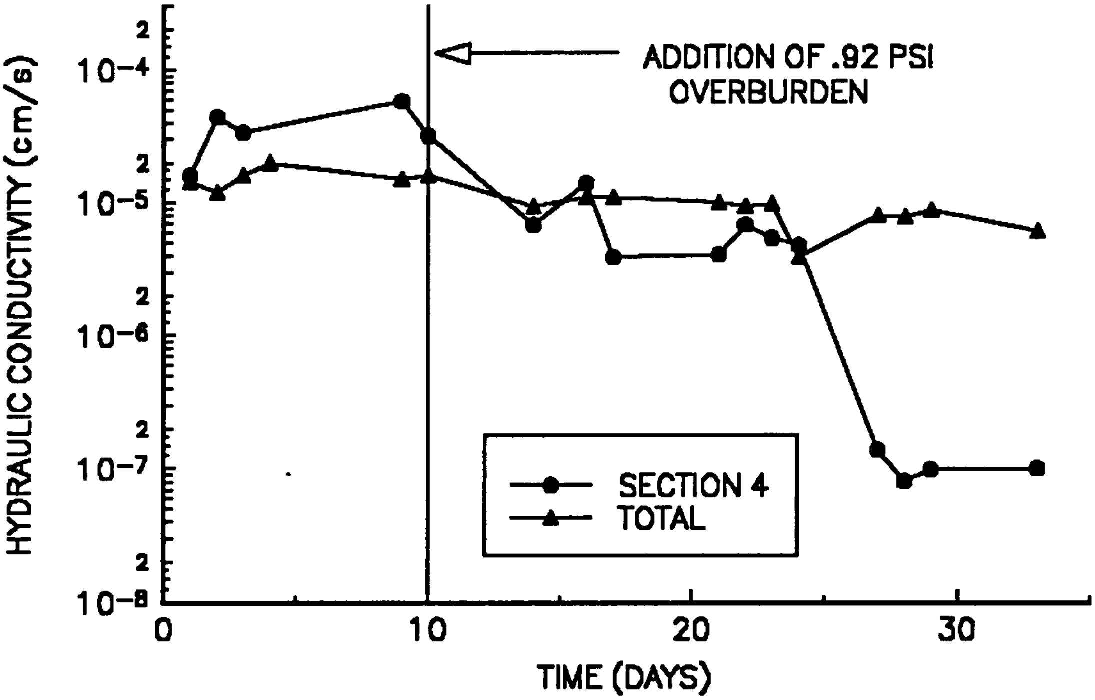
APPENDIX A

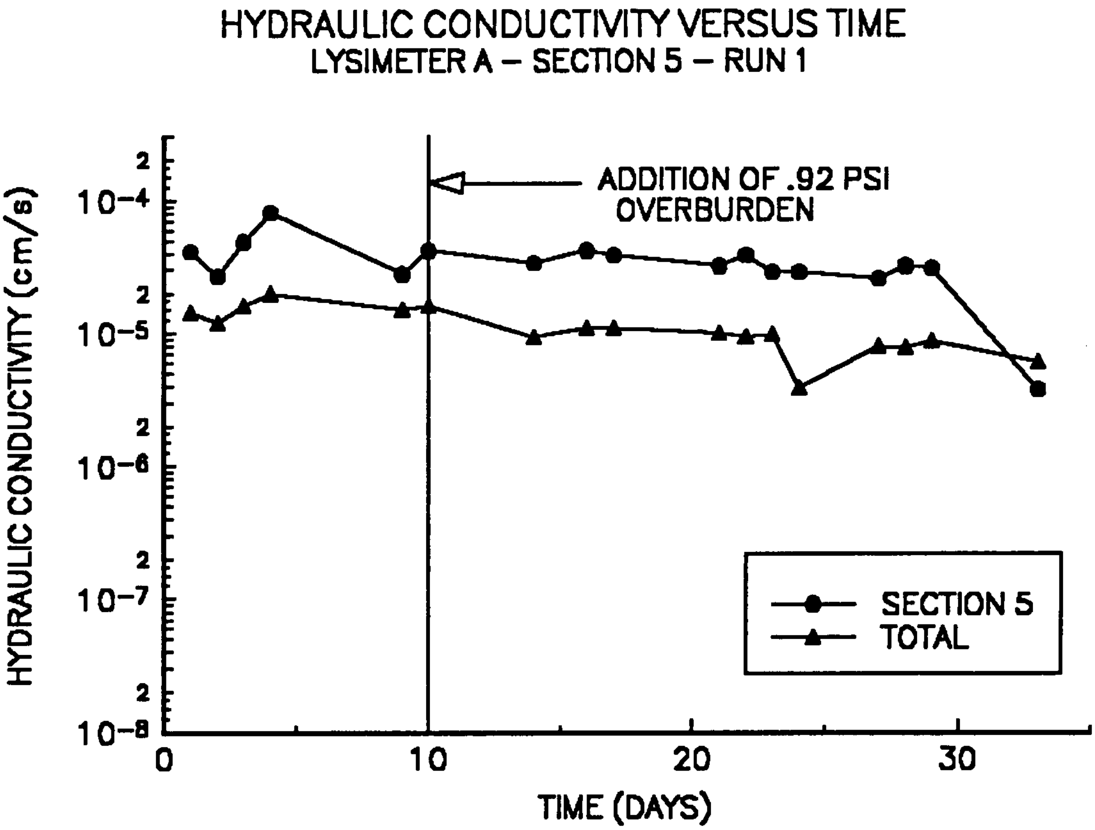

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 1 – RUN 1
ADDITION OF 3 PSI OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
SECTION 1
TOTAL
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
0
10
20
30

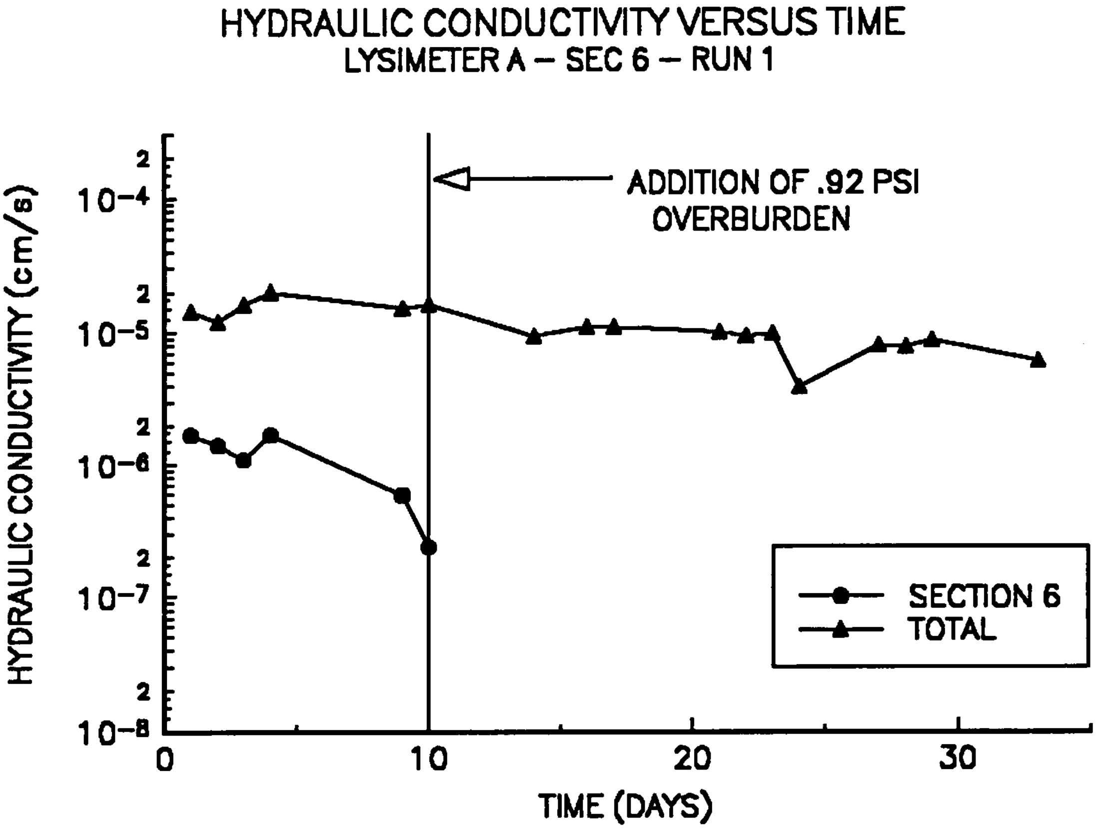

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 2 – RUN 1
ADDITION OF .92 PSI
OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
Section 2
TOTAL
0
10
20
30


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 3 – RUN 1
ADDITION OF .92 PSI OVERBURDEN
SECTION 3
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
10−4
10−5
10−6
10−7
10−8
2
0
10
20
30

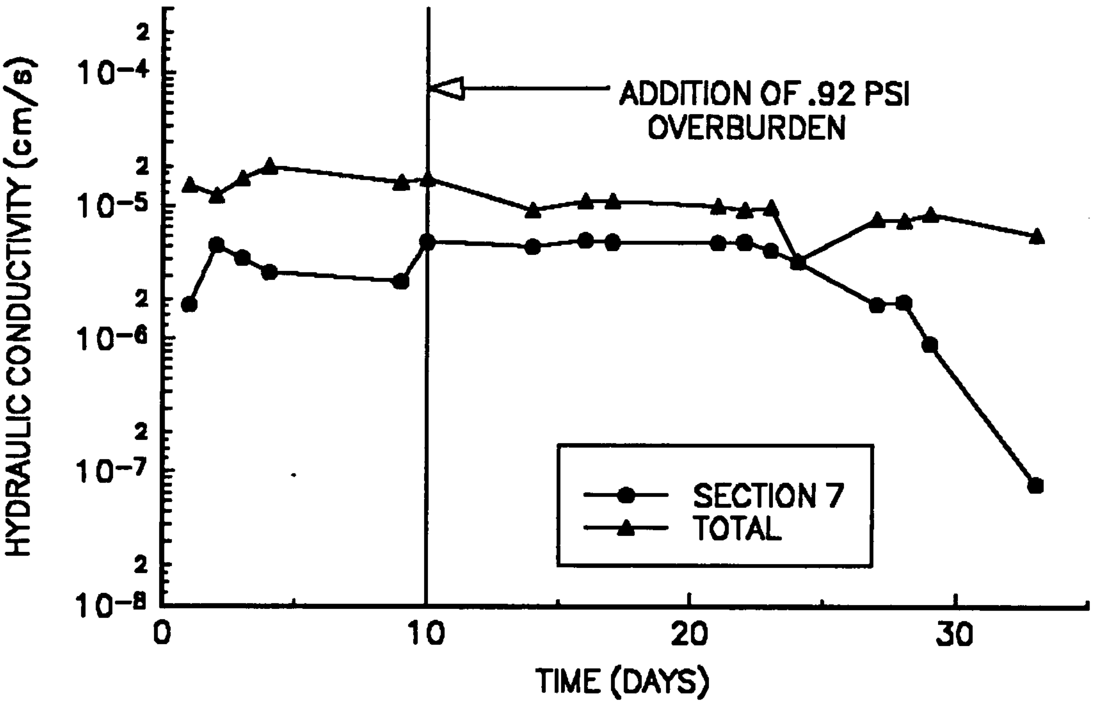
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 4 – RUN 1

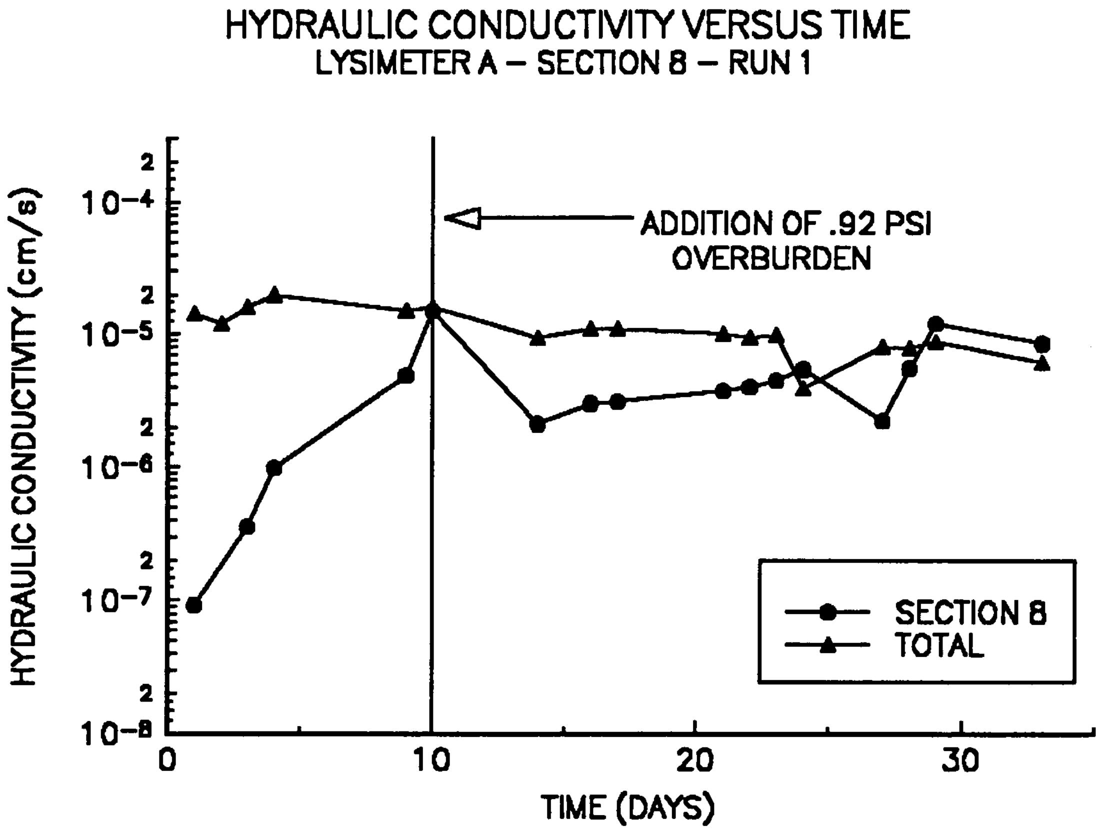


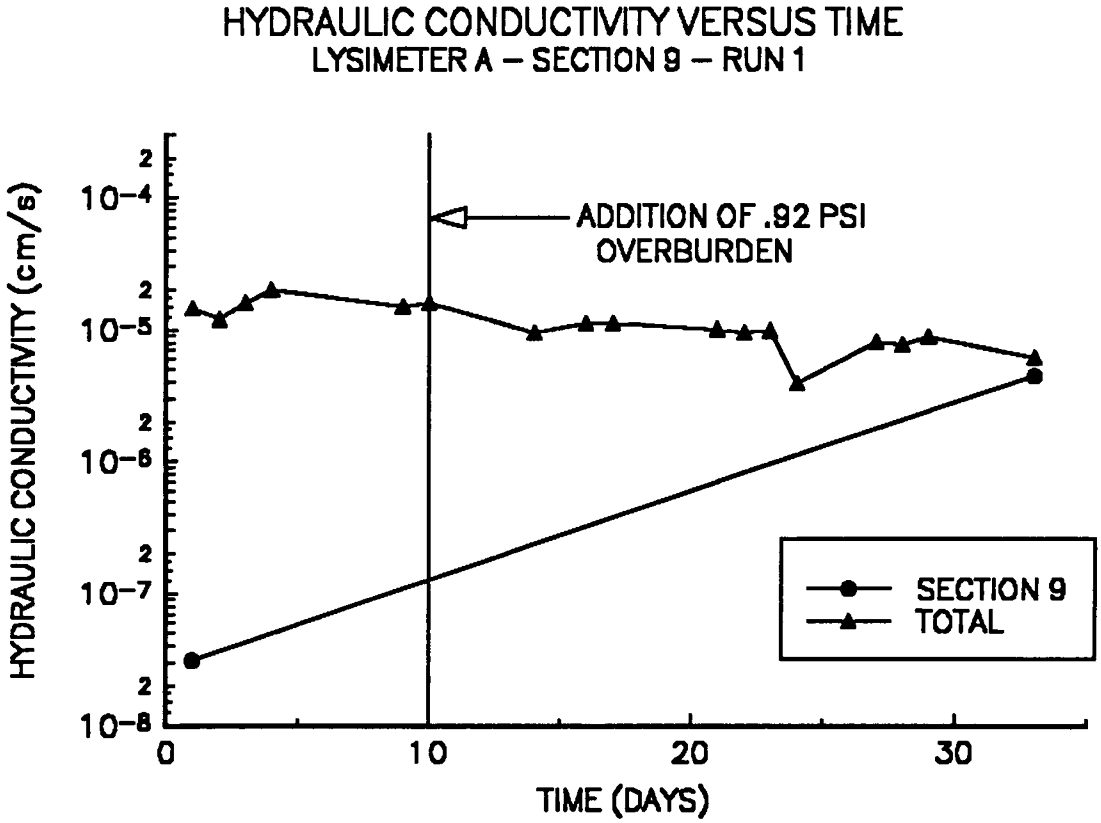

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 5 – RUN 1
ADDITION OF .92 PSI
OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
2
10^{-4}
2
10^{-5}
2
10^{-6}
2
10^{-7}
2
10^{-8}
0
10
20
30
TIME (DAYS)
SECTION 5
TOTAL


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SEC 6 – RUN 1
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
ADDITION OF .92 PSI
OVERBURDEN
SECTION 6
TOTAL

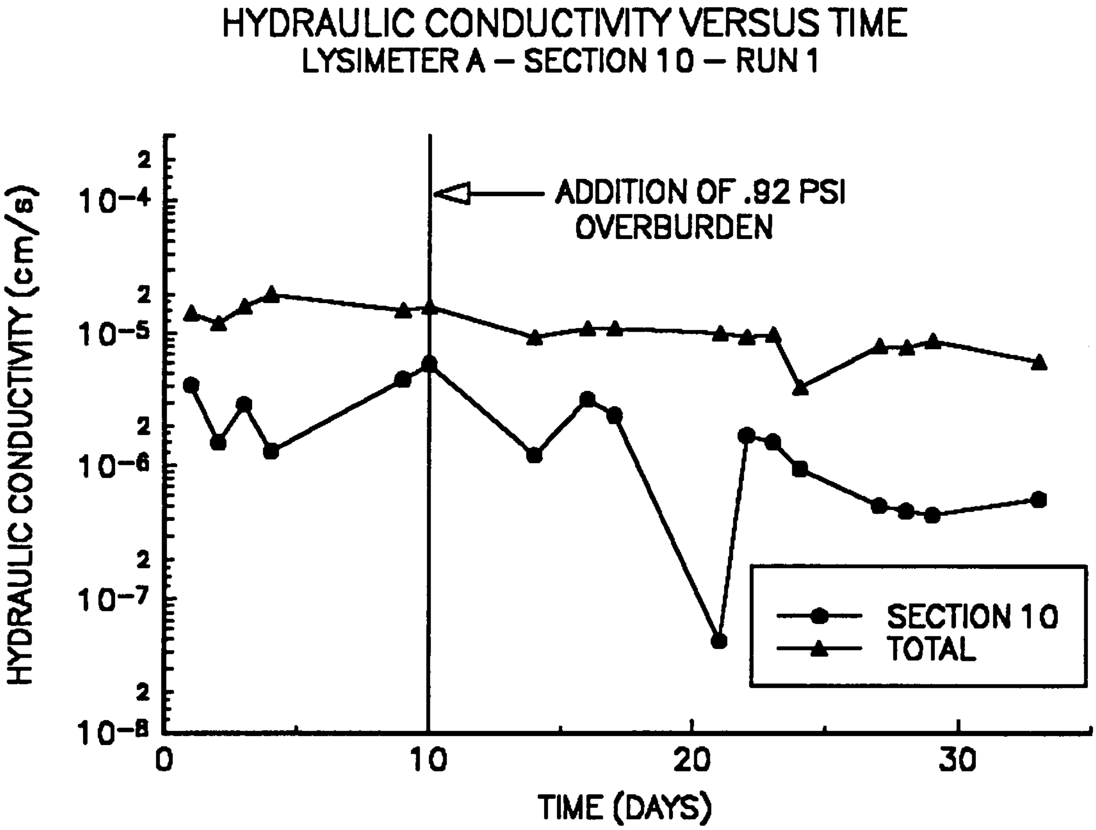
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 7 – RUN 1

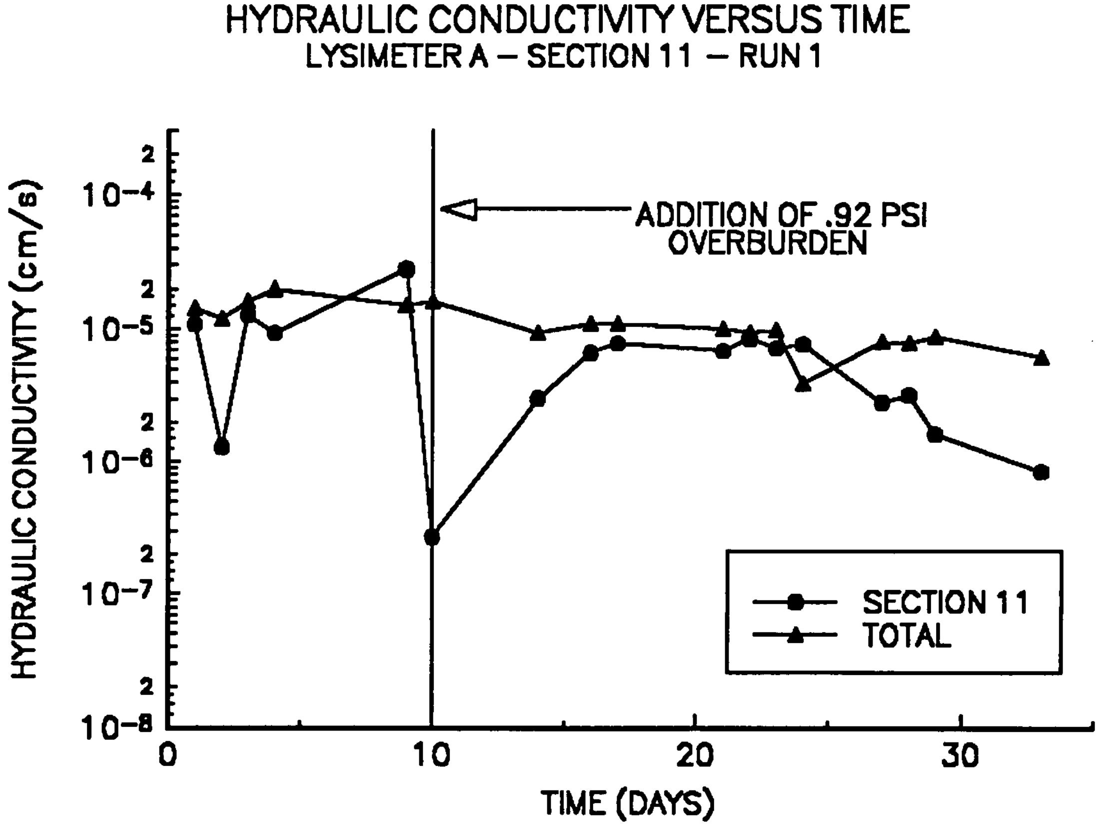



HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 8 – RUN 1
ADDITION OF .92 PSI OVERBURDEN
SECTION 8
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
0
10
20
30
10−4
10−5
10−6
10−7
10−8
2

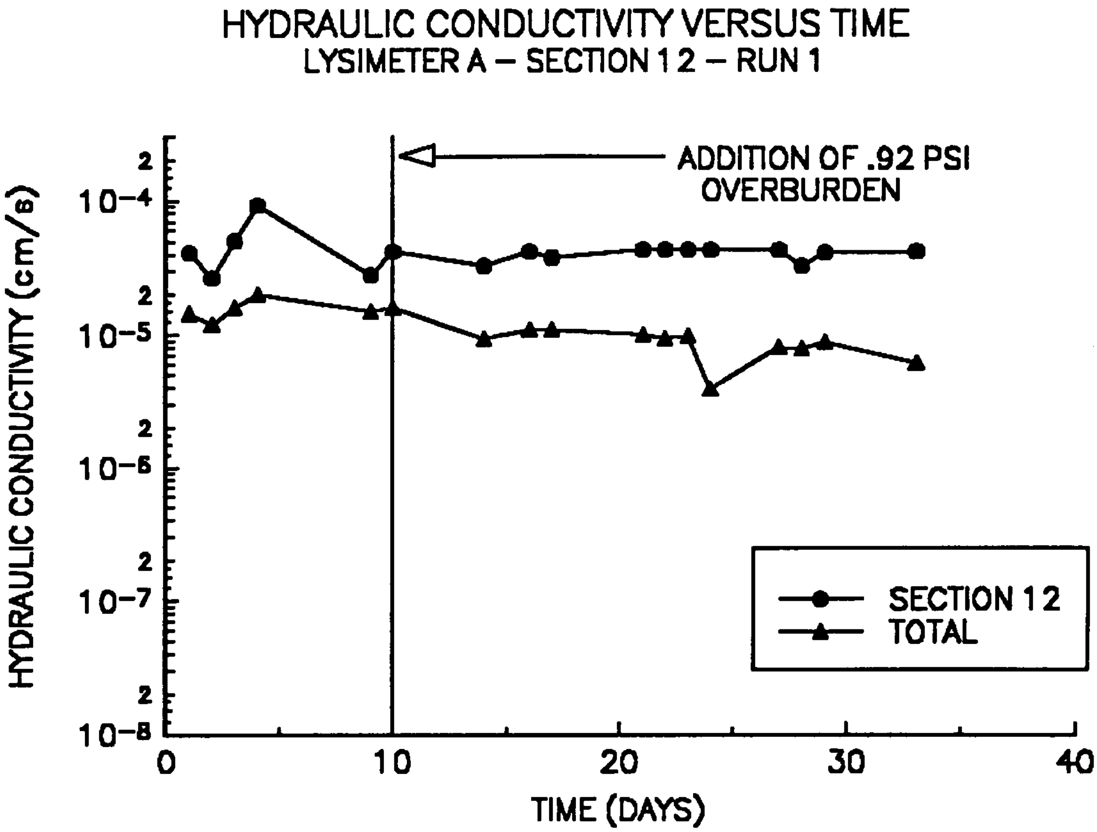


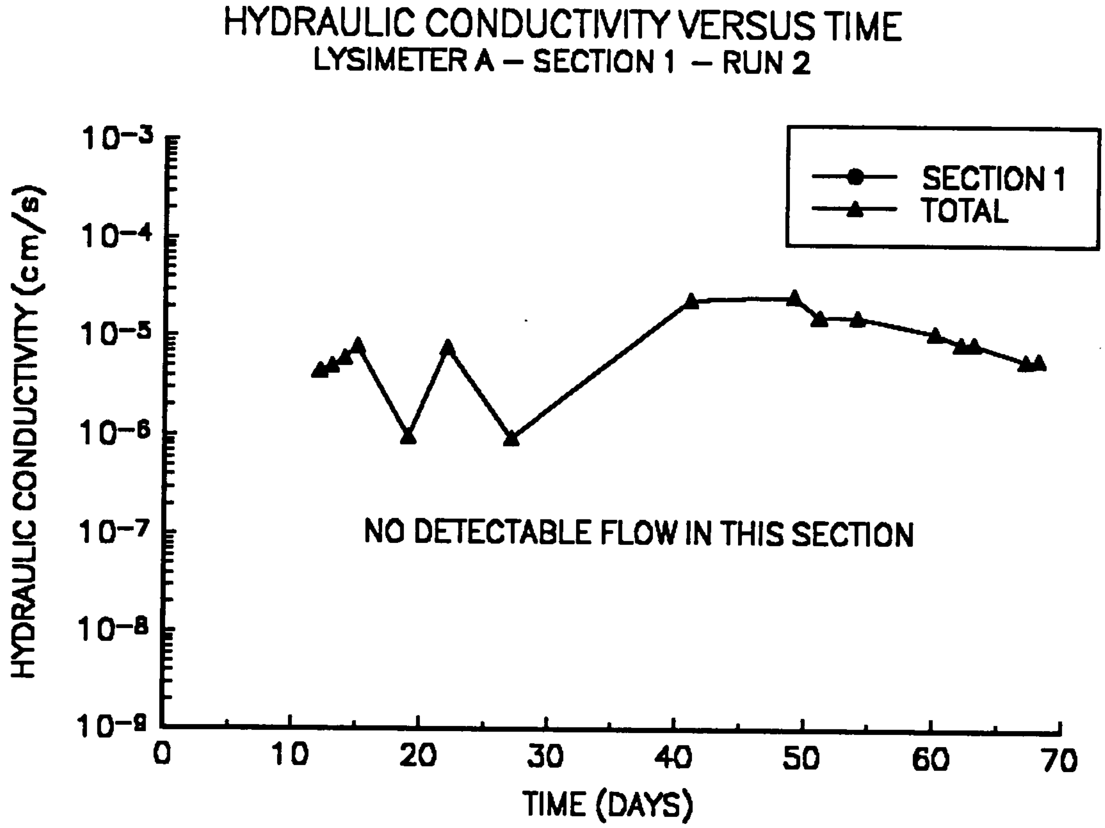
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 9 – RUN 1
ADDITION OF .92 PSI OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
SECTION 9
TOTAL

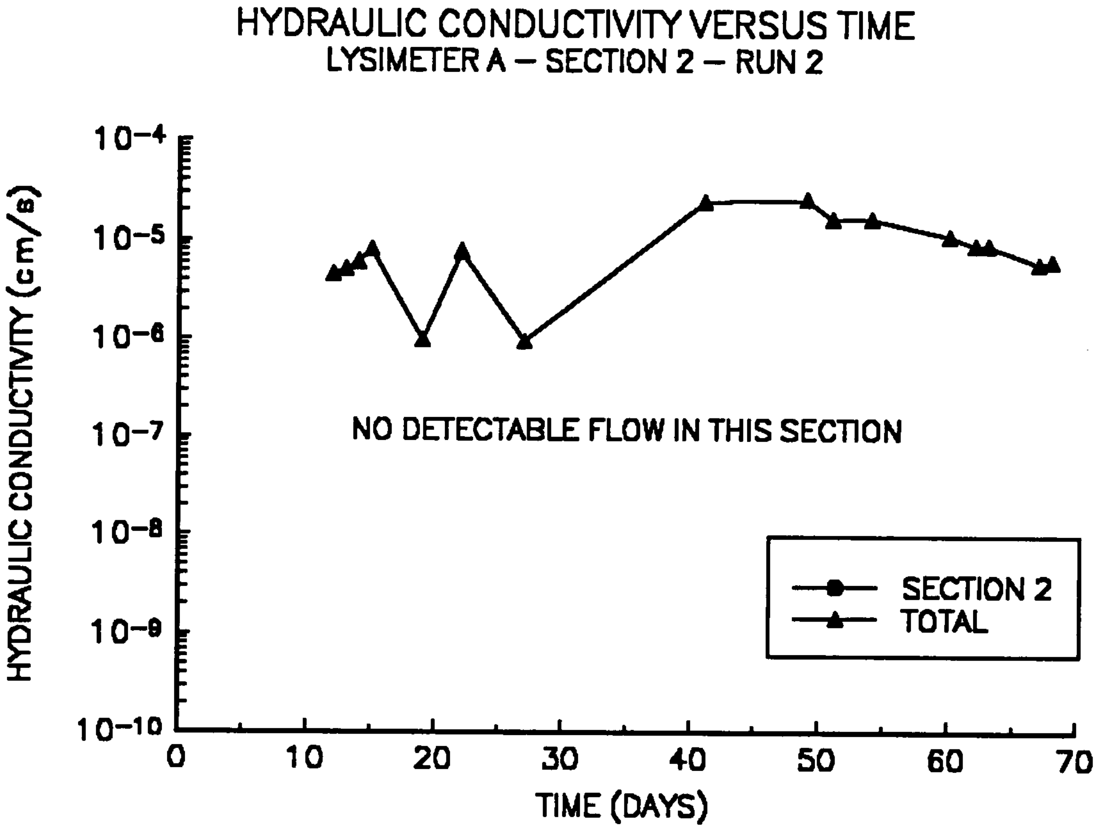

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 10 – RUN 1
ADDITION OF .92 PSI OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
SECTION 10
TOTAL
0
10
20
30



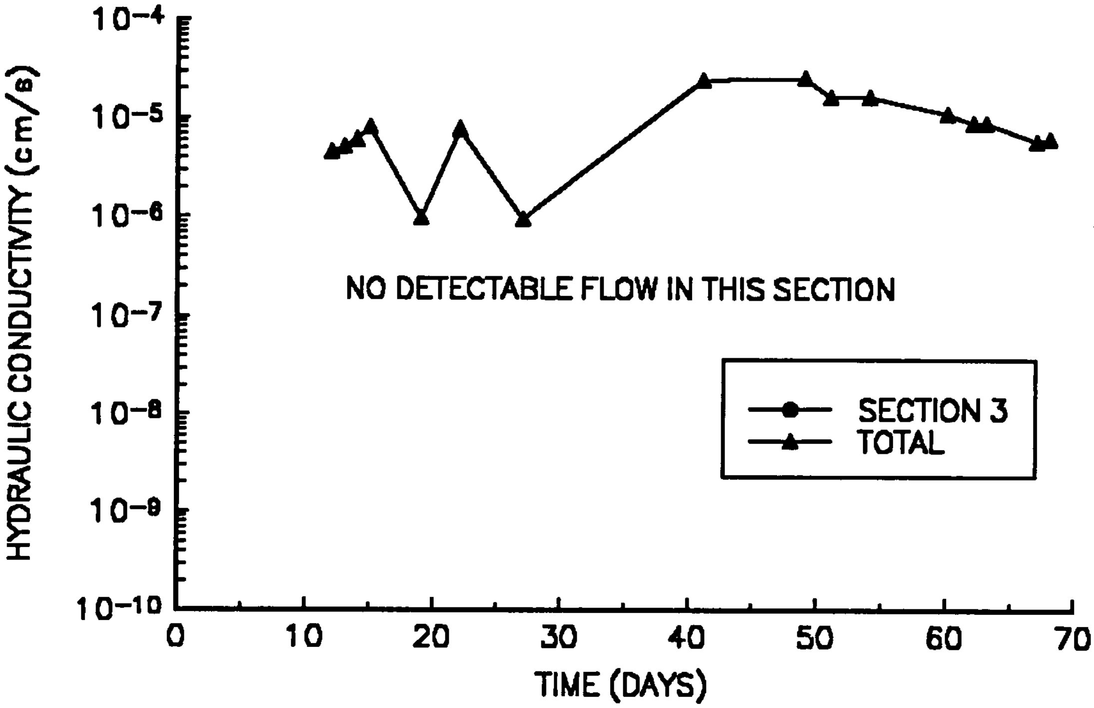
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 11 – RUN 1
HYDRAULIC CONDUCTIVITY (cm/s)
2
10⁻⁴
2
10⁻⁵
2
10⁻⁶
2
10⁻⁷
2
10⁻⁸
0
10
20
30
TIME (DAYS)
ADDITION OF .92 PSI OVERBURDEN
SECTION 11
TOTAL

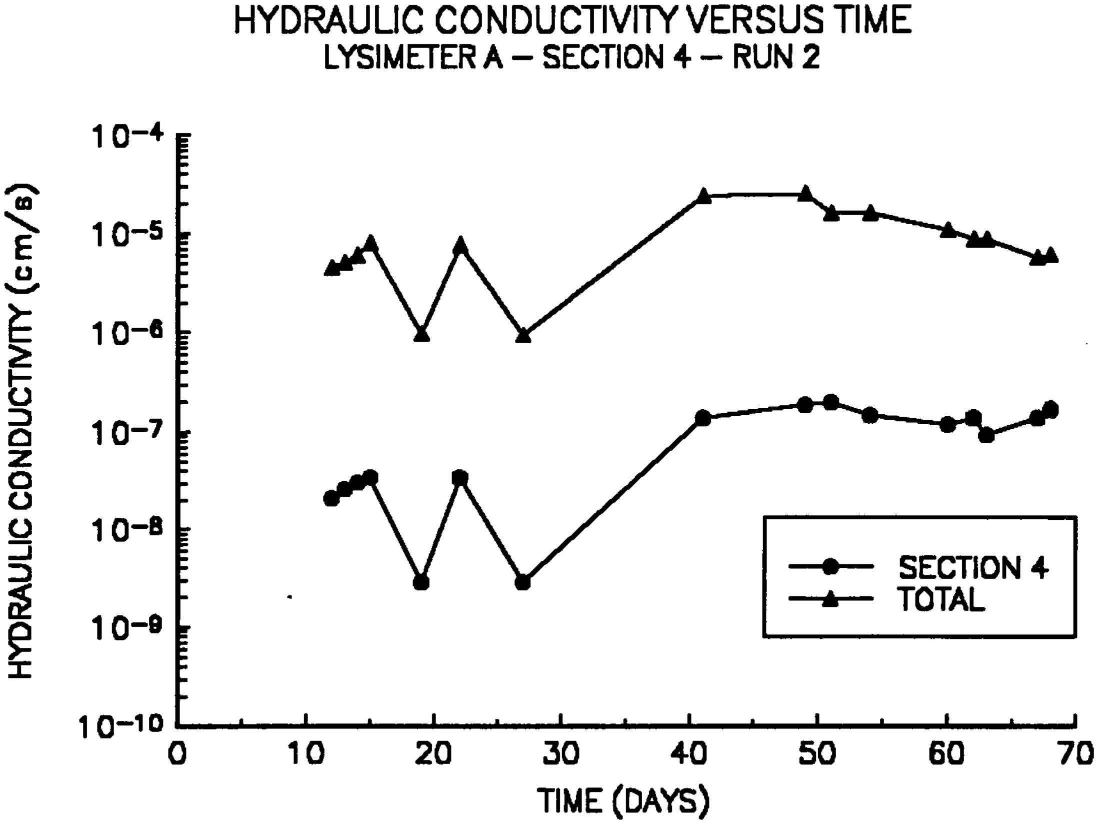

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 12 – RUN 1
ADDITION OF .92 PSI OVERBURDEN
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
2
0
10
20
30
40
TIME (DAYS)
SECTION 12
TOTAL

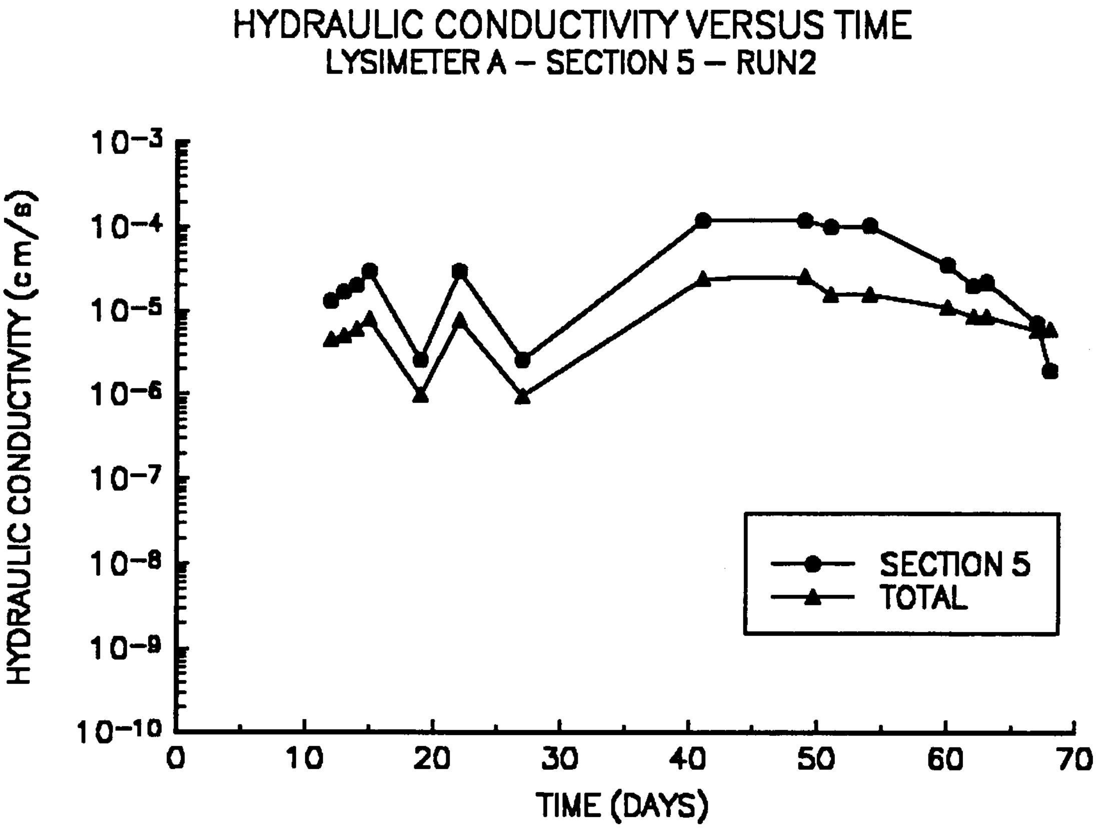

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 1 – RUN 2
SECTION 1
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−3
10−4
10−5
10−6
10−7
10−8
10−9
NO DETECTABLE FLOW IN THIS SECTION
0
10
20
30
40
50
60
70
TIME (DAYS)


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 2 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
NO DETECTABLE FLOW IN THIS SECTION
SECTION 2
TOTAL
0
10
20
30
40
50
60
70
TIME (DAYS)

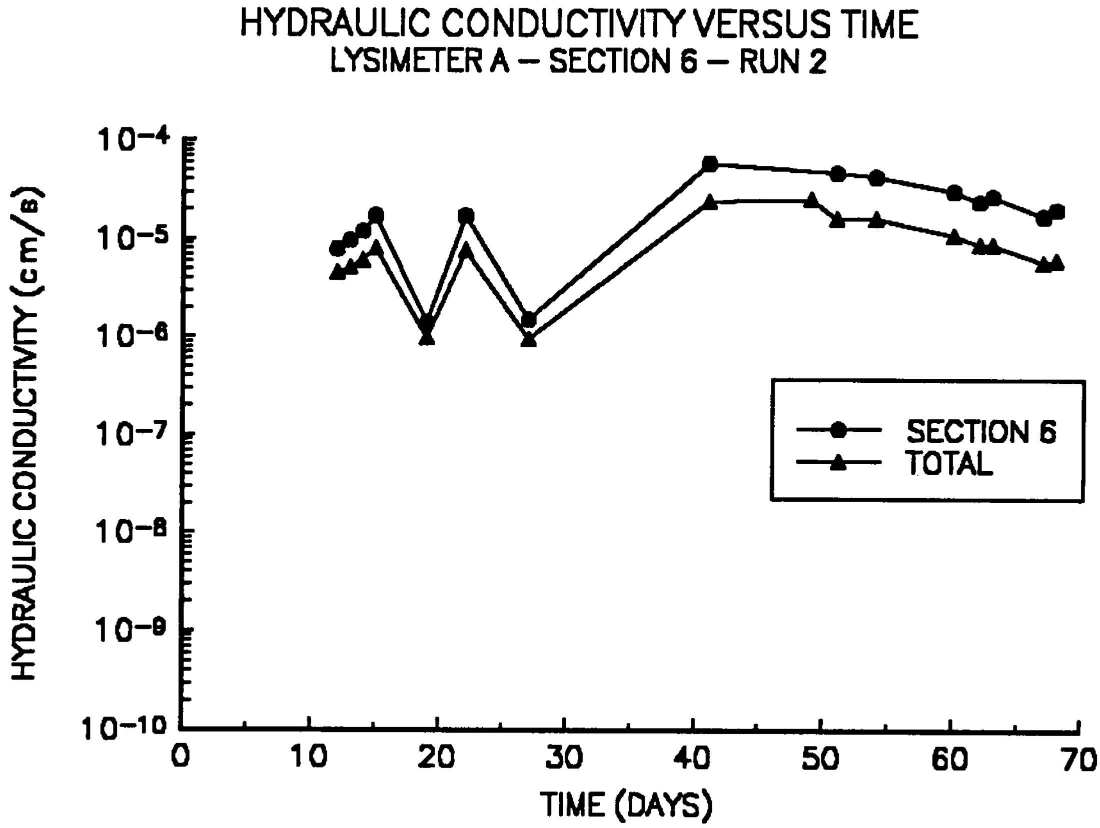
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 3 – RUN 2

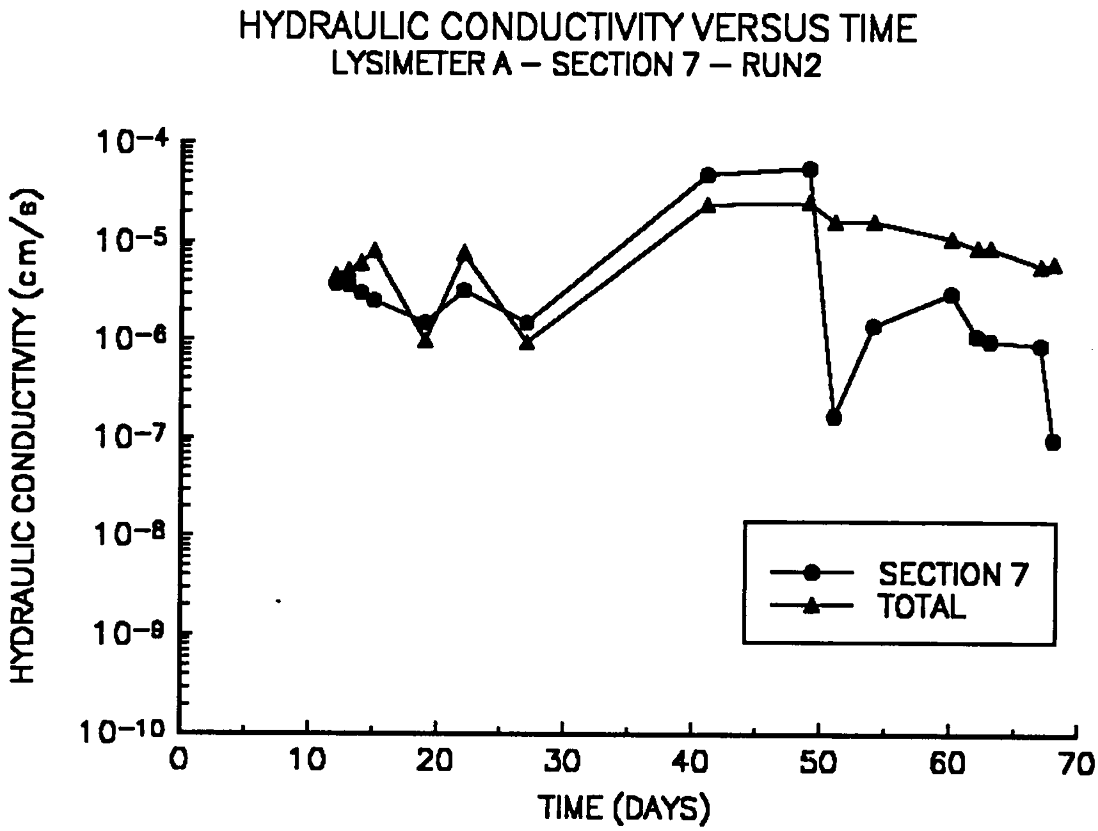


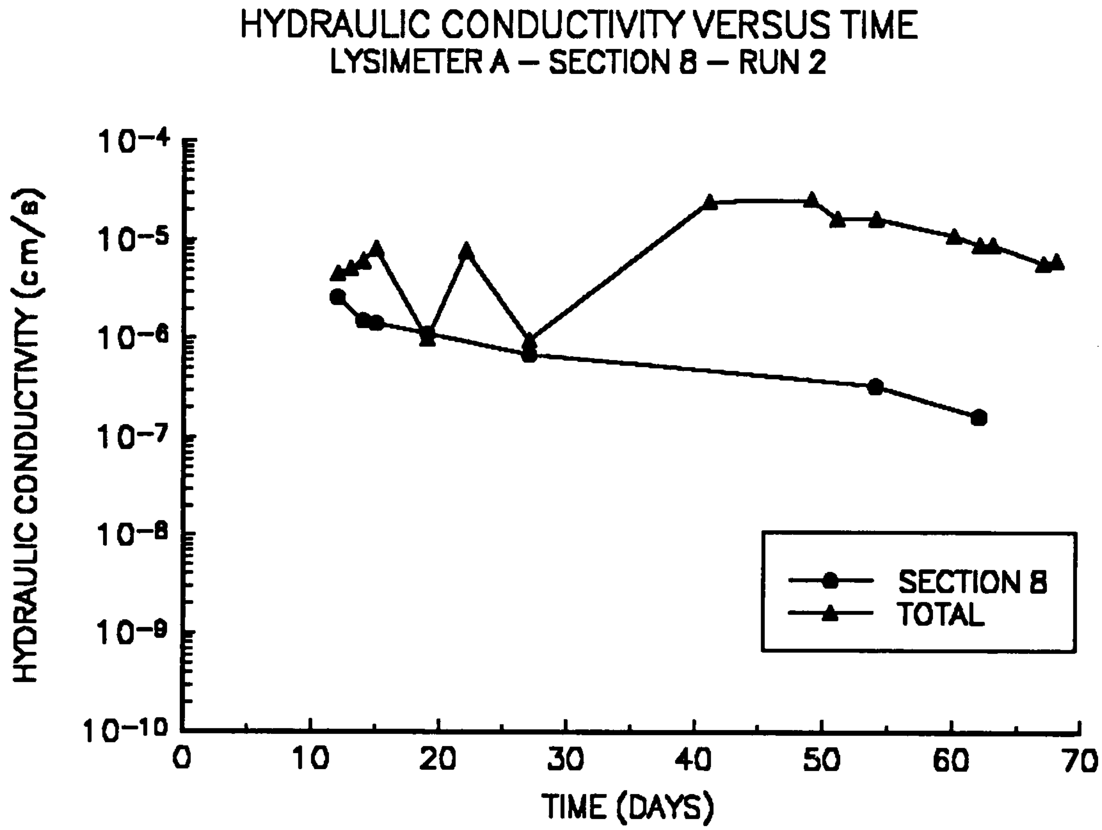

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 4 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 4
TOTAL



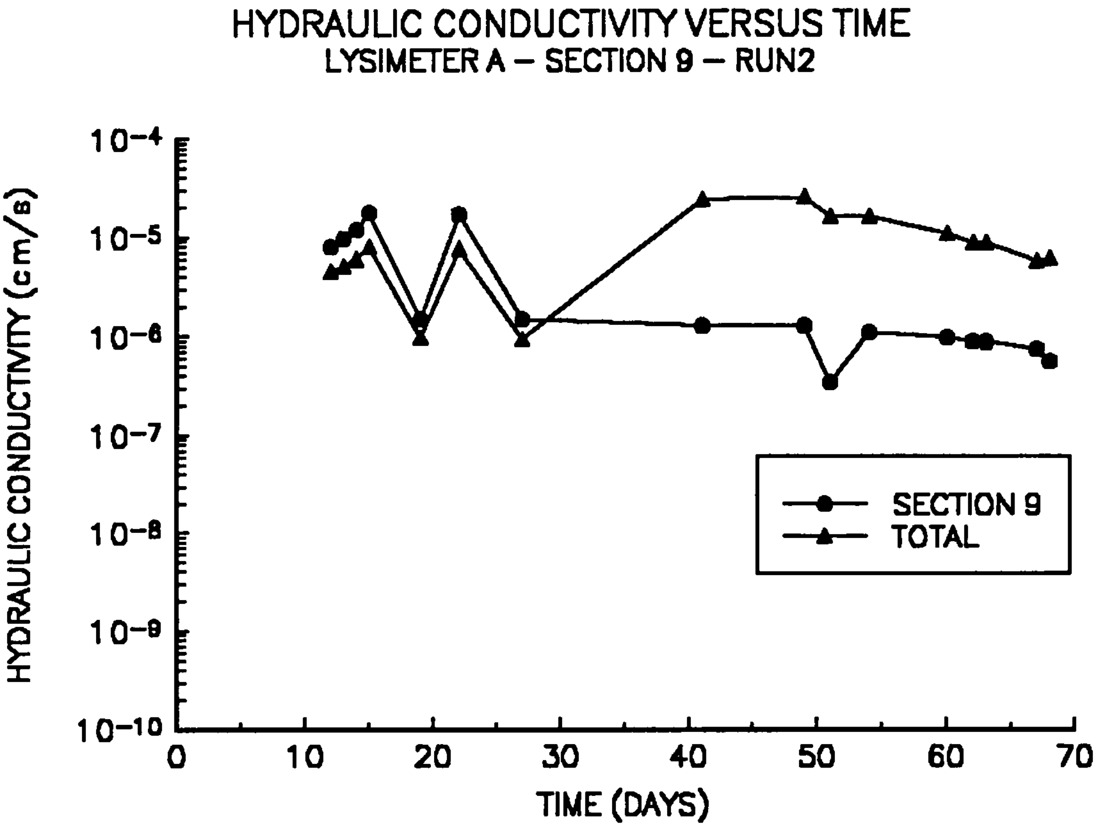
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 5 – RUN2
HYDRAULIC CONDUCTIVITY (cm/s)
10−3
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 5
TOTAL


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 6 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 6
TOTAL

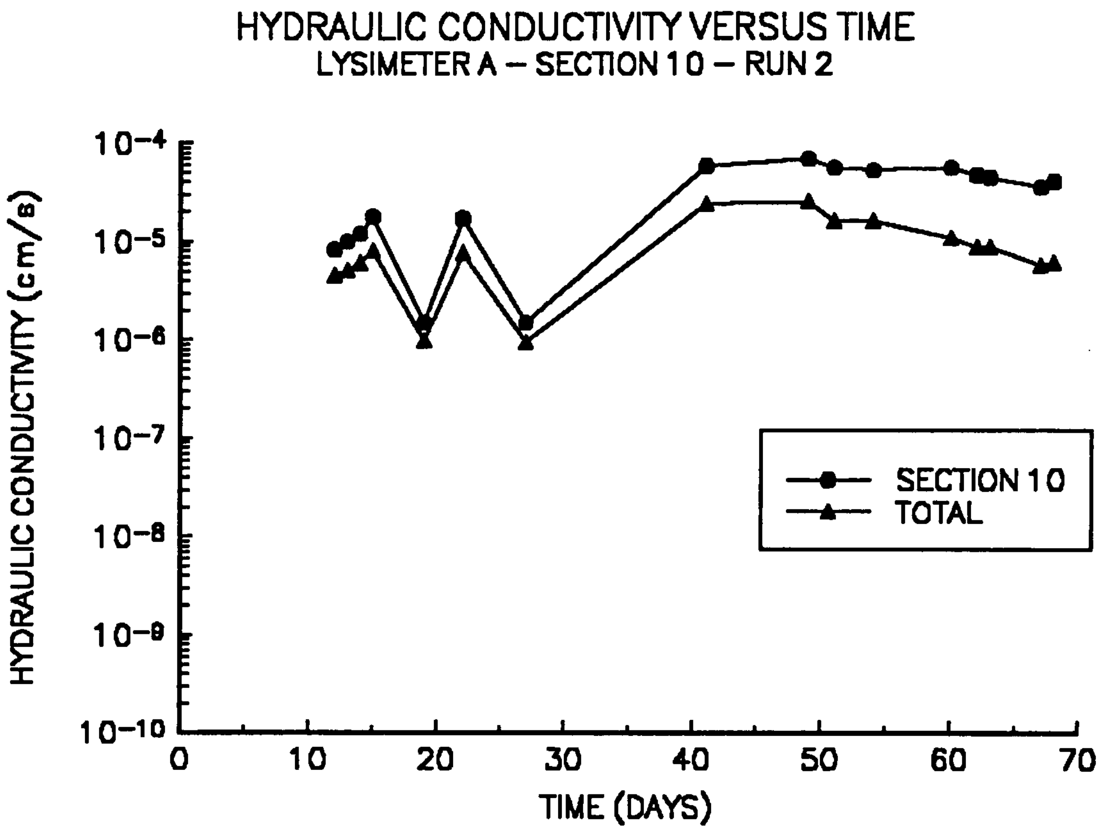

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 7 – RUN2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 7
TOTAL



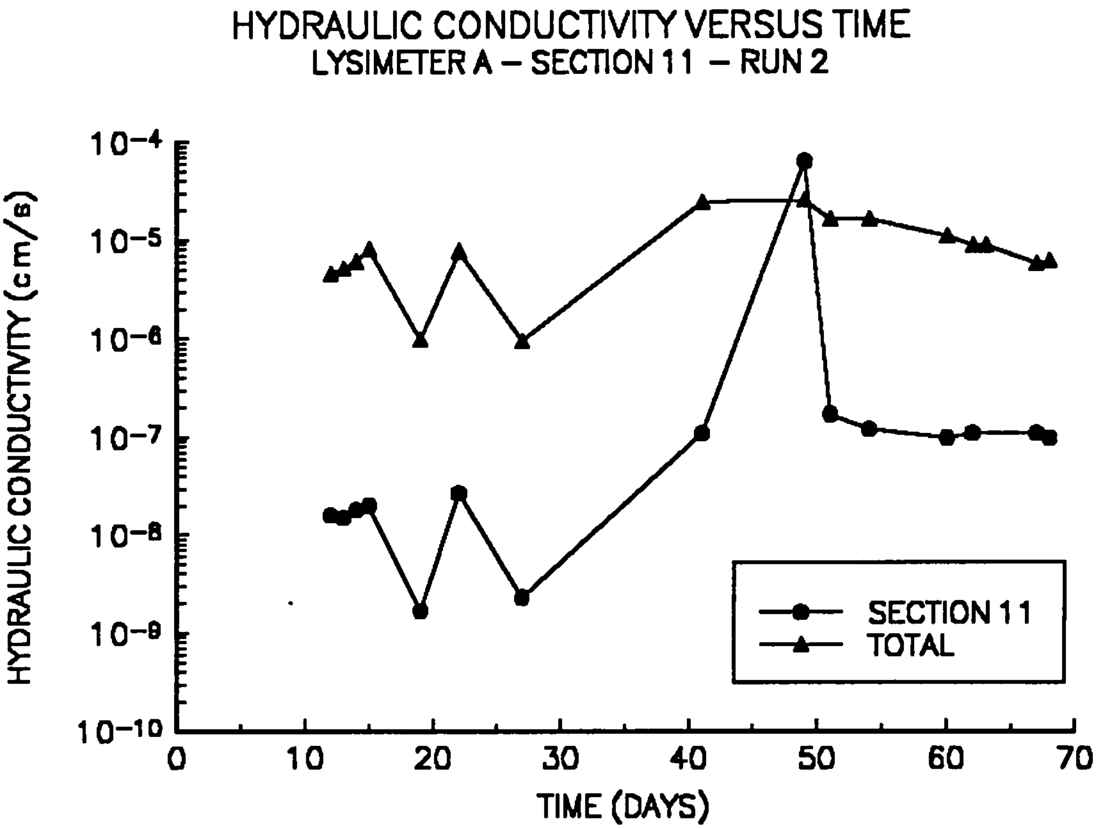
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 8 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 8
TOTAL



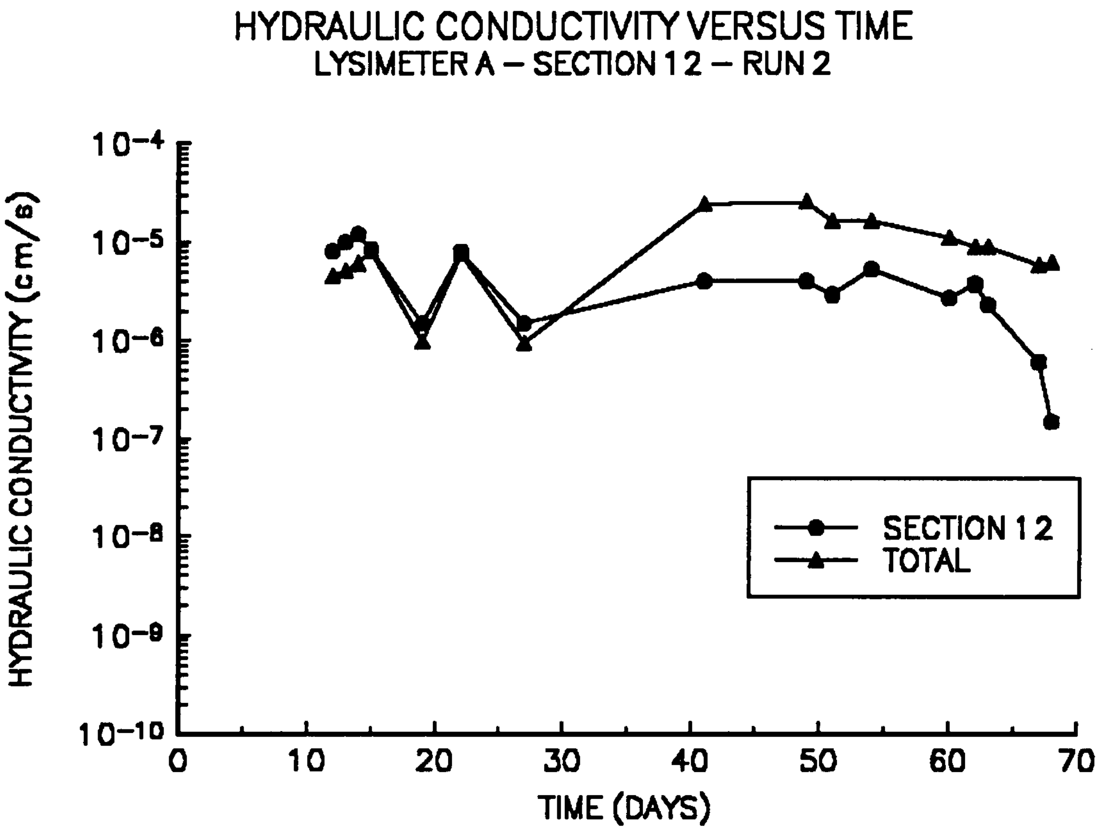
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 9 – RUN2
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 9
TOTAL

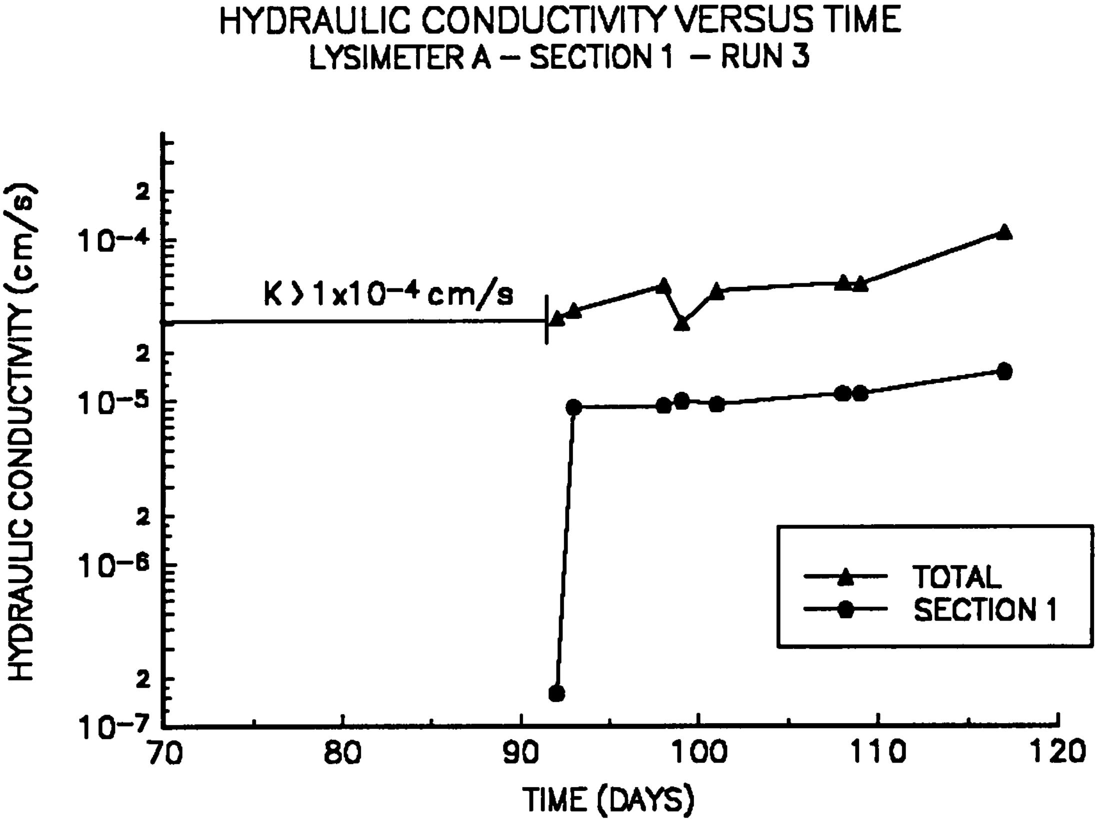


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 10 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 10
TOTAL

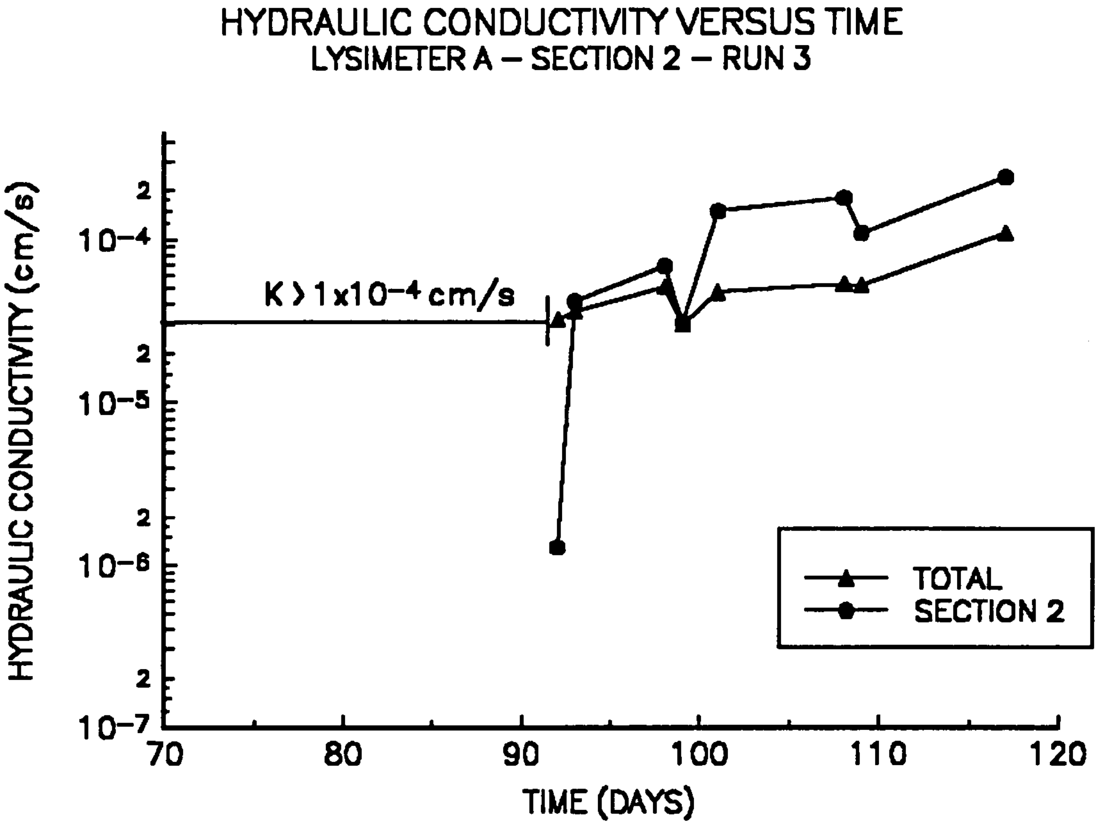


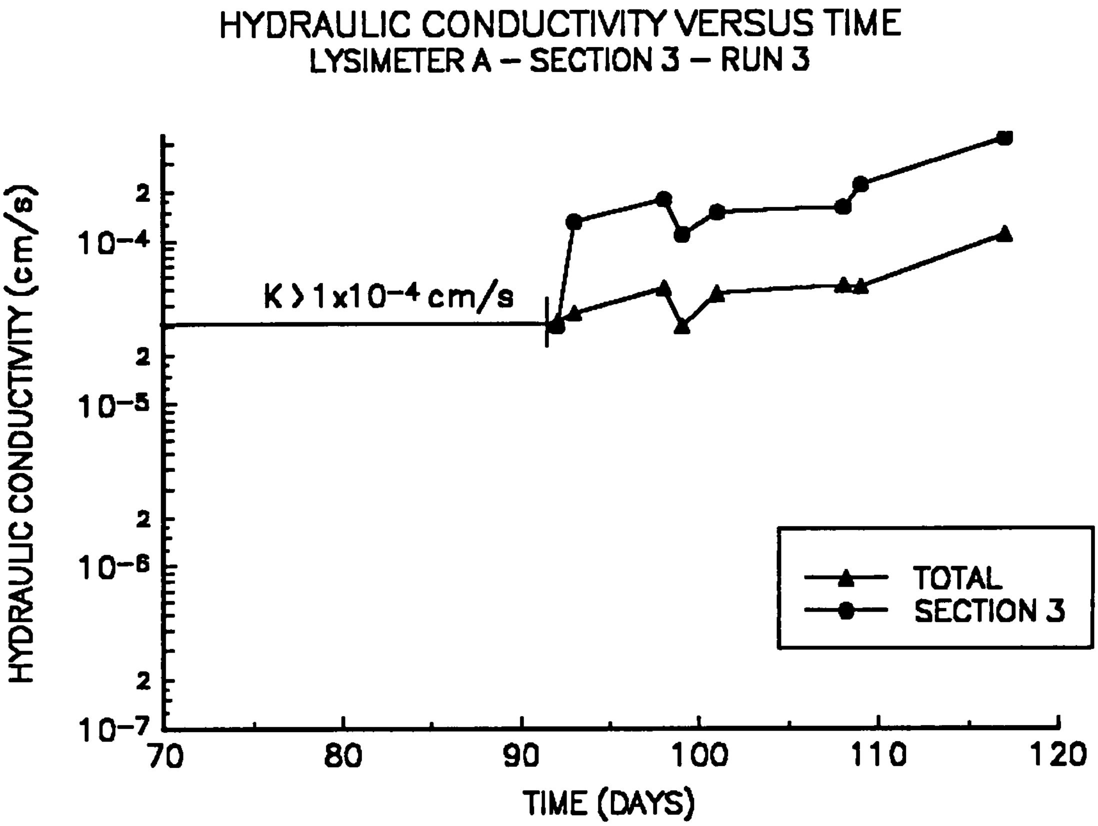
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 11 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 11
TOTAL

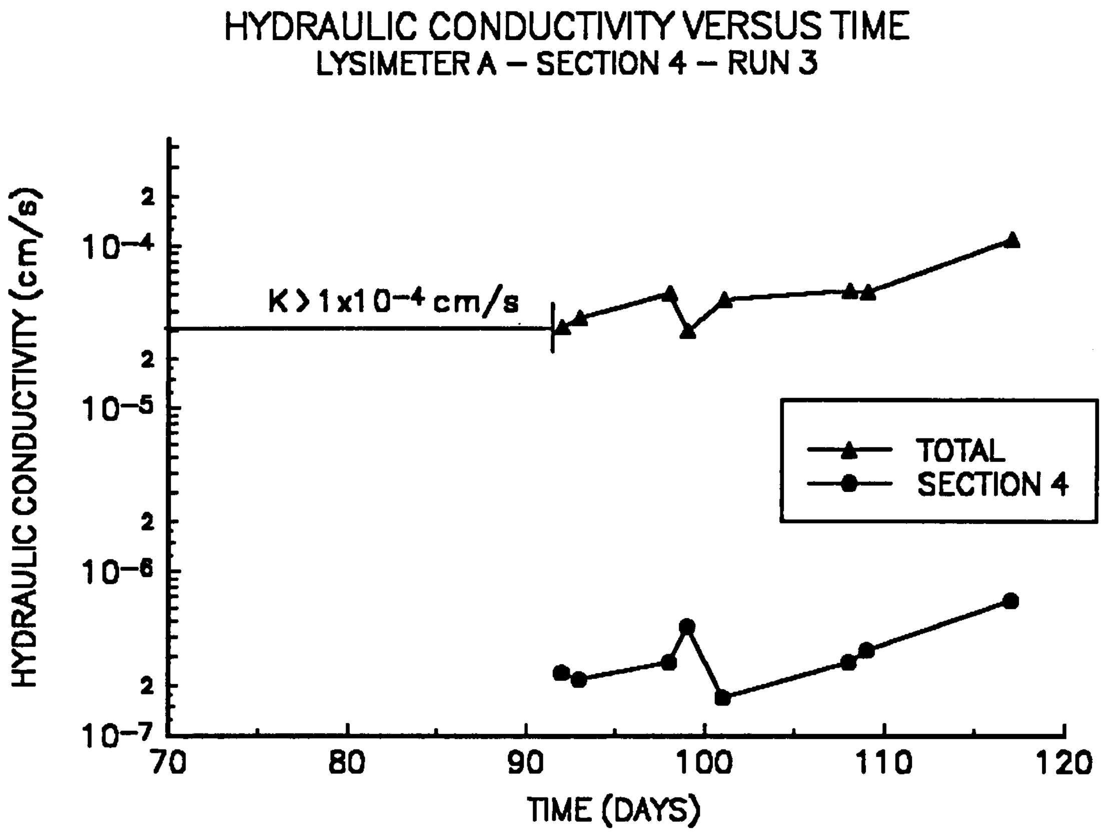

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 12 – RUN 2
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 12
TOTAL

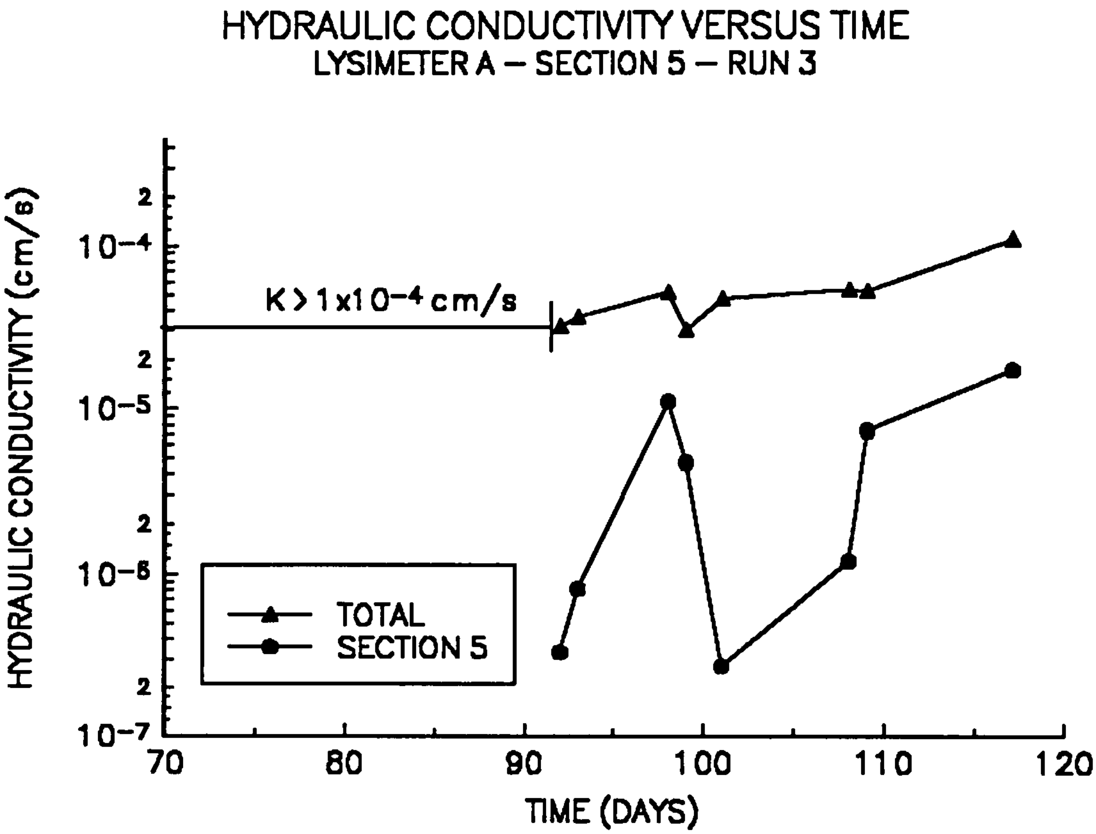


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 1 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
K > 1x10^{-4} cm/s
2
10^{-4}
2
10^{-5}
2
10^{-6}
2
10^{-7}
70
80
90
100
110
120
TIME (DAYS)
TOTAL
SECTION 1

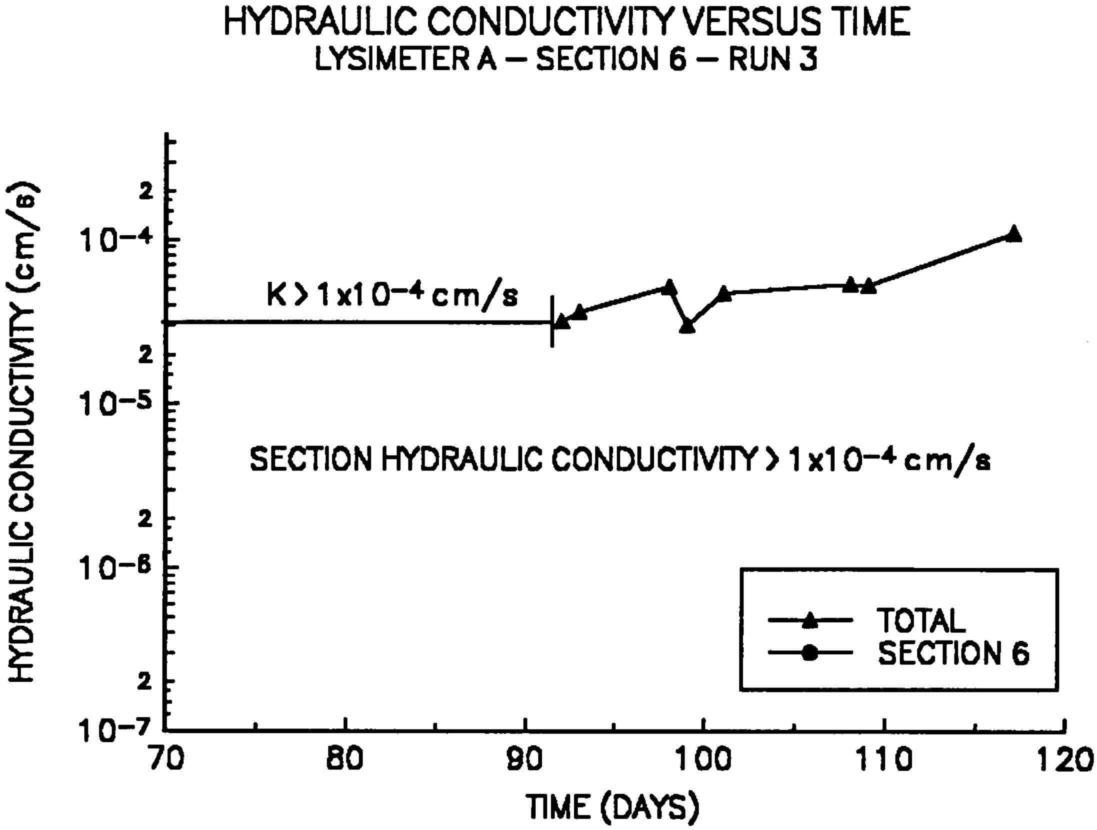

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 2 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
K > 1x10-4 cm/s
TOTAL
SECTION 2
10-4
10-5
10-6
10-7
2
70
80
90
100
110
120


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 3 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
K > 1x10-4 cm/s
TOTAL
SECTION 3
10-4
10-5
10-6
10-7
2
70
80
90
100
110
120

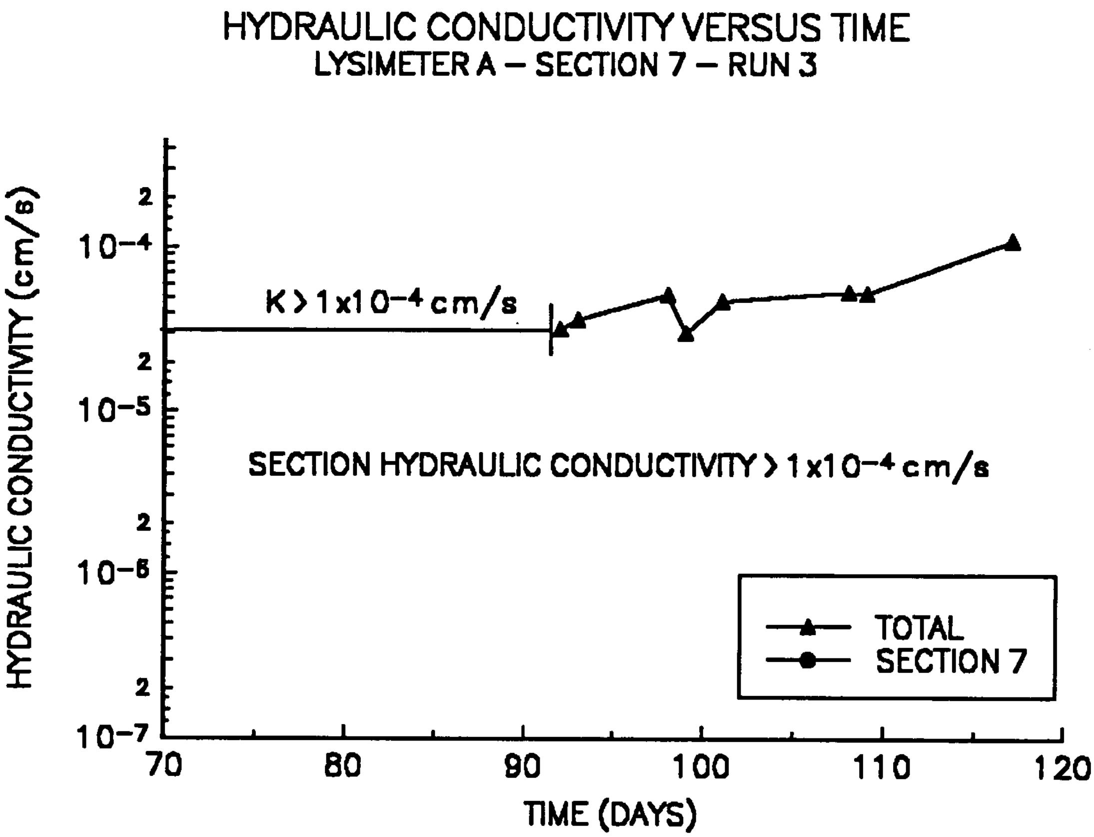

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 4 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
K > 1x10⁻⁴ cm/s
TOTAL
SECTION 4
TIME (DAYS)
70
80
90
100
110
120



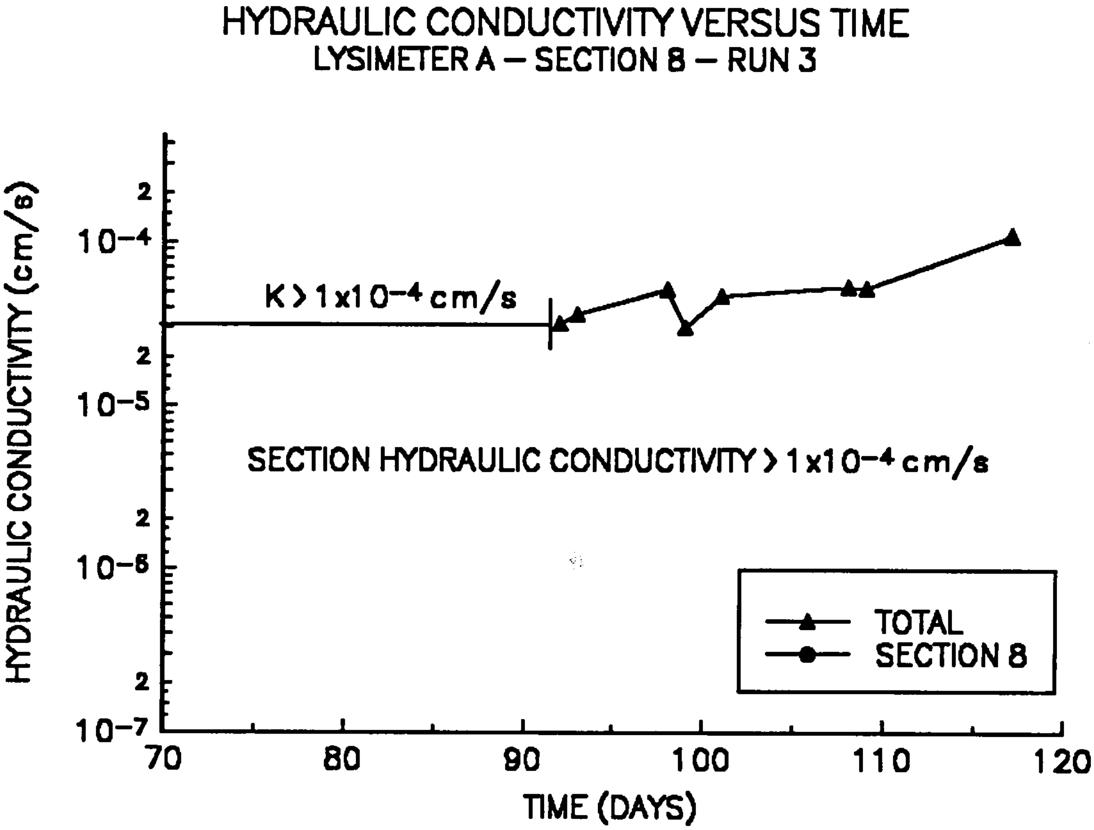
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 5 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
K > 1x10-4 cm/s
TOTAL
SECTION 5
10-4
10-5
10-6
10-7
2
70
80
90
100
110
120



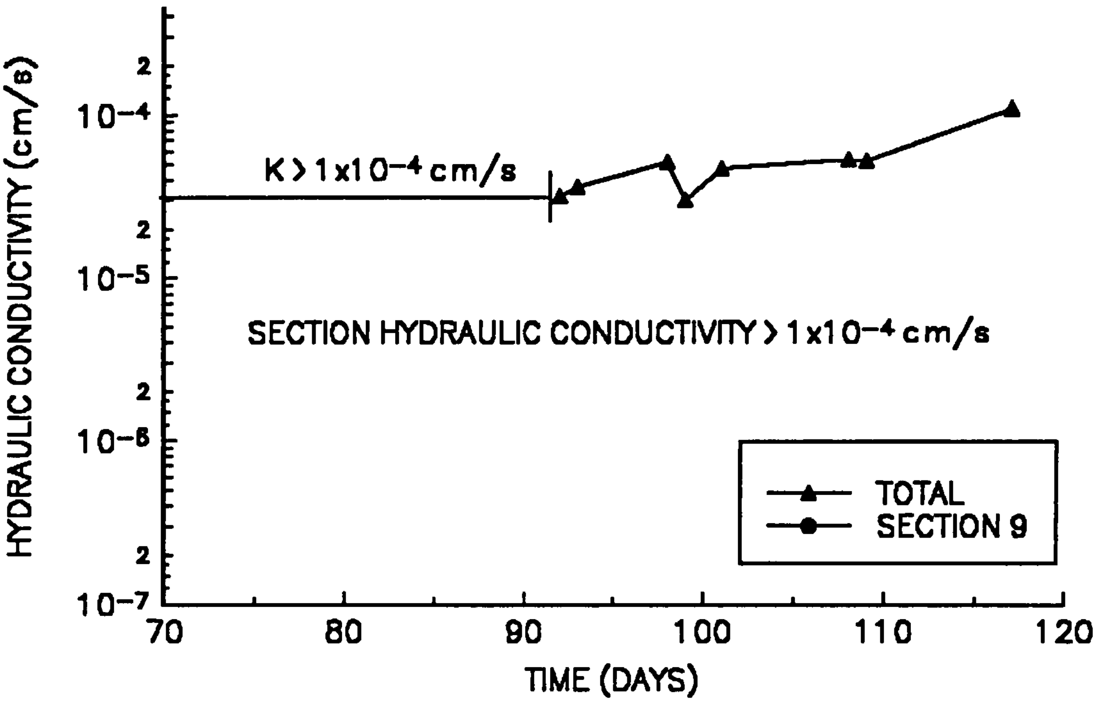
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 6 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−4
K > 1x10−4 cm/s
2
10−5
SECTION HYDRAULIC CONDUCTIVITY > 1x10−4 cm/s
2
10−6
2
10−7
TOTAL
SECTION 6
70
80
90
100
110
120
TIME (DAYS)

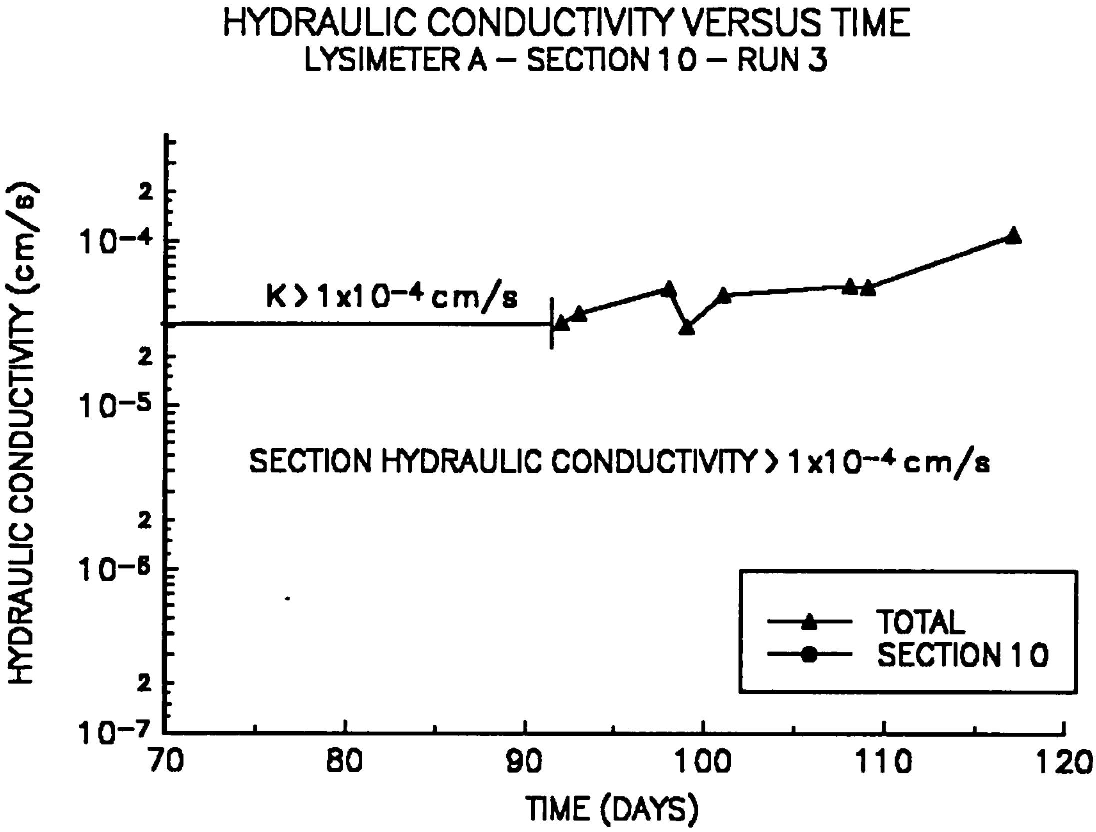


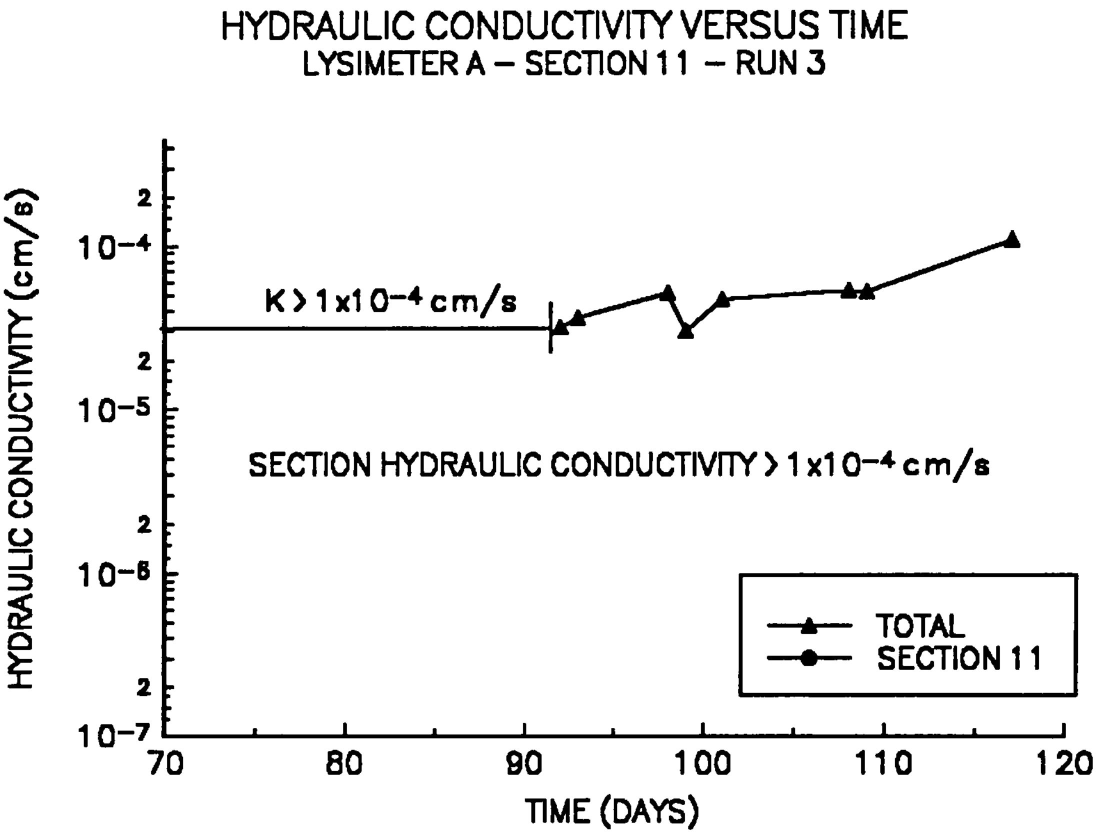
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 7 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
K > 1x10-4 cm/s
SECTION HYDRAULIC CONDUCTIVITY > 1x10-4 cm/s
TOTAL
SECTION 7
TIME (DAYS)

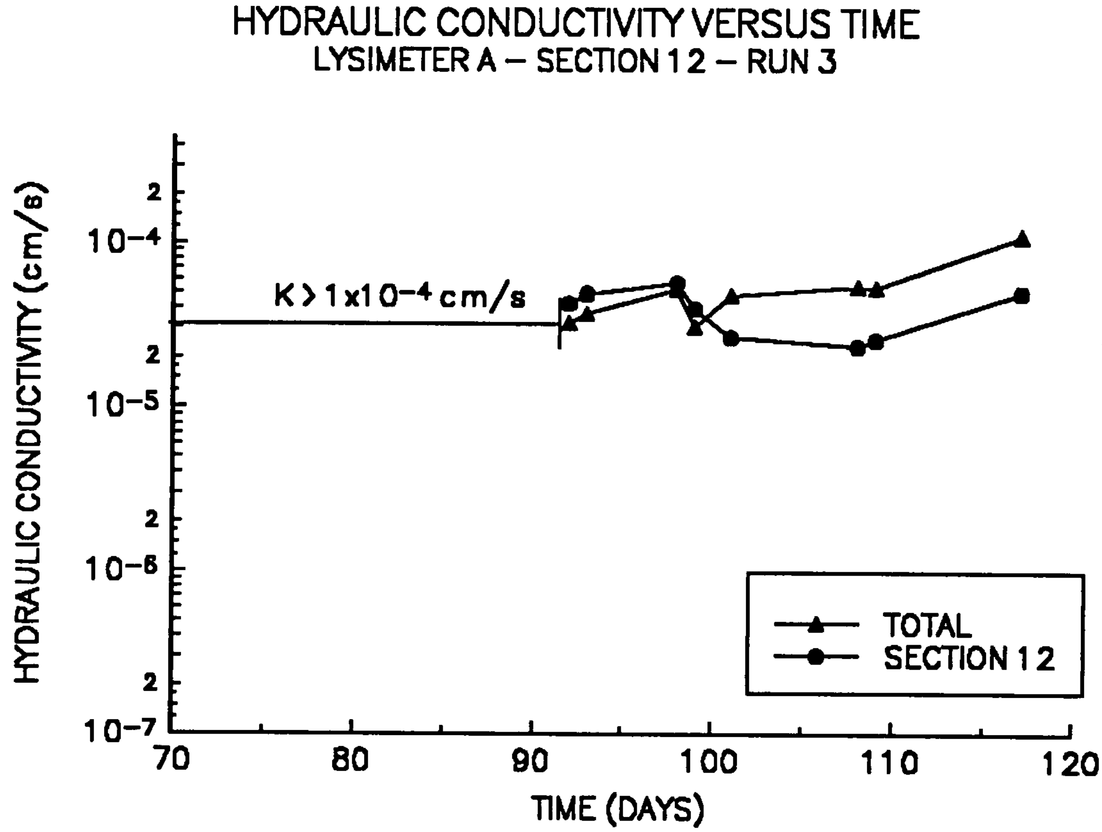

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 8 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10⁻⁴
K > 1x10⁻⁴ cm/s
2
10⁻⁵
SECTION HYDRAULIC CONDUCTIVITY > 1x10⁻⁴ cm/s
2
10⁻⁶
2
10⁻⁷
TOTAL
SECTION 8
70
80
90
100
110
120
TIME (DAYS)

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 9 – RUN 3



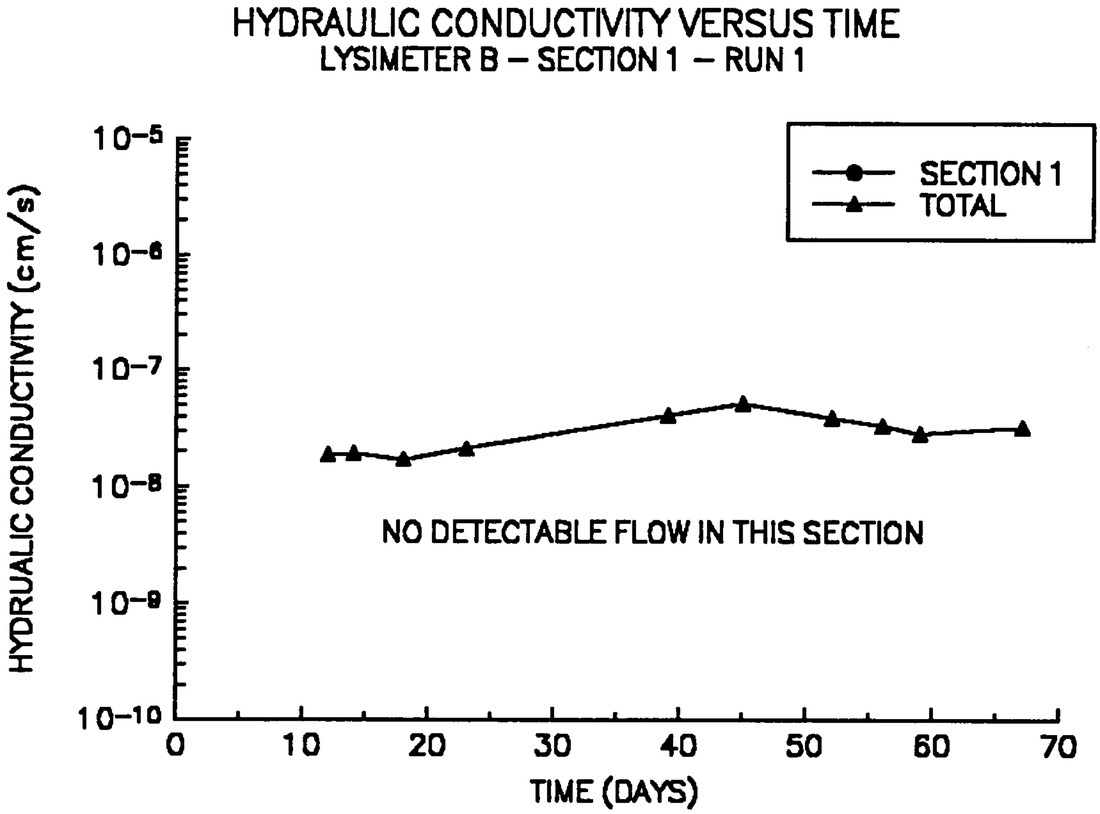

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 10 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
K > 1x10⁻⁴ cm/s
SECTION HYDRAULIC CONDUCTIVITY > 1x10⁻⁴ cm/s
TOTAL
SECTION 10
TIME (DAYS)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
2
70
80
90
100
110
120

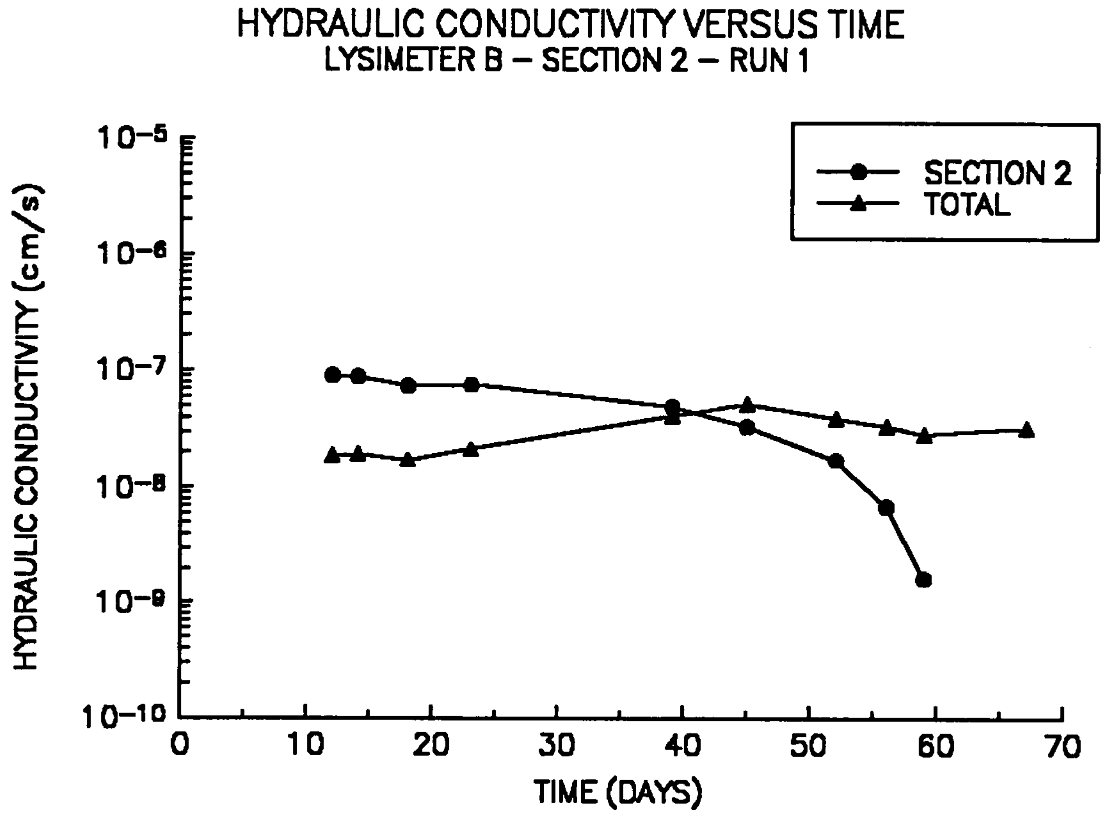

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 11 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−4
2
10−5
2
10−6
2
10−7
K > 1x10−4 cm/s
SECTION HYDRAULIC CONDUCTIVITY > 1x10−4 cm/s
TOTAL
SECTION 11
70
80
90
100
110
120
TIME (DAYS)

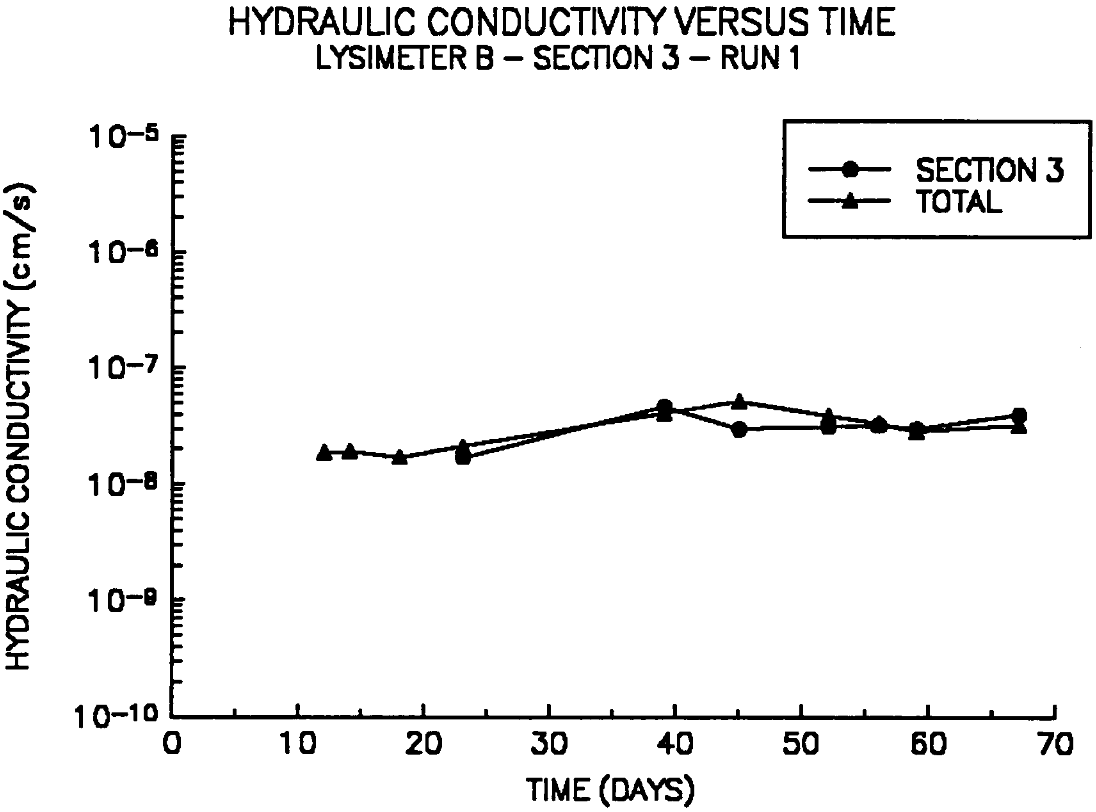


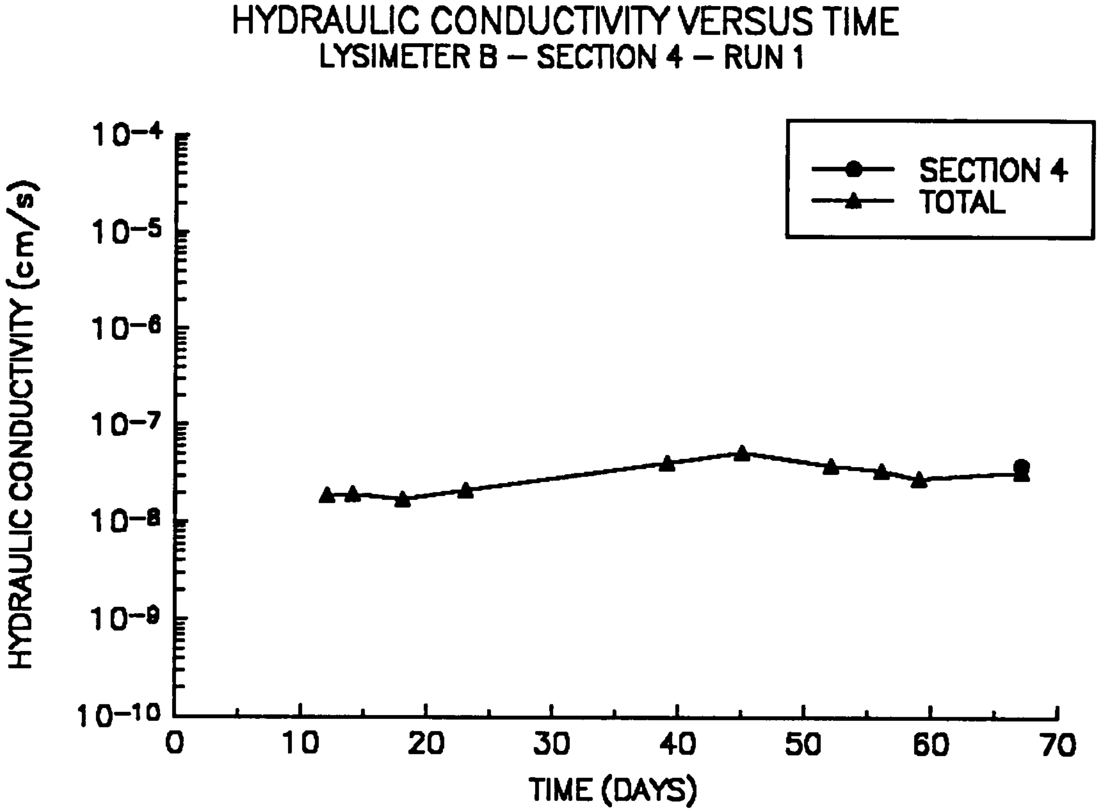
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER A – SECTION 12 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−4
K > 1x10−4 cm/s
2
10−5
2
10−6
2
10−7
70
80
90
100
110
120
TIME (DAYS)
TOTAL
SECTION 12

Appendix B

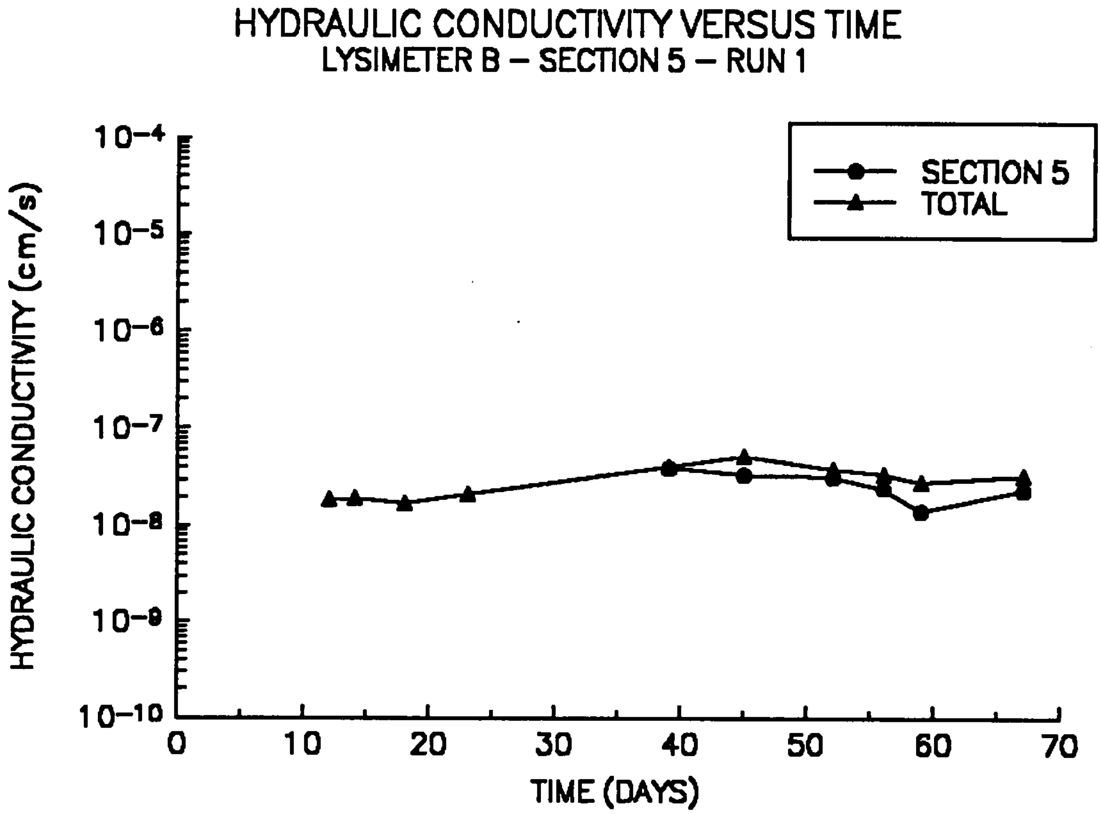

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 1 – RUN 1
SECTION 1
TOTAL
NO DETECTABLE FLOW IN THIS SECTION
HYDRUALIC CONDUCTIVITY (cm/s)
TIME (DAYS)
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70

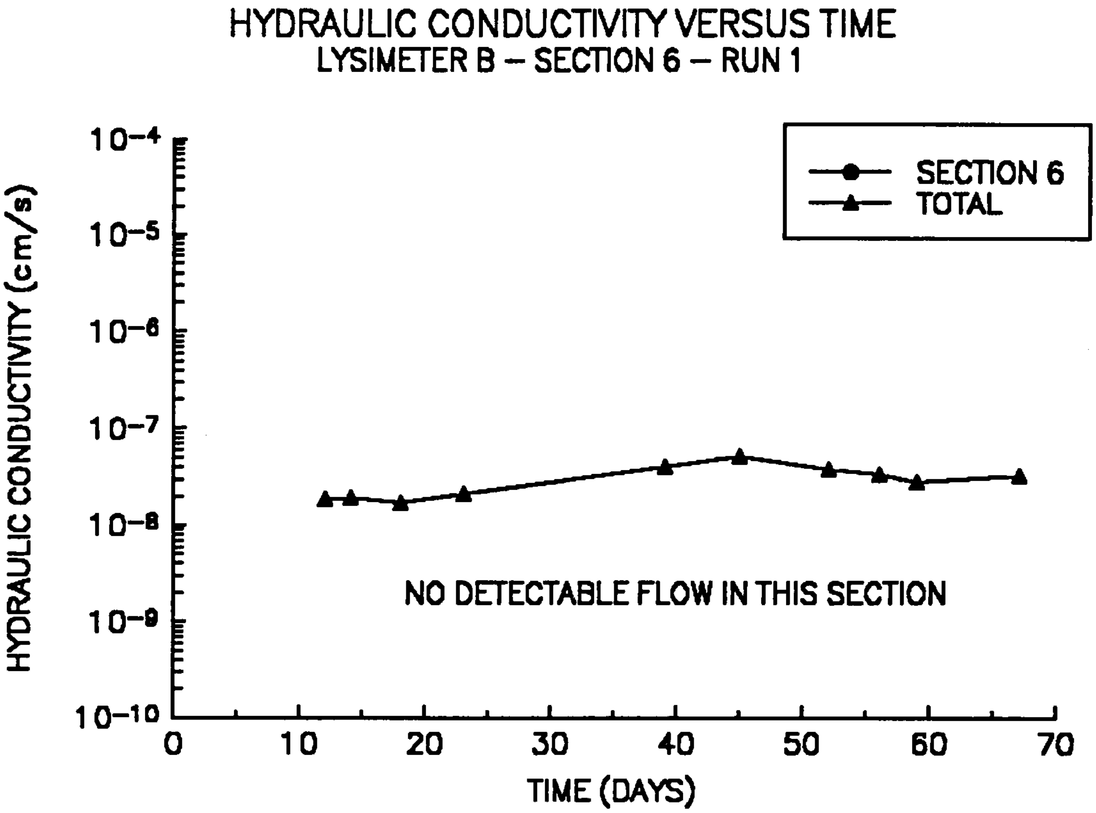

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 2 – RUN 1
SECTION 2
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
10
20
30
40
50
60
70
TIME (DAYS)


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 3 – RUN 1
SECTION 3
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
10
20
30
40
50
60
70
TIME (DAYS)

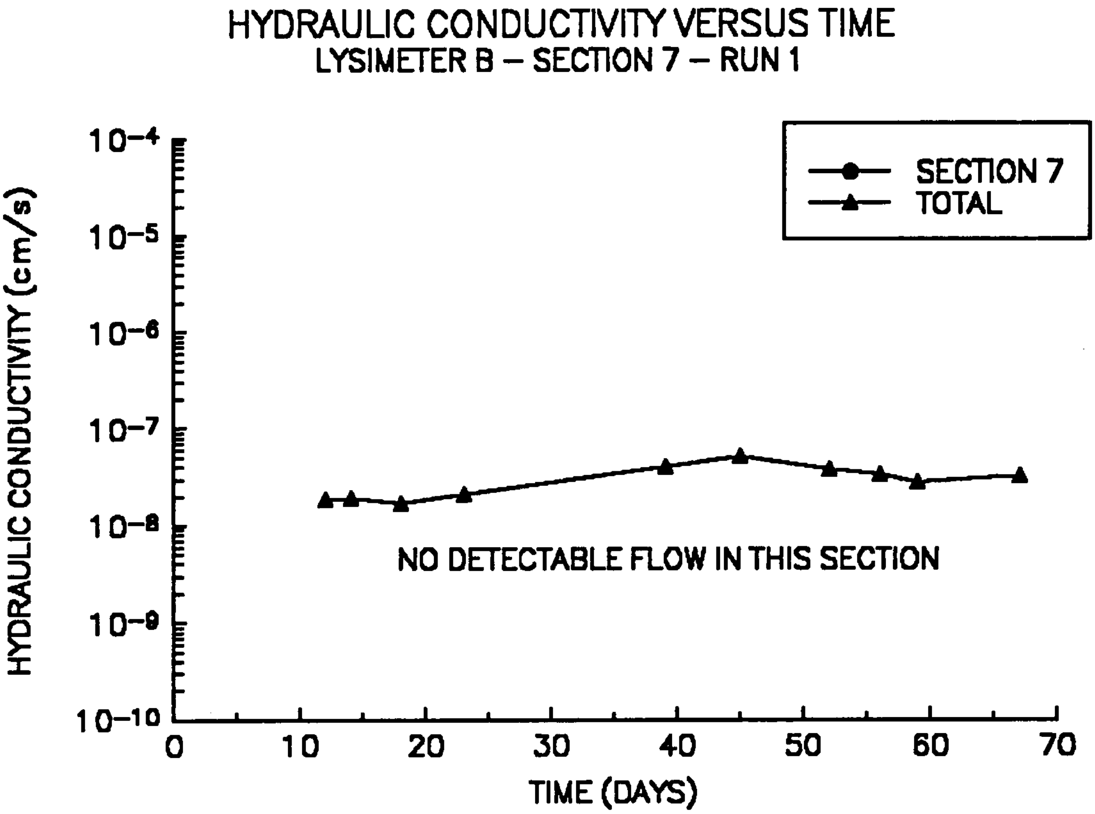


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 4 – RUN 1
SECTION 4
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)

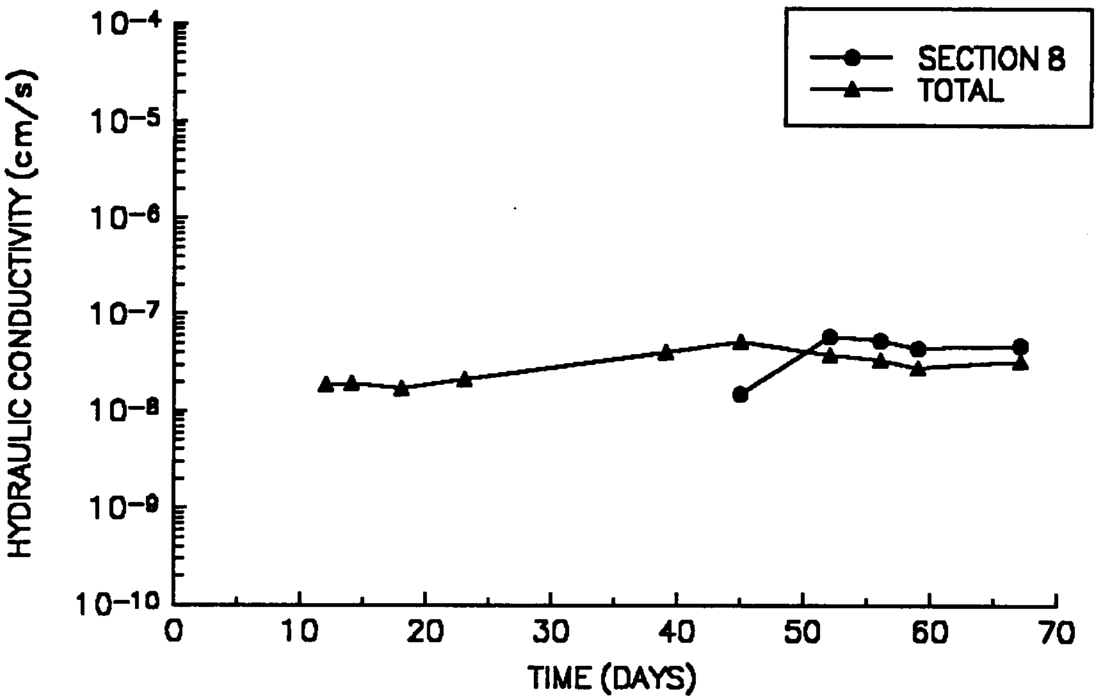

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 5 – RUN 1
SECTION 5
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)

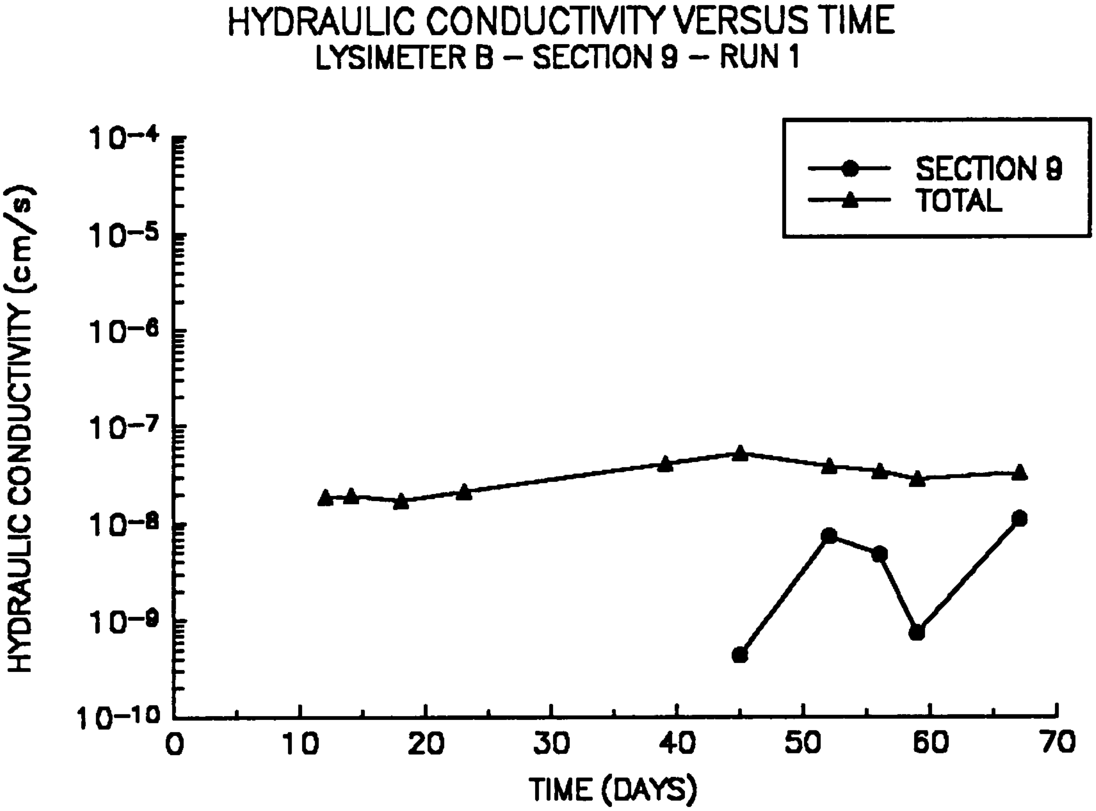


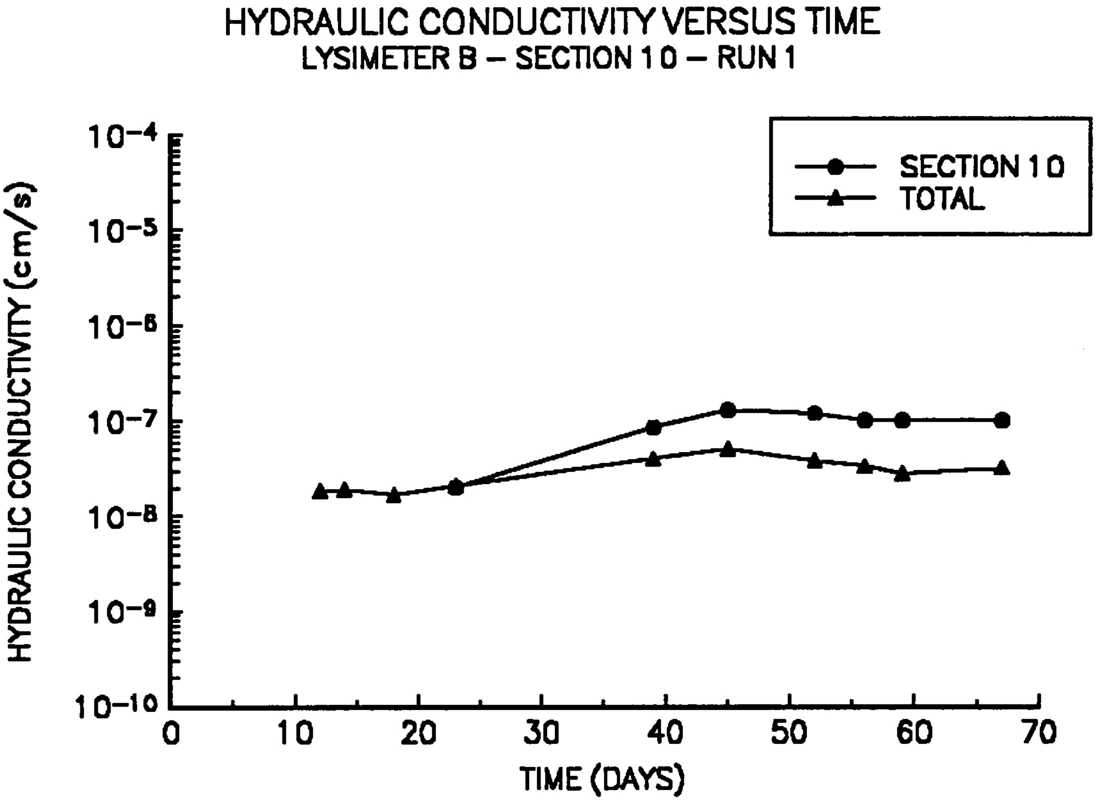
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 6 – RUN 1
SECTION 6
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)
NO DETECTABLE FLOW IN THIS SECTION

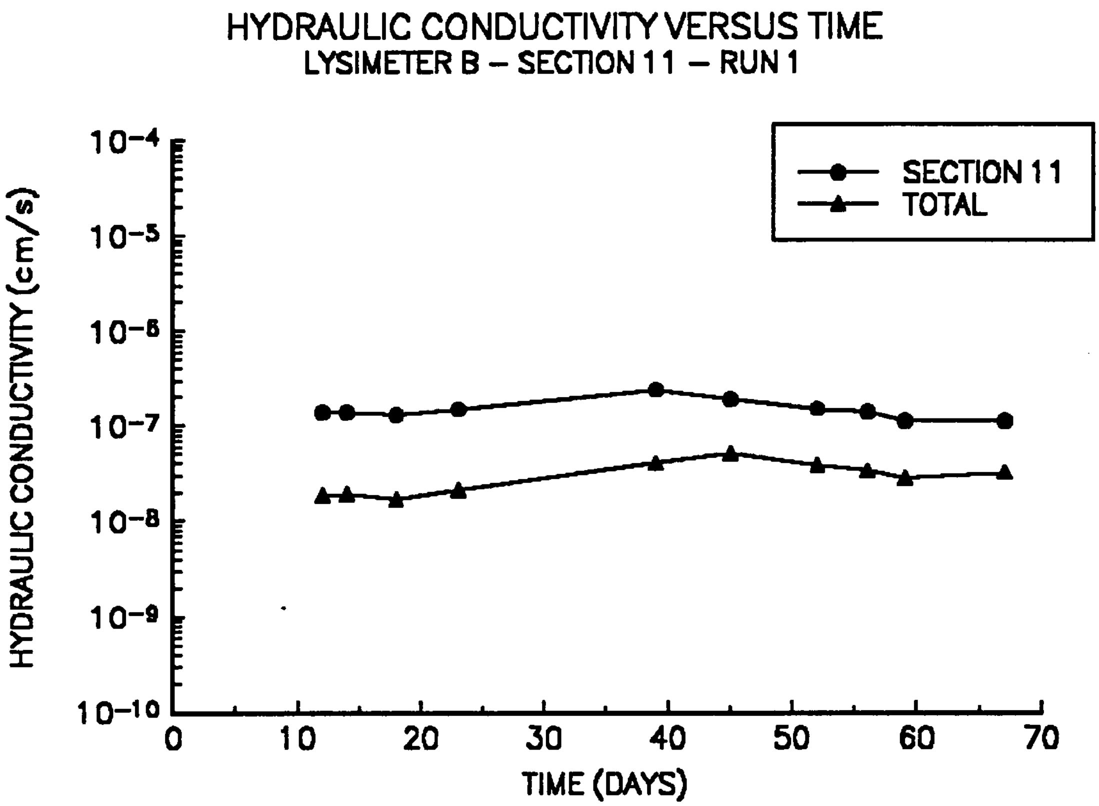

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 7 – RUN 1
SECTION 7
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
NO DETECTABLE FLOW IN THIS SECTION
0
10
20
30
40
50
60
70
TIME (DAYS)

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 8 – RUN 1

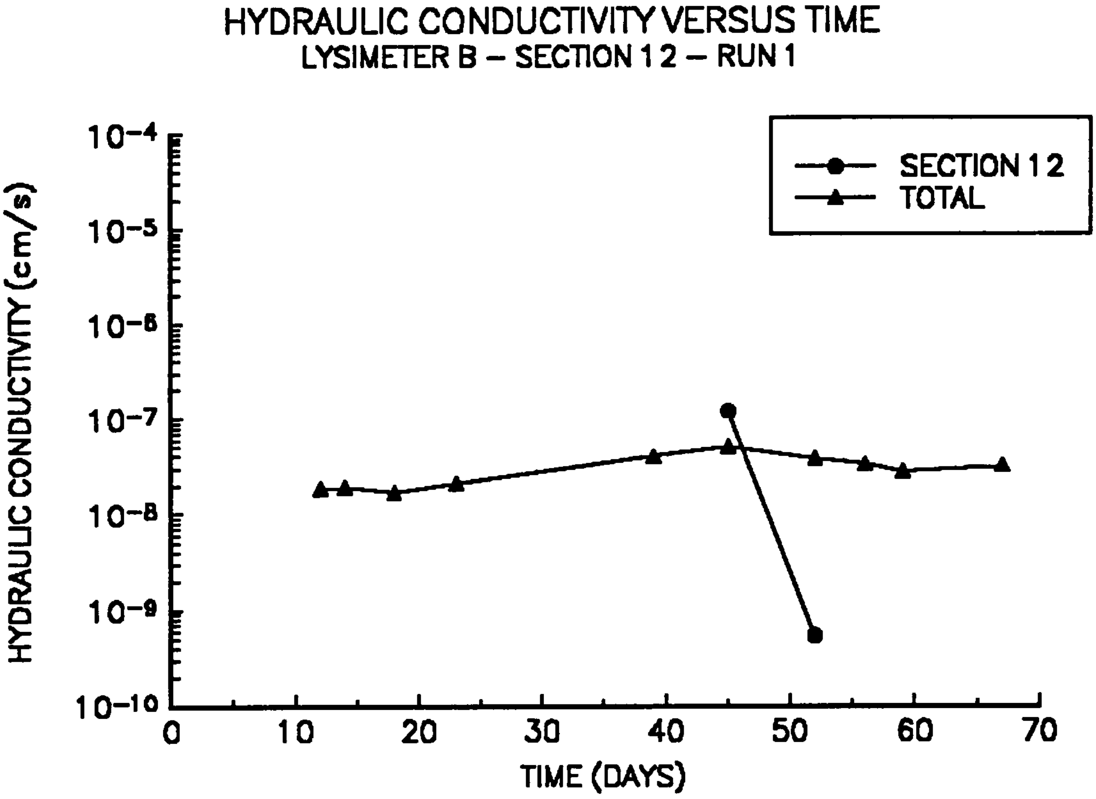



HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 9 – RUN 1
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
10
20
30
40
50
60
70
TIME (DAYS)
SECTION 9
TOTAL

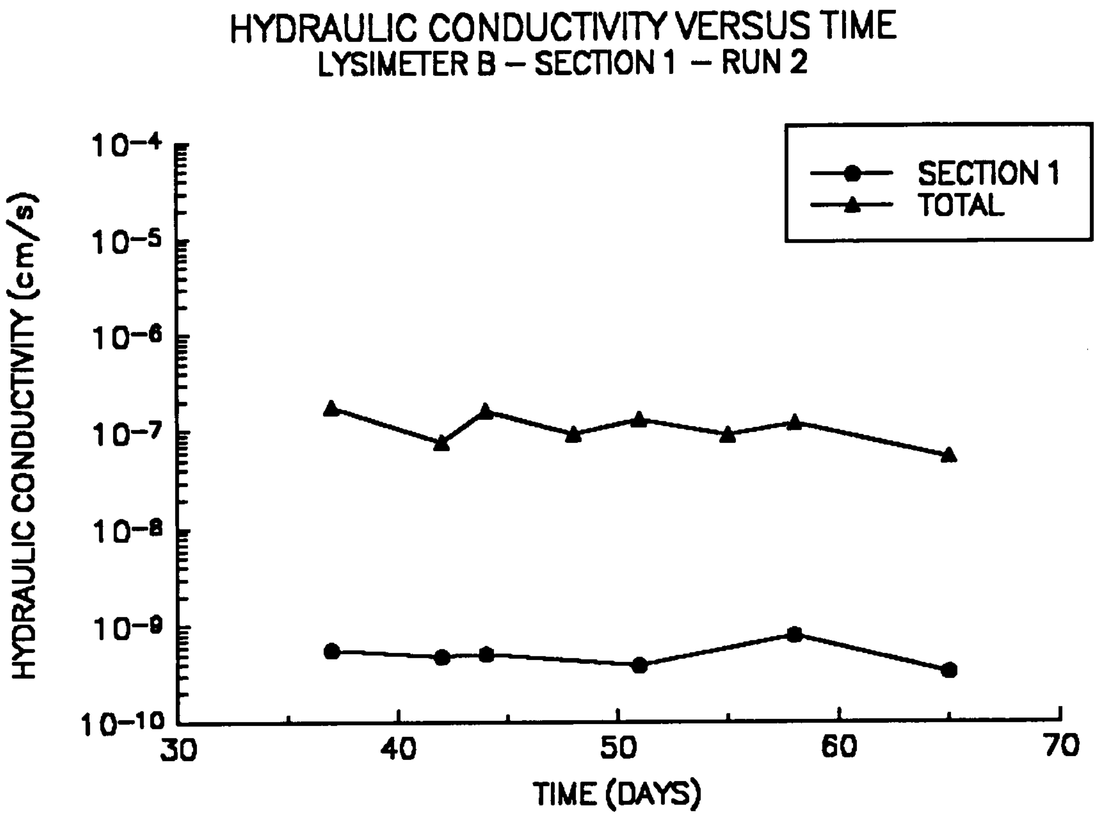

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 10 – RUN 1
SECTION 10
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
10
20
30
40
50
60
70
TIME (DAYS)



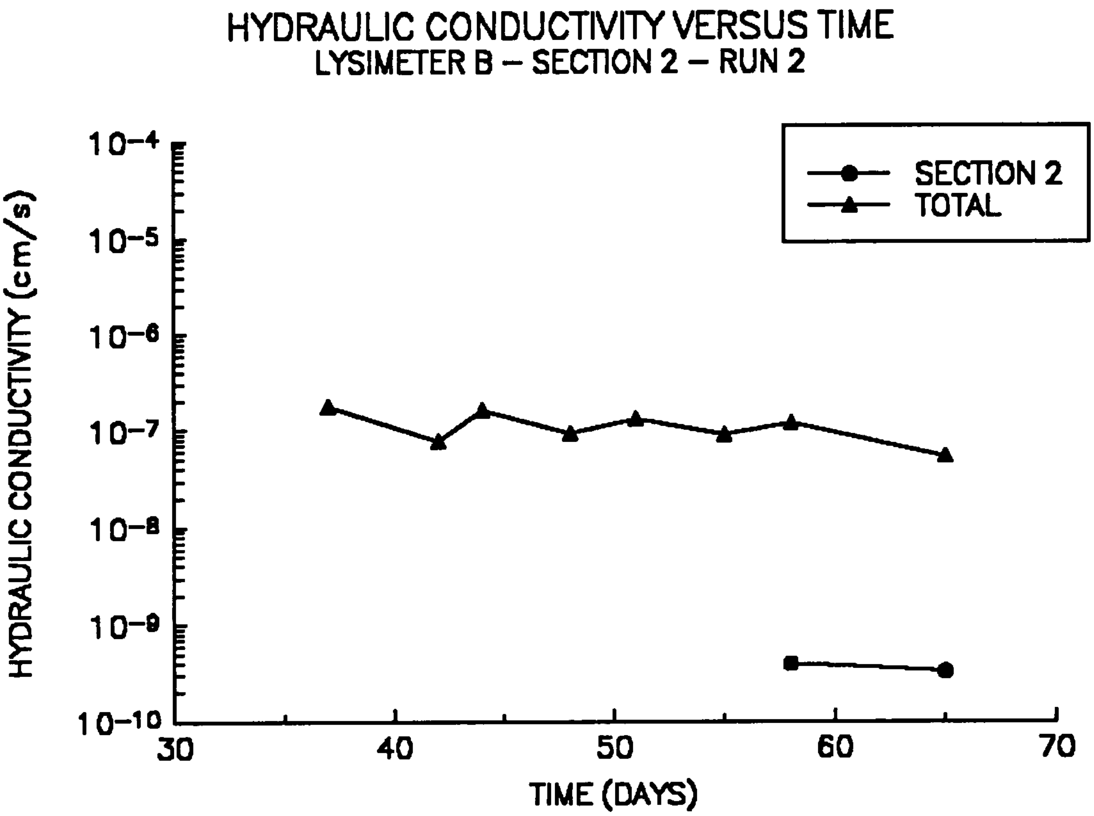
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 11 – RUN 1
SECTION 11
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)



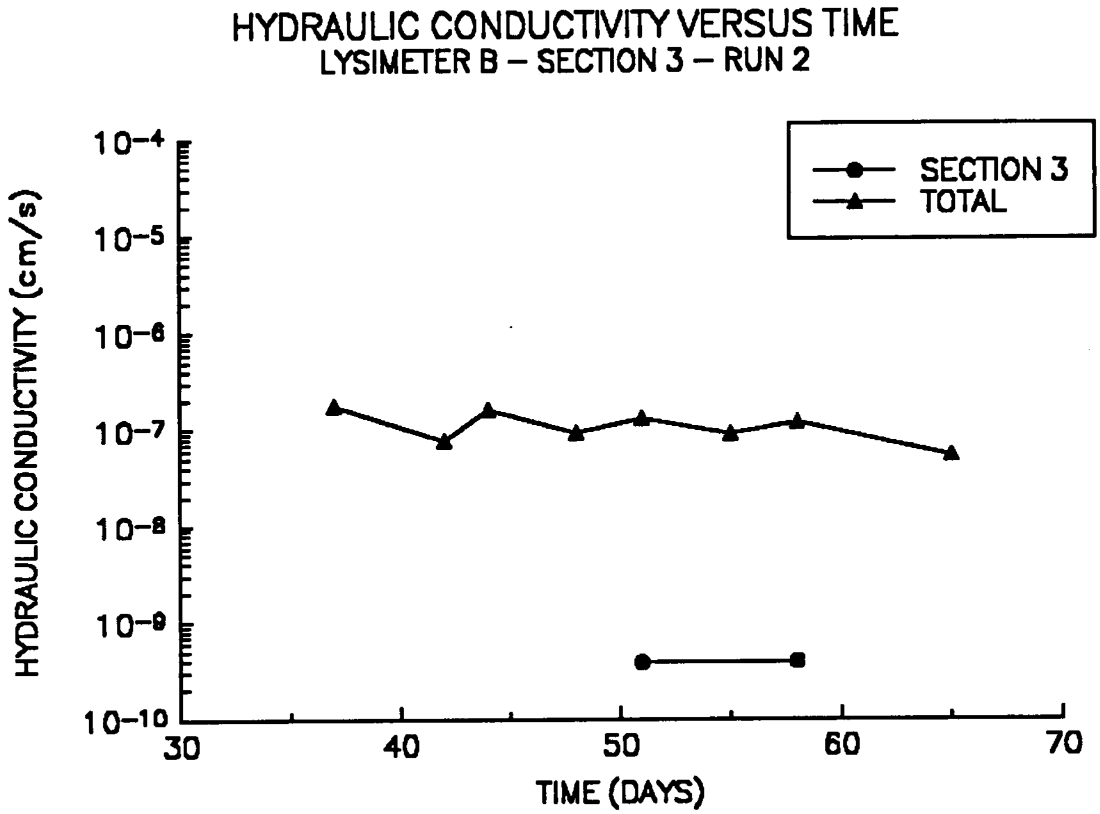
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 12 – RUN 1
SECTION 12
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
0
10
20
30
40
50
60
70
TIME (DAYS)

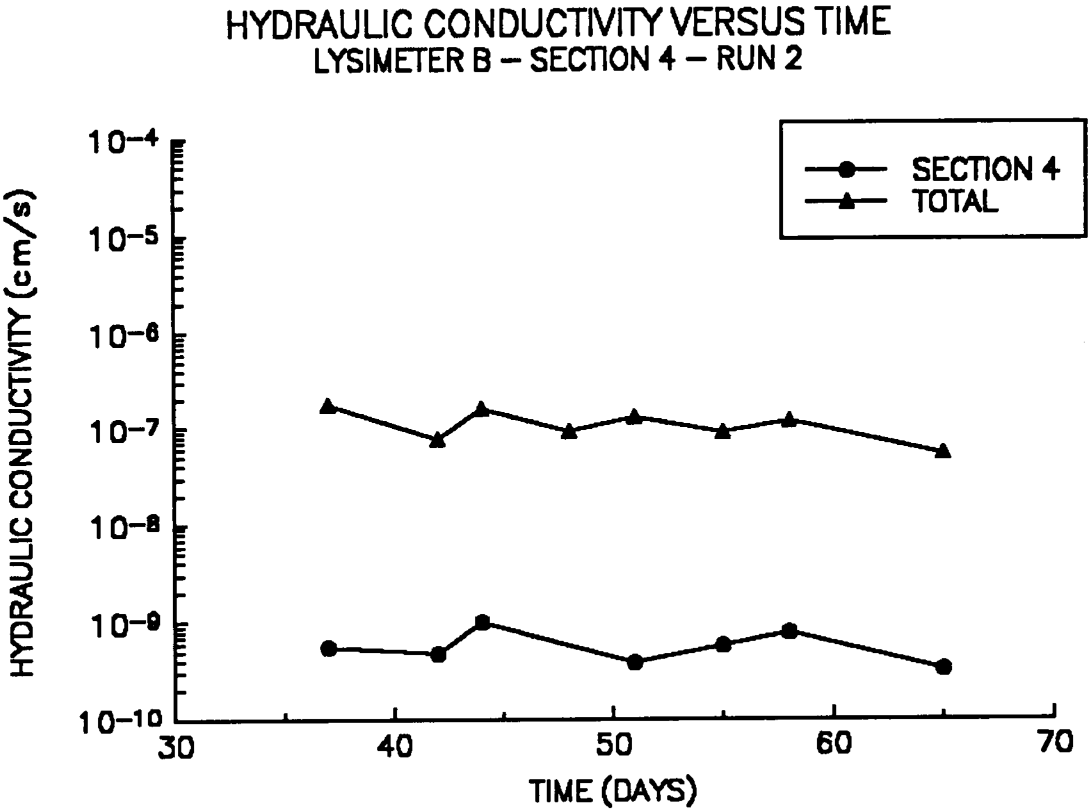


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 1 – RUN 2
SECTION 1
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
30
40
50
60
70
TIME (DAYS)

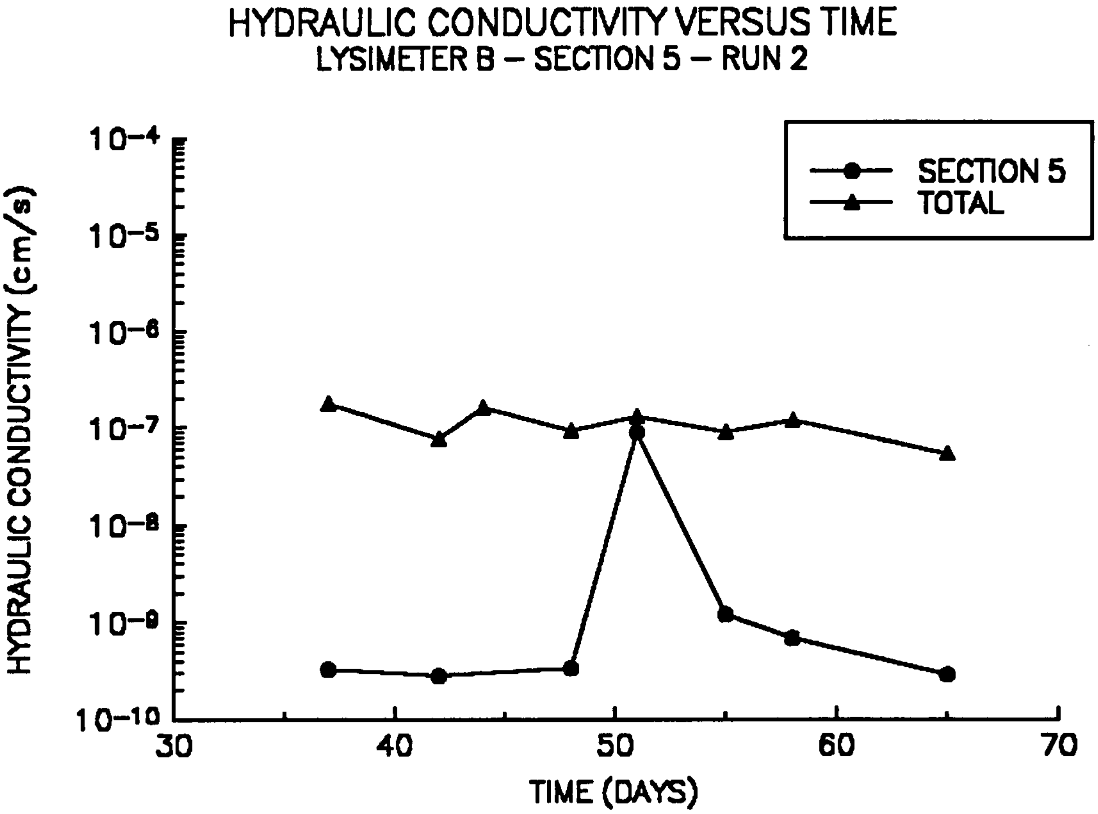


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 2 – RUN 2
SECTION 2
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
30
40
50
60
70
TIME (DAYS)


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 3 – RUN 2
SECTION 3
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
30
40
50
60
70
TIME (DAYS)

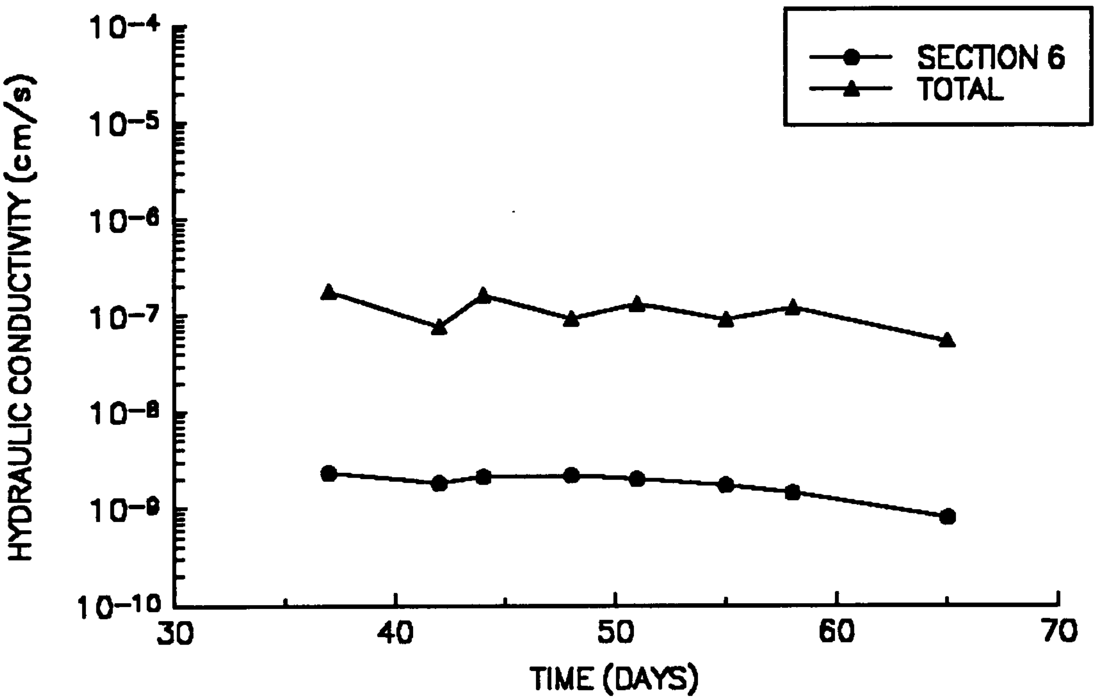


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 4 – RUN 2
SECTION 4
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
30
40
50
60
70
TIME (DAYS)

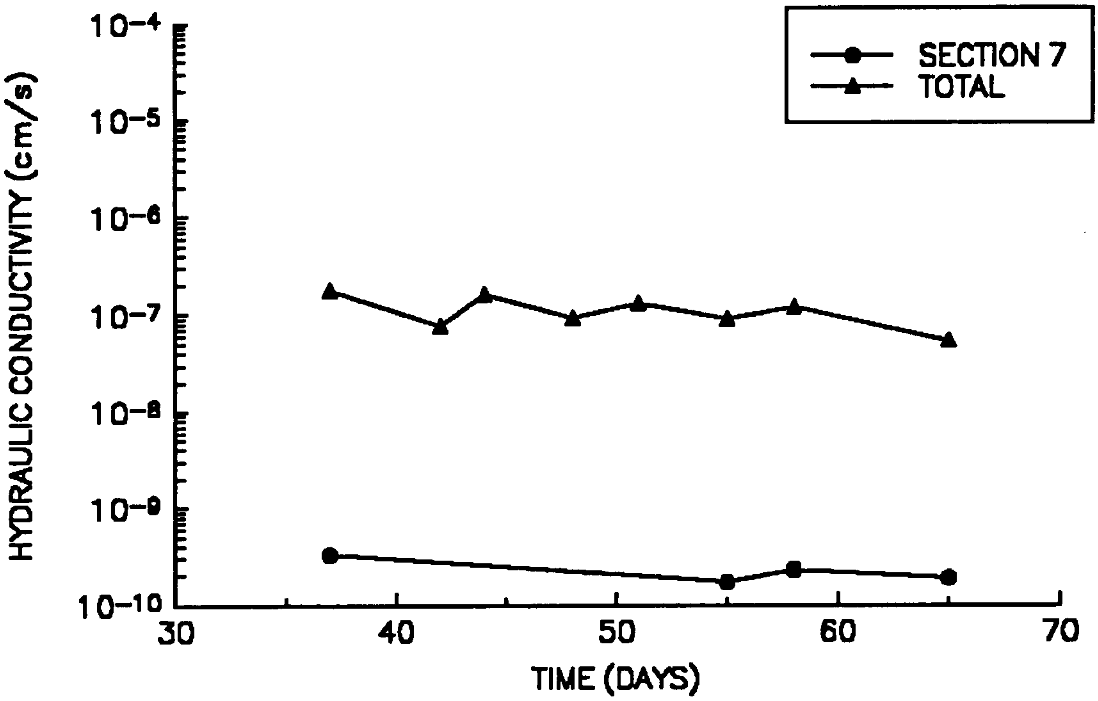


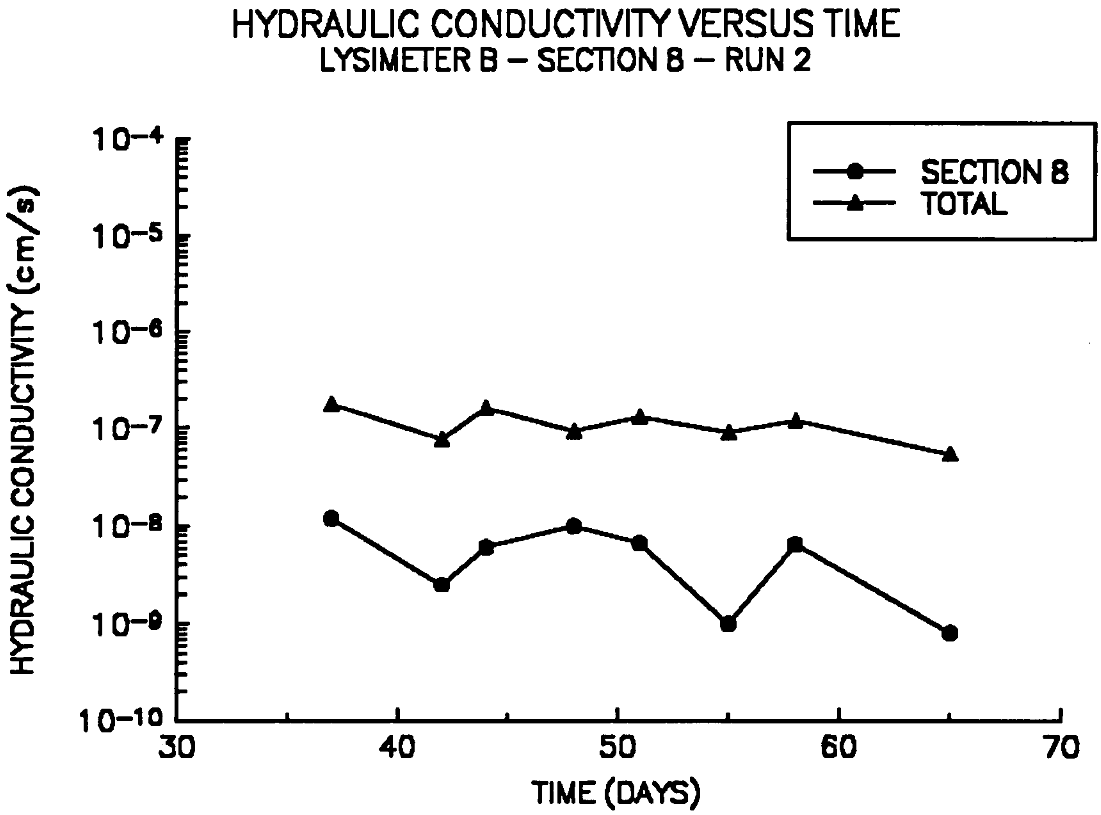
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 5 – RUN 2
SECTION 5
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
30
40
50
60
70
TIME (DAYS)

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 6 – RUN 2

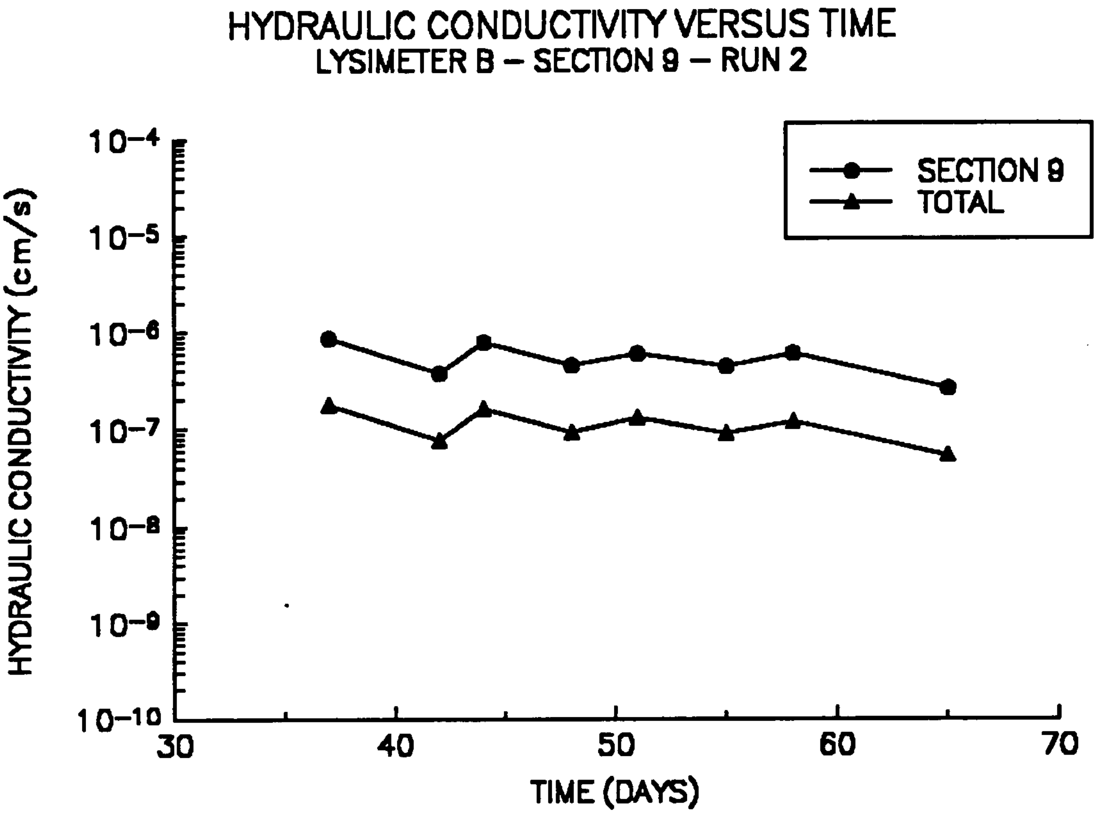


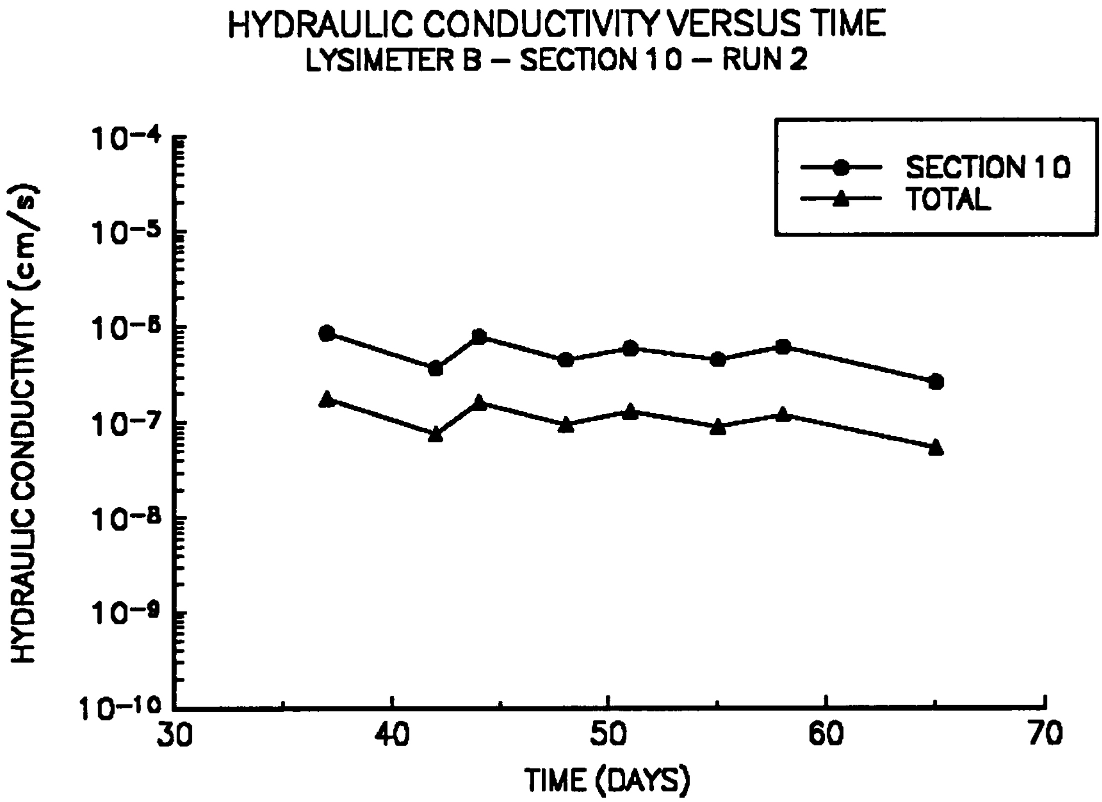
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 7 – RUN 2

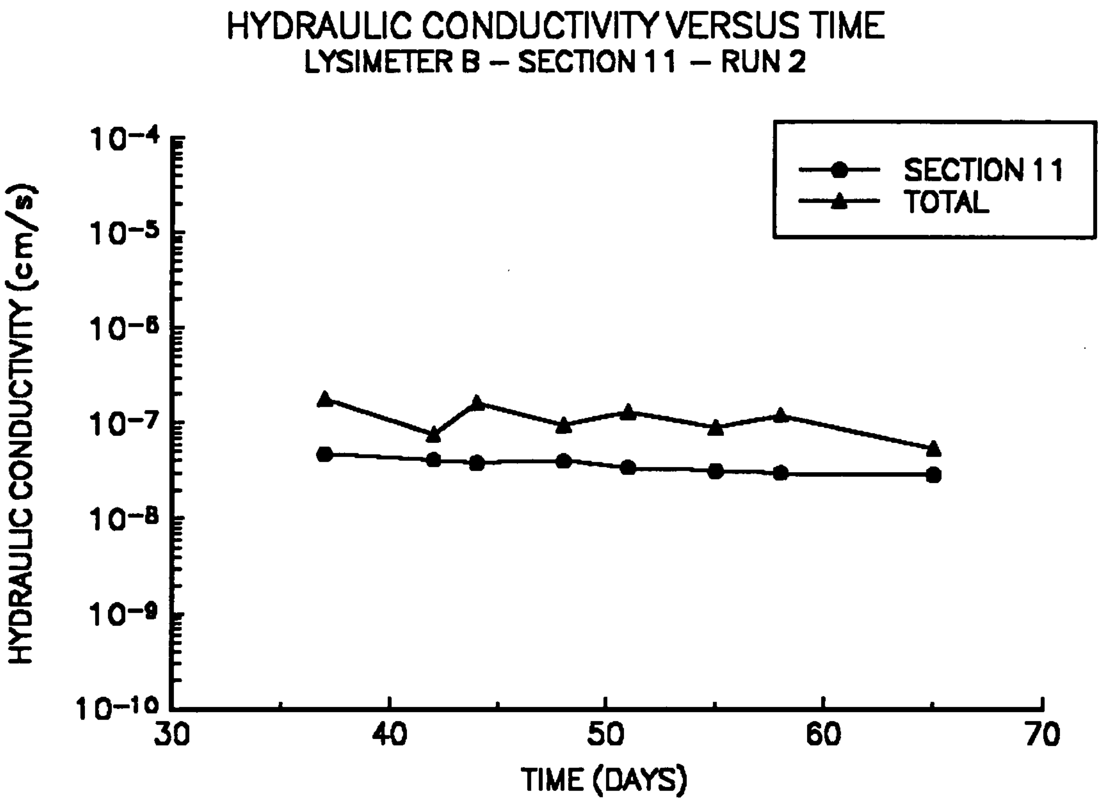


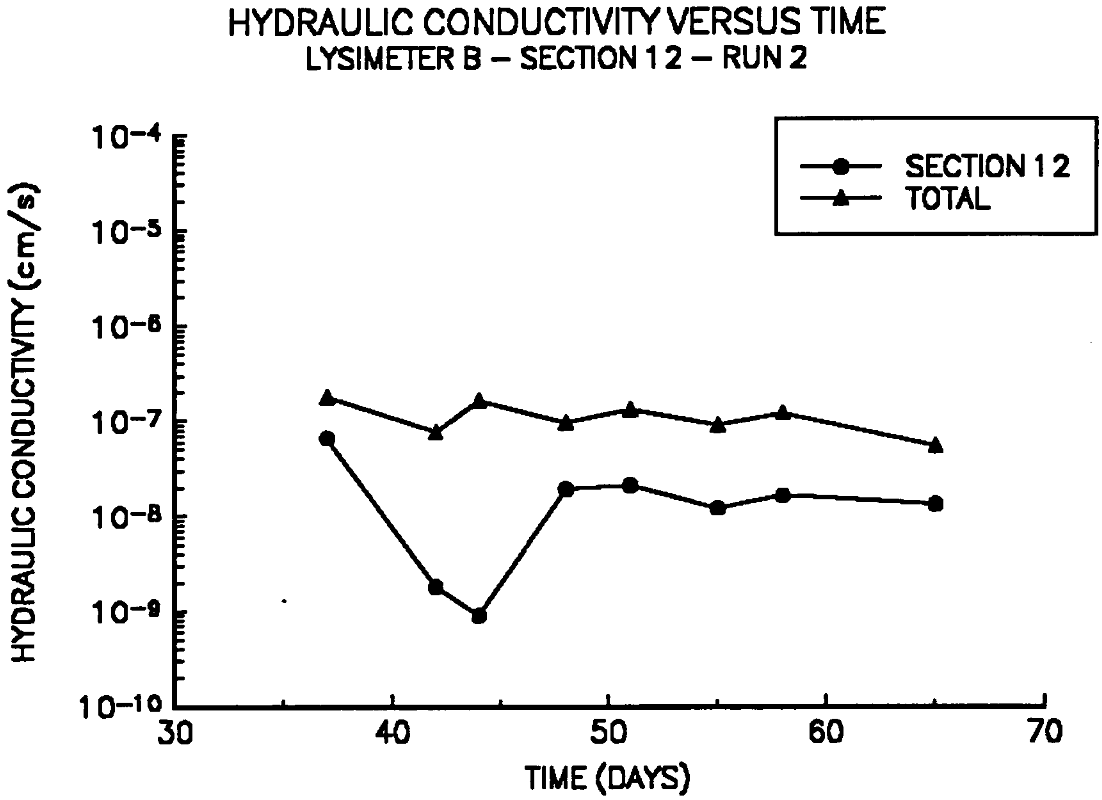


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 8 – RUN 2
SECTION 8
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
30
40
50
60
70
TIME (DAYS)

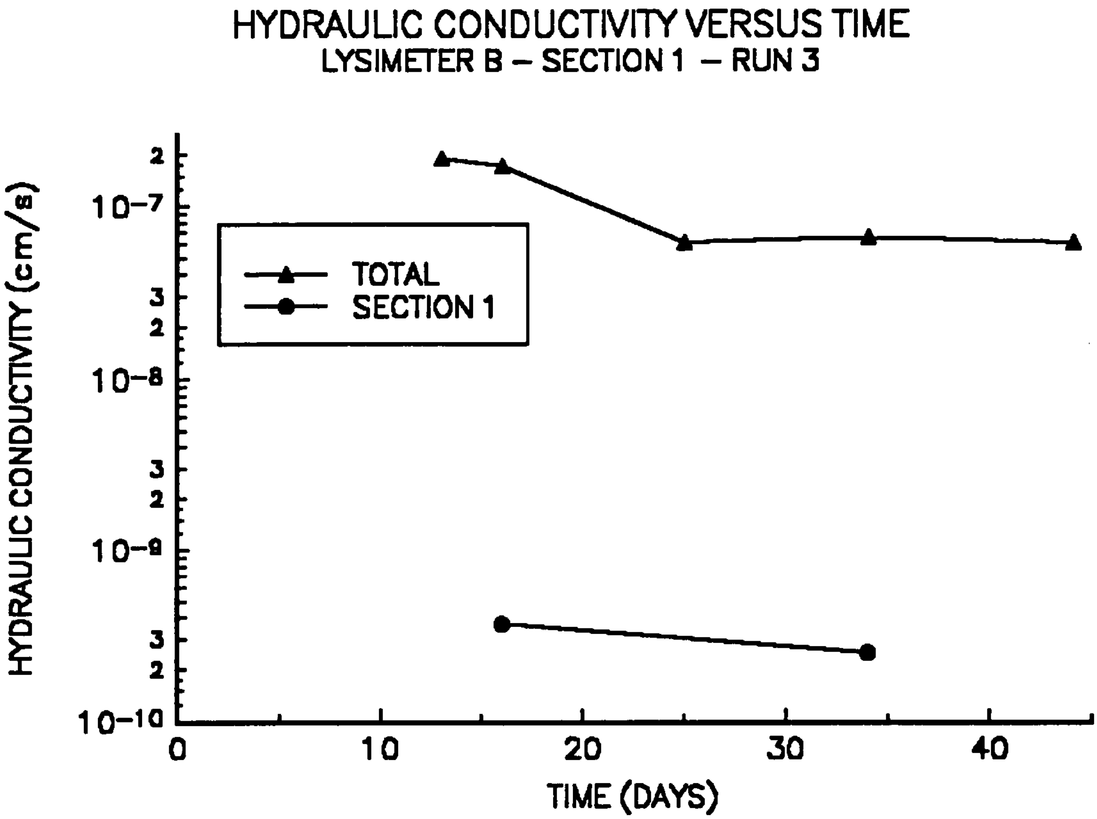

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 9 – RUN 2
SECTION 9
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
30
40
50
60
70
TIME (DAYS)


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 10 – RUN 2
SECTION 10
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
30
40
50
60
70
TIME (DAYS)

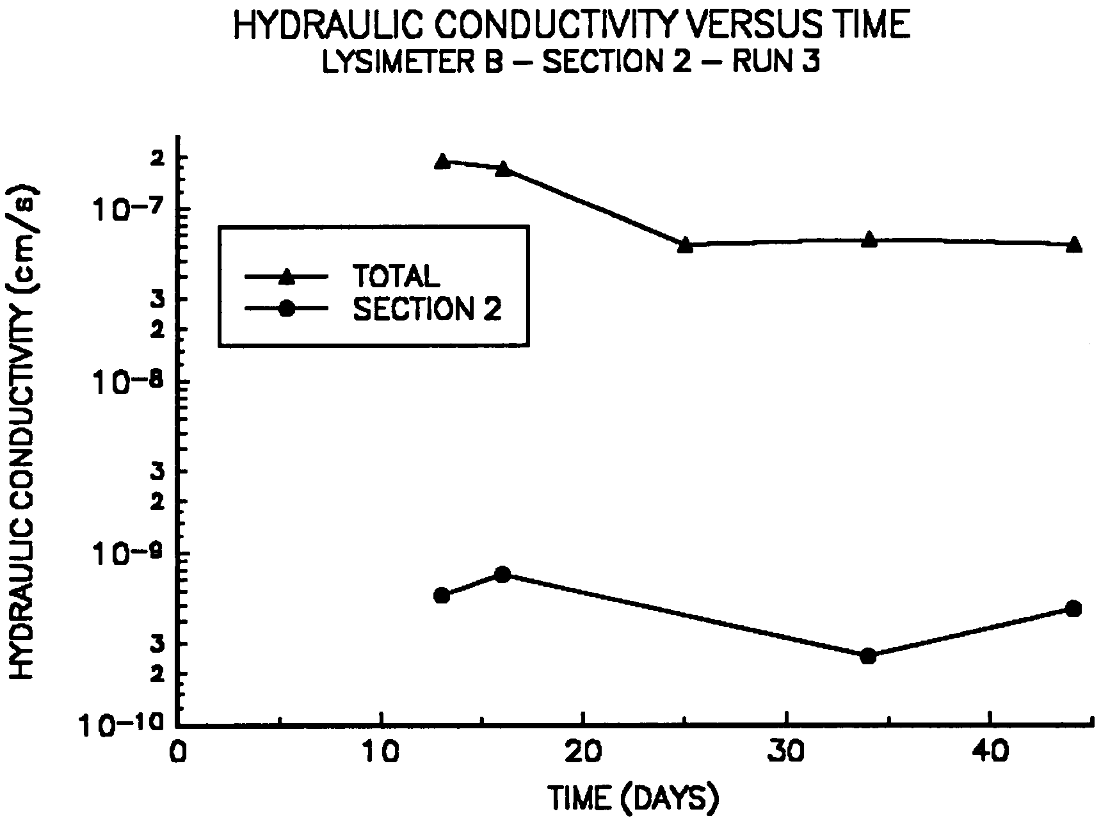

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 11 – RUN 2
SECTION 11
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
30
40
50
60
70
TIME (DAYS)

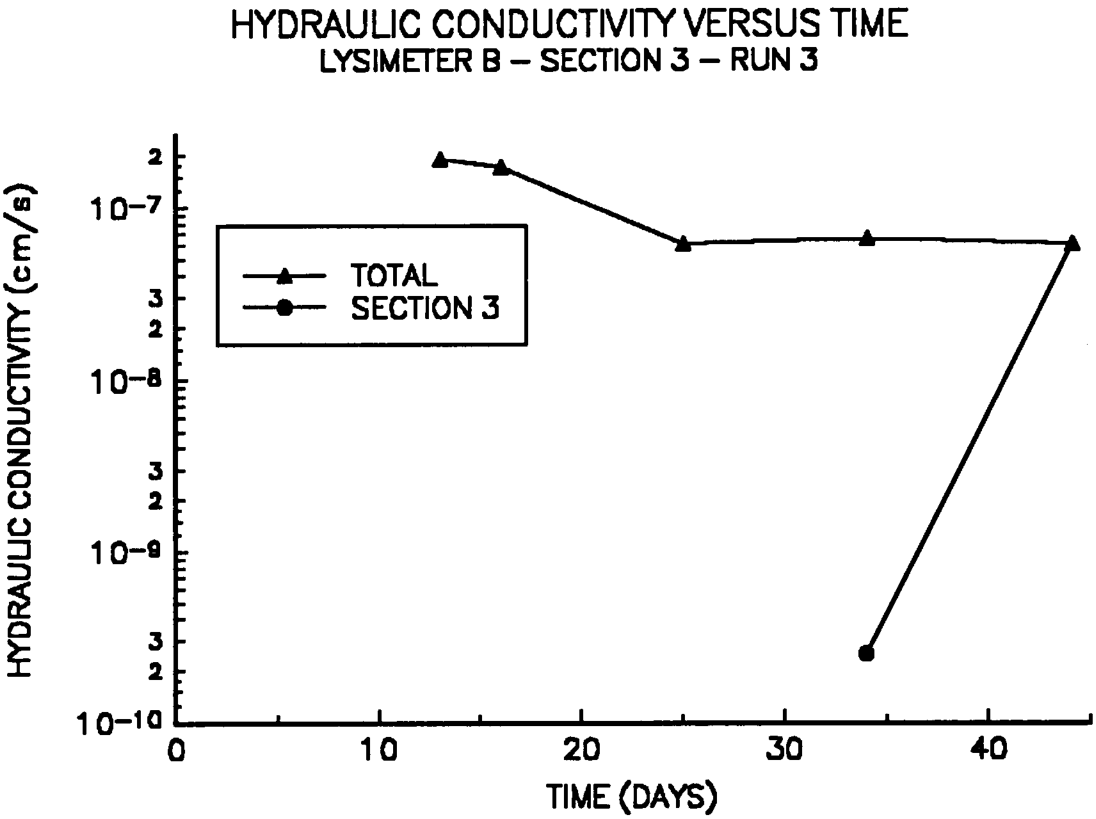


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 12 – RUN 2
SECTION 12
TOTAL
HYDRAULIC CONDUCTIVITY (cm/s)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
30
40
50
60
70
TIME (DAYS)

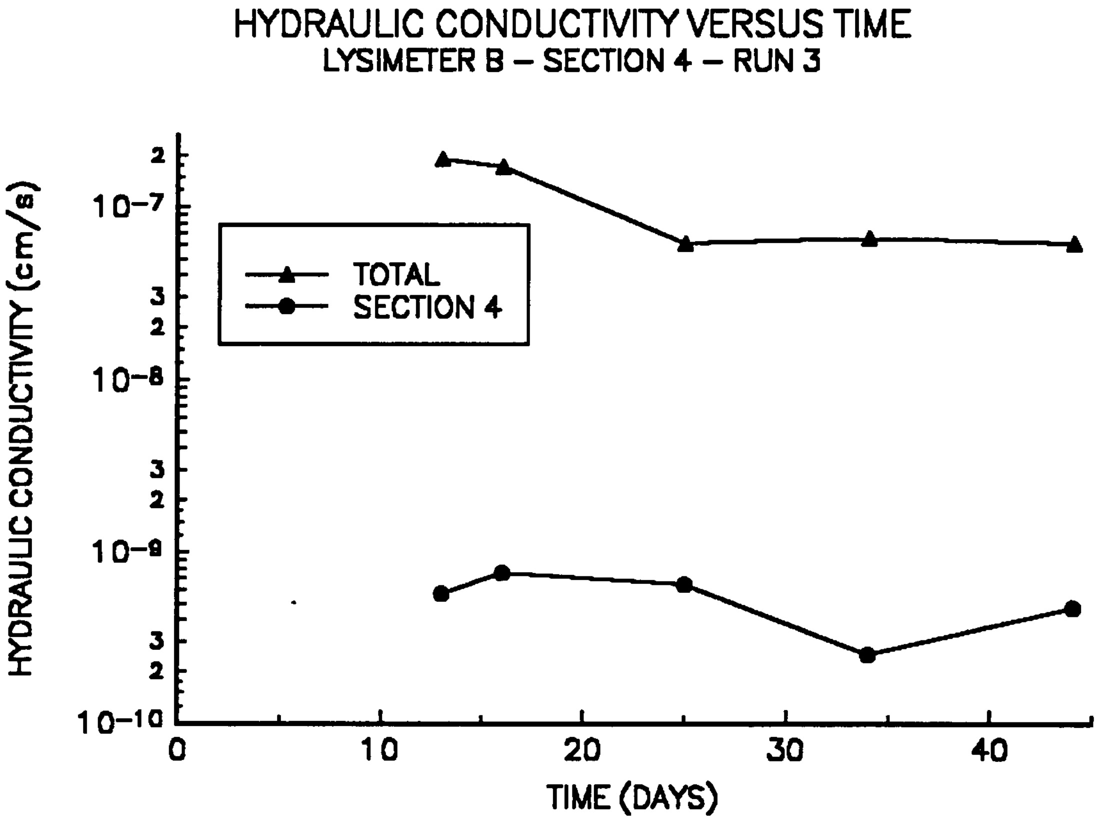


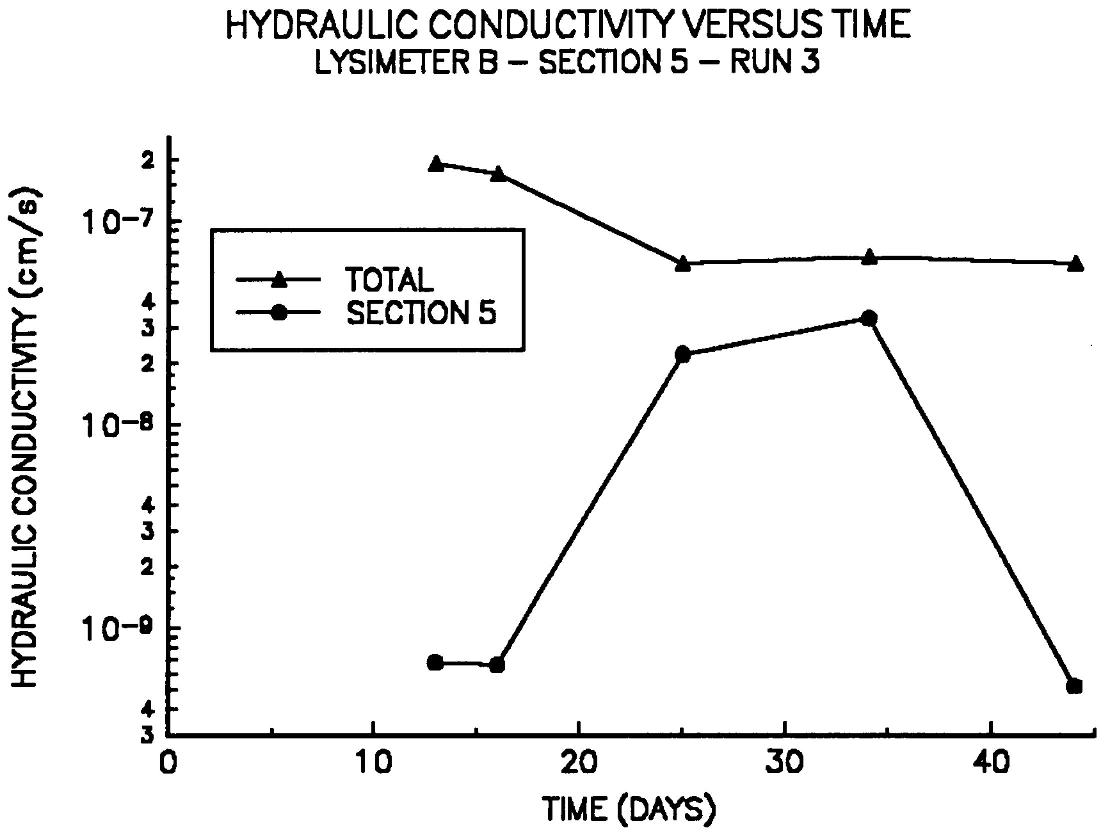
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 1 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−7
3
2
10−8
3
2
10−9
3
2
10−10
0
10
20
30
40
TIME (DAYS)
TOTAL
SECTION 1


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 2 – RUN 3
TOTAL
SECTION 2
HYDRAULIC CONDUCTIVITY (cm/s)
10−7
10−8
10−9
10−10
TIME (DAYS)
0
10
20
30
40

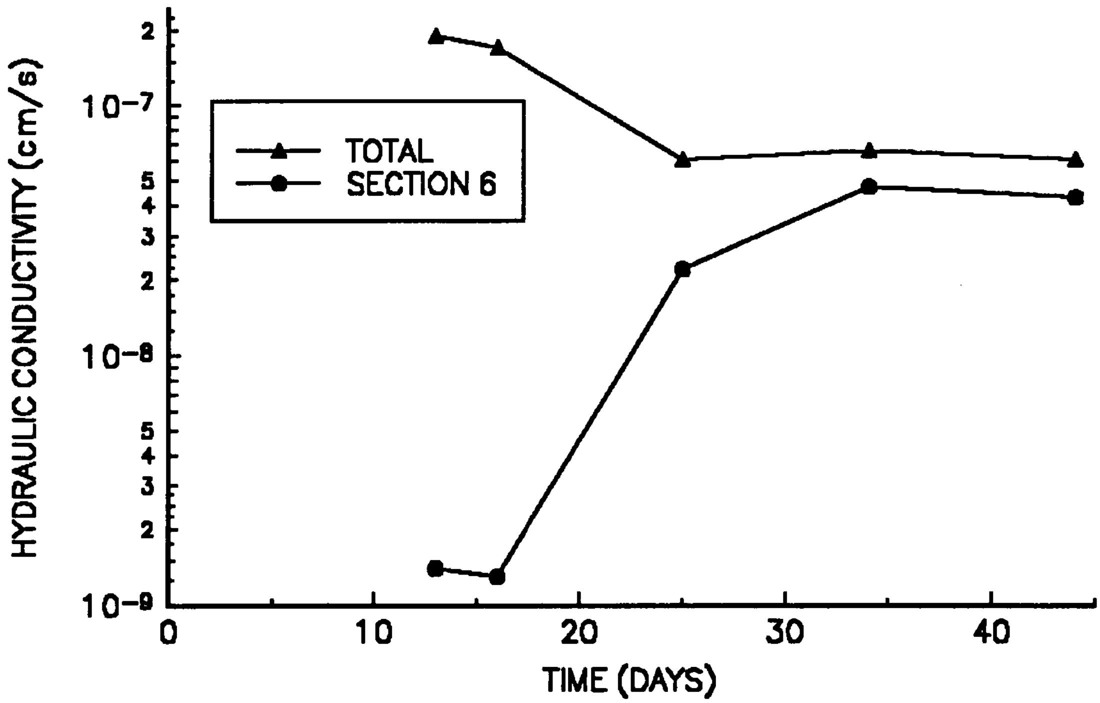


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 3 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−7
3
2
10−8
3
2
10−9
3
2
10−10
TOTAL
SECTION 3
0
10
20
30
40
TIME (DAYS)

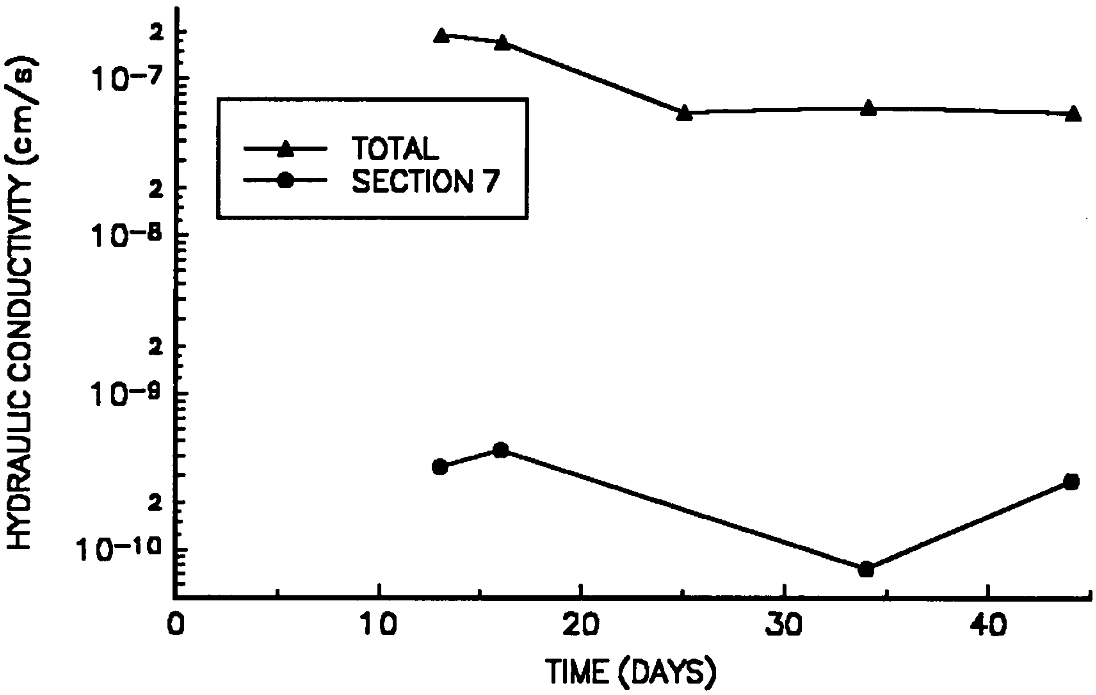

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 4 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
TOTAL
SECTION 4
2
10−7
3
2
10−8
3
2
10−9
3
2
10−10
0
10
20
30
40

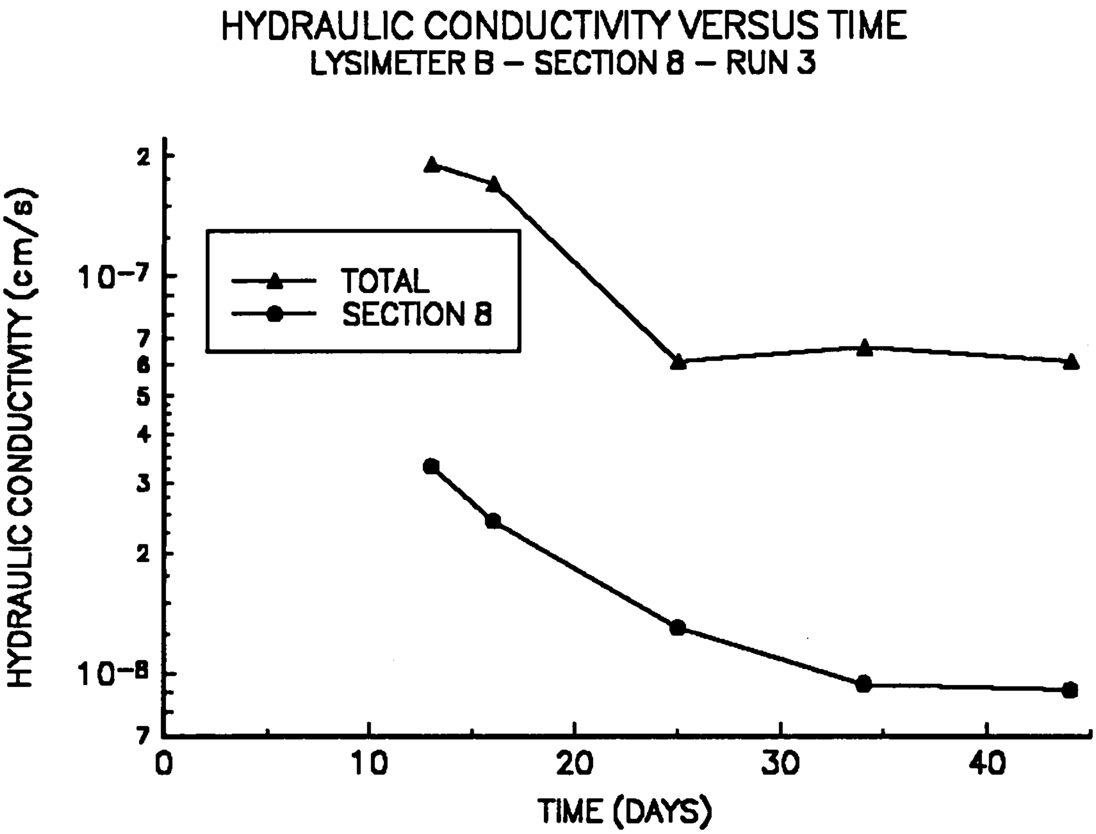

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 5 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
2
10−7
4
3
2
10−8
4
3
2
10−9
4
3
TOTAL
SECTION 5
0
10
20
30
40
TIME (DAYS)

HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 6 – RUN 3

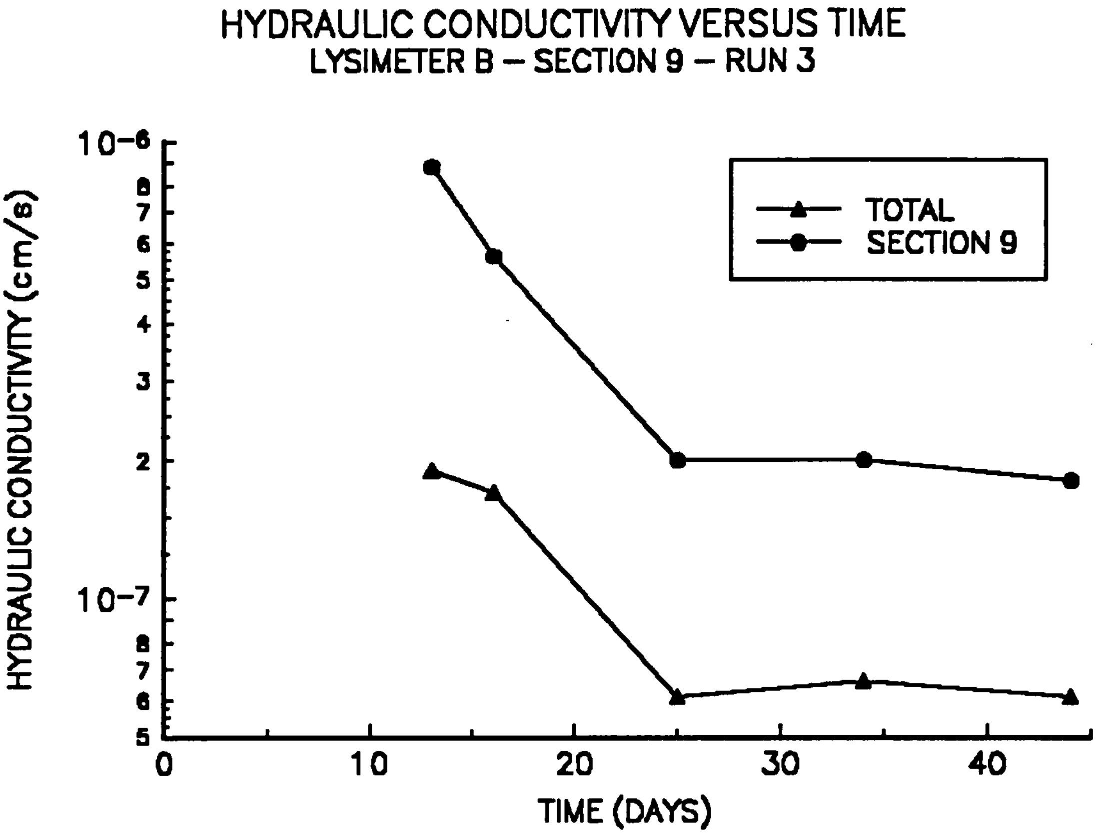


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 7 – RUN 3



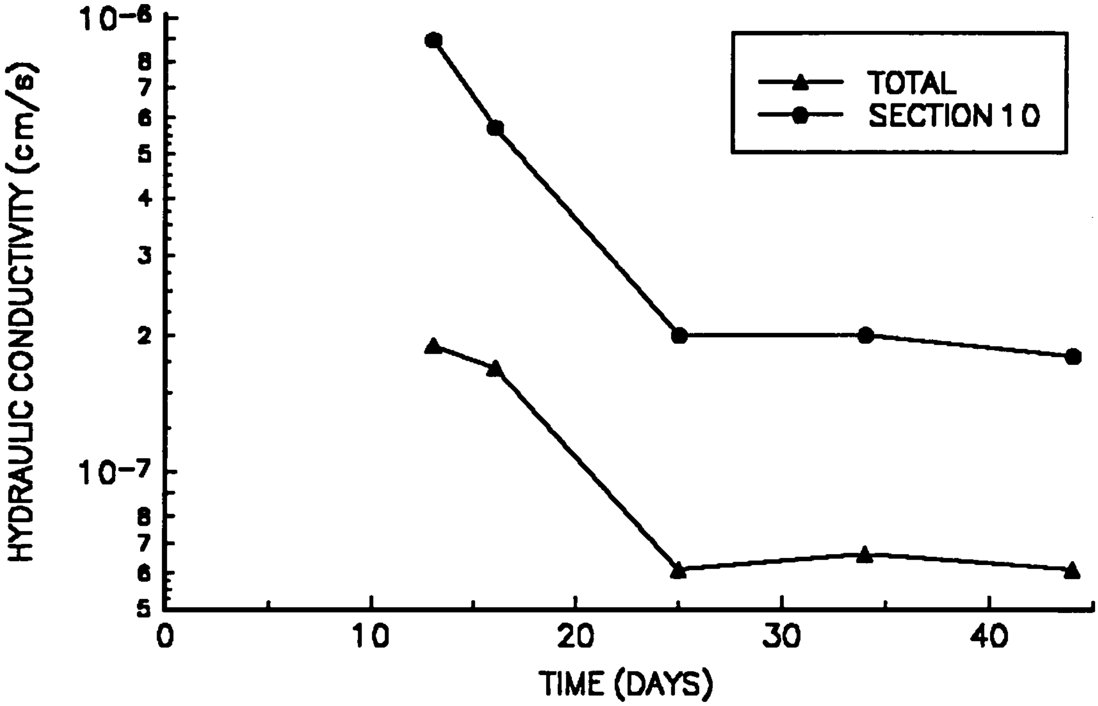


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 8 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
TOTAL
SECTION 8
2
10⁻⁷
7
6
5
4
3
2
10⁻⁸
7
0
10
20
30
40

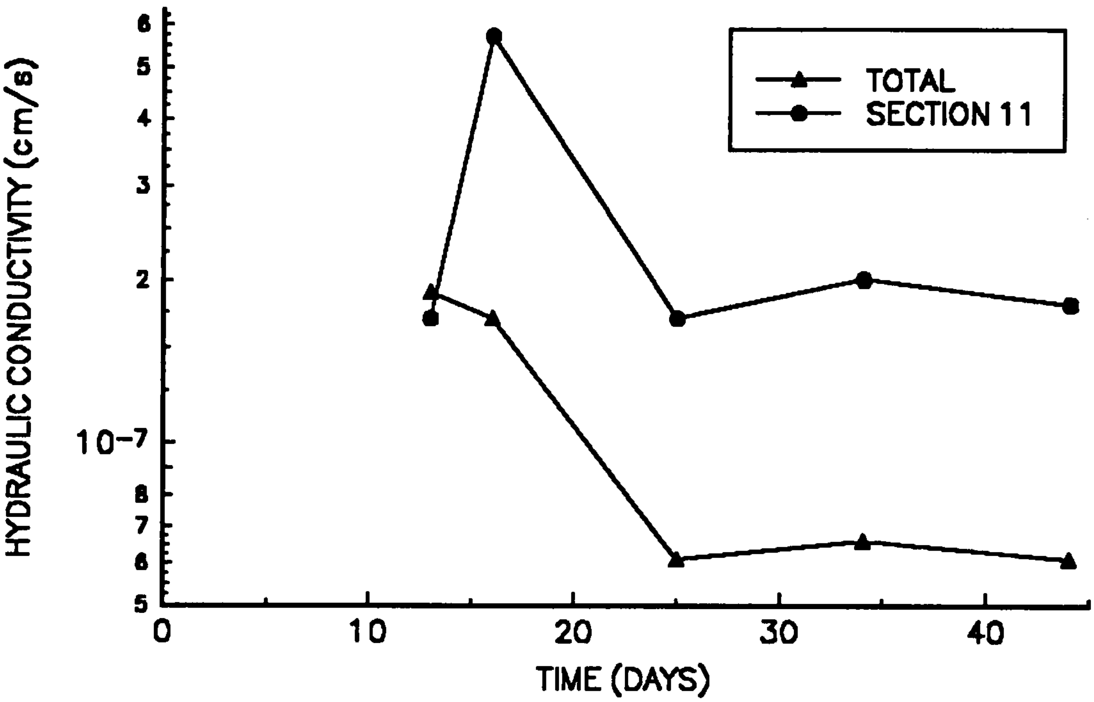


HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 9 – RUN 3
HYDRAULIC CONDUCTIVITY (cm/s)
TIME (DAYS)
TOTAL
SECTION 9

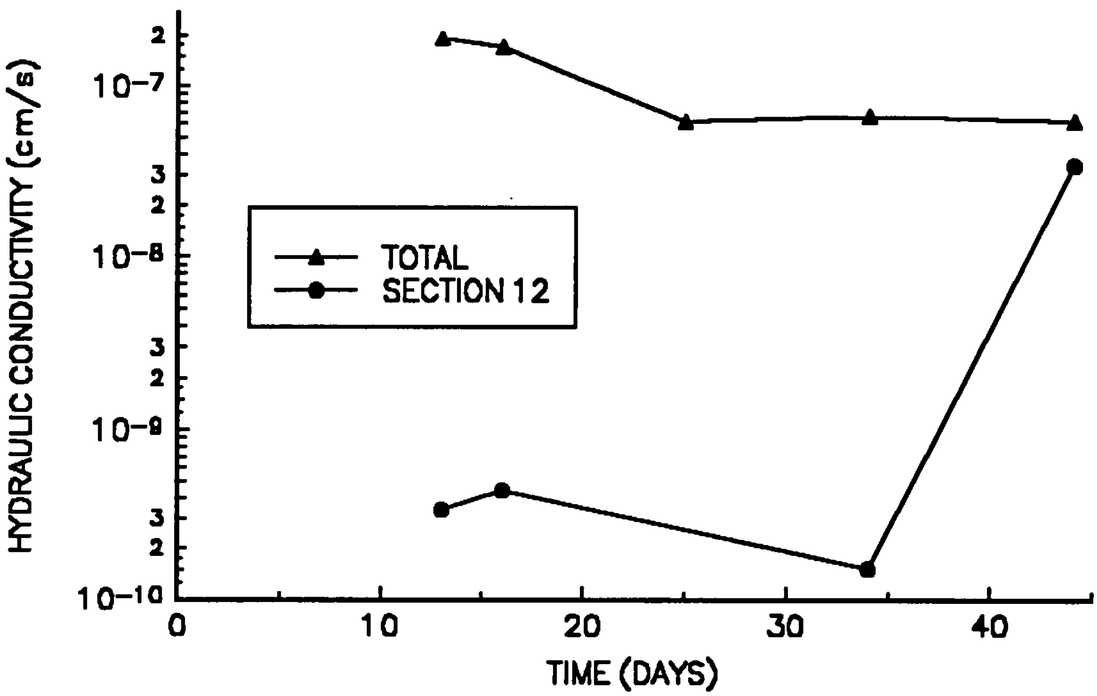
HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 10 – RUN 3



HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 11 – RUN 3



HYDRAULIC CONDUCTIVITY VERSUS TIME
LYSIMETER B – SECTION 12 – RUN 3



VITA

Daniel Raymond Boles was born in Columbus, Ohio in 1968. He grew up in Chattanooga, Tennessee. He attended the University of Tennessee, Knoxville from 1986 to 1992 and received his Bachelor of Science degree in Civil Engineering. During this time he served as president of the University of Tennessee Cycling Team. He was also a Co-op student with the Federal Highway Administration where he worked in Sterling, Virginia, Asheville, North Carolina, and Williamsburg, Virginia. Upon receiving his undergraduate, degree he went to work for Consolidated Technologies, Inc. in Chattanooga, Tennessee prior to beginning graduate school in the fall of 1992 at the University of Tennessee, Knoxville. He graduated in May 1994 with his Master of Science in Civil Engineering. In the spring of 1994 he will begin work with LAW Engineering Company in Knoxville, Tennessee. He will be married to Amy Elizabeth Lindsey in the fall of 1994.