FLUID RETENTION IN LEACH DUMPS BY CAPILLARY FORCES

by

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A

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ABSTRACT

This paper deals with the phenomenon of water held in a leach dump due to capillarity. Water is shown to be retained in the fine pores of the ore as well as in the interstices between the rock and soil particles. Upon drainage, Chino leach dump material show two distinct capillary systems and a double capillary curve is obtained.

Both the igneous and the sedimentary rocks composing the leach material are shown to have appreciable porosity. Fluid flow is restricted to the interstices between the rock and soil particles. The irreducible water saturations are found to be 88% for the -48 mesh material and 23% for the +48 mesh to one inch material. The composite sample had an irreducible water saturation of 52 percent. The irreducible water saturation in the pores of the ore was found to be between 73-76%. Very coarse pores or channels between large rocks exhibit essentially zero capillary retained water.

The presence of fine material in a dump gives an alternate explanation for the apparent perched water tables. Namely, the water can be retained as the result of capillary action. If capillary pressure data is obtained on the dump suspected of having a perched water table, the question of the existence of the perched water table can be resolved.

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INTRODUCTION

(Section 1.1)

BASIC METHODS OF FLUID RETENTION IN SOILS

In the area of leaching, whether it is in situ or dump, there are eight basic ways in which water can be held.[1] These are: (A) The groundwater table, (B) capillary water, (C) zones of open capillary water where air and water alternately fill the pores, (D) water held in the pores of the rock by capillary action, (E) water film on rock particles, hygroscopic water as rocks are preferentially water wet, (F) water vapor in the voids above the zones of open capillary water, (G) gravitational water loosely linked with the rock, pendular water, and (H) gravitational water more strongly linked to the rock, funicular water (see Figure 1.1).

(A) The ground water table in the zone of complete saturation is the level to which water would rise in either a pipe or a well bore that is sufficiently large in diameter for the forces of capillarity to have minimal effect. (B) Capillary water is the water held in the zones between the rock fragments by capillary action. It extends above and is connected to the groundwater table. (C) The zones of open capillary water can either be filled with water or with air, depending on the capillary pressure. (This will be discussed in detail later in section 1.4). (D) The water held in the pores of the rock by capillary action is the water saturation (S_w) in the rock's natural porosity (ϕ). (This is discussed in detail in section 1.2.) (E) Hygroscopic water is the

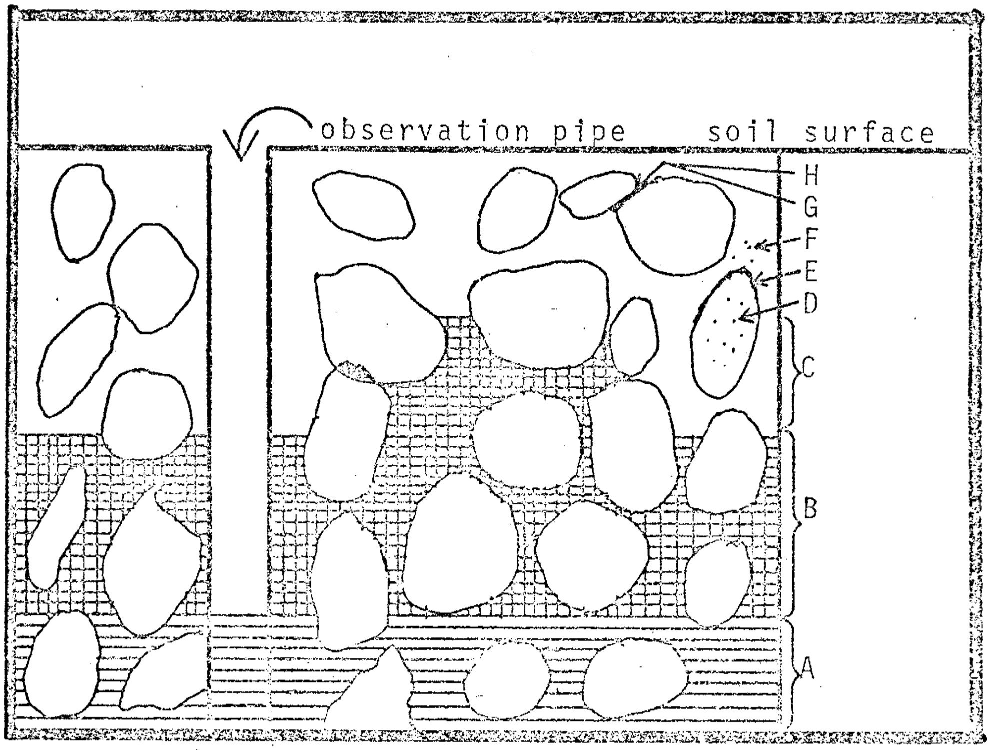

Figure 1.1 How water is retained in soils

water that condenses on the surface of rock particles when the dry particles come into contact with humid air. (F) Water vapor completely fills the voids in the upper zone, shifting from regions of higher pressure to regions of much lower pressure. (G) & (H) Pendular water and funicular water are more easily understood by viewing Figures 1.2-1.4. Pendular water is held by capillarity between particles or rock fragments that come in contact with each other as shown in Figure 1.2. This water forms rings around the contact points, called pendular rings. As the water saturation in the zone increases, the size of the rings increase until they become interconnected or funicular. Figure 1.3 shows the intermediate step where both the water and the air can be considered funicular. If the water saturation becomes very great, only the water will be funicular, having air bubbles (insular) trapped in the pore spaces as shown in Figure 1.4.

(Section 1.2)

DISCUSSION OF ROCK AND SOIL POROSITY

In order to obtain a better knowledge of the materials used in this study, the following facts should be noted. All rocks and soils in general are known to have both porosity and capillarity. A rock, whether igneous or sedimentary, and all fragments of it down to microscopic size, i.e. soil, exhibit porosity. Crystalline igneous

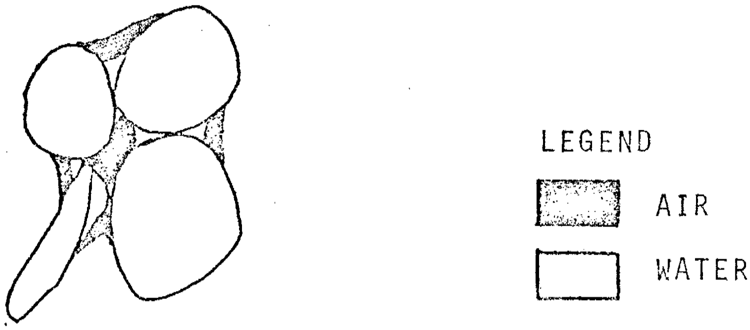

Figure 1.2 Pendular water

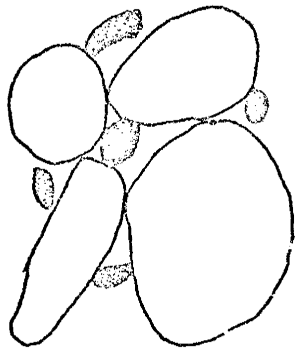

Figure 1.3 Funicular water & air

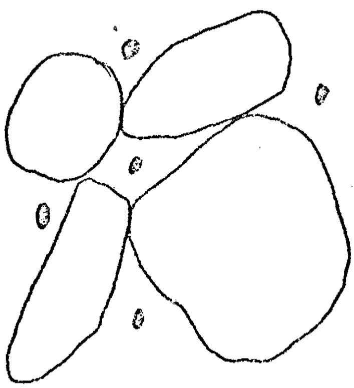

Figure 1.4 Funicular water, insular air

rocks like quartz monzonite have intercrystalline porosity of a low order of magnitude. The feld spars, however, are easily decomposed and this decomposition yields increased porosity in the rock. Sedimentary rocks may have porosity as stated above if they include fragments of igenous rock, but they also have porosity due to the voids left in between the grains. If the sand grains were all perfect spheres with zero porosity and of the same diameter, the porosity of the rock would vary from 26% to 87.6%, depending on the stacking arrangement used. (See Table 1.1, Appendix.) The actual porosities of sediments are much lower due to the void spaces between larger grains having been filled with smaller grains. In addition, cementing material, usually carbonate or silica that holds the rock together, occupies some of the original pore space. Porosities taken on the rock types used in this study yielded the following results:[2] for quartz monzonite porphyry, $\overline{\phi} = 15.5\%$, for altered sediments having a thin layer of chalcocite or pyrite on the outside, $\overline{\phi} = 8.2\%$, for altered quartz monzonite having an inner layer (vein) of chalcocite or pyrite, $\overline{\phi} = 11.5\%$, and for altered quartz monzonite without any layers of pyrite or chalcocite, $\overline{\phi} = 10.3\%$. The average of the Chino rocks studies was $\overline{\phi} = 12\%$. (See Table 1.2, Appendix.) The soil porosity, which includes the porosity of the rock in the soil has been found to range from 25-90%. Table 1.3 in the Appendix gives porosities for various soil types. The porosities on the actual samples used ranged from 29 to 42%. (See Table 1.4, Appendix.) Although rock has porosity it does not follow that the pores will be filled with water (in an arid desert, sandstone could be nearly bone dry). The amount of pore space filled is measured as the percentage water saturation. Under normal drainage conditions some of the water will not leave the pore spaces; this is called the irreducible water saturation (S_{wi}). Even a rock subjected to centrifugal force many times the pull of gravity retains its irreducible water saturation. The two possible explanations for this phenomenon are, electromolecular forces in soils, and capillary action.

(Section 1.3)

ELECTROMOLECULAR FORCES IN SOILS

Between the rock particles and the surrounding water, electromolecular forces of interaction exist. Water consists of polar molecules containing positive hydrogen ions and negative hydroxyl ions. The clays have a negative surface charge in their free state. Because of the abundance of ions in water, clays usually have a one-molecule-thick layer of cations covering the surface of the clays. This layer is referred to as the "Stern Layer"[3] and attracts the water molecules to the clays. The attractive forces operate at very small distances, not exceeding 0.25-0.5μ (μ = one micron = 10^{-6} meters). The water molecules in the first few tens of molecular layers are firmly bound to the clay and to other water molecules.

(Section 1.4)

CAPILLARITY IN ROCKS AND SOILS

Capillarity deals with the phenomenon of fluid rise and retention in extremely small diameter tubes. The rise is due to adhesion tension between the fluid and the walls of the tube and is limited by the weight of the column of fluid in the tube. Capillary pressure can be expressed as

$$P_c = P_a - P_w \tag{1.1}$$

or

$$P_c = g(\rho_w - \rho_a)h \tag{1.2}$$

where P_w = pressure in the water

P_a = air pressure

P_c = capillary pressure, dynes/cm^2

g = gravitational constant, cm/sec^2

$(\rho_w - \rho_a) = \Delta\rho$ = difference in densities between water and air, g/cm^3

h = height, cm

Changing equation 1.2 into engineering units and solving for h[4]

$$h_{ft} = 2.31\ P_c psi \qquad (1.3)$$

To better understand capillarity, consider the following example. (See Figure 1.5.) If a transparent pipe filled with sand was placed in water, we would observe that the water at first rapidly rises in the pipe, then moderately and finally its motion becomes invisible to the naked eye. The height of maximum rise of water is called the "static height of capillary rise" (hereafter referred to as h_k). The pressure at AB will be atmospheric. Capillary forces, compelling the fluid to rise between the sand grains, operate so that in the wetted part of the pipe a pressure lower than atmospheric is established. If we put atmospheric pressure equal to zero, then the pressure in the region EFUV is considered negative and at the plane UV equal to $-\rho g h_k$. Designating atmospheric pressure as P_a, at the plane UV, $P_w = P_a - \rho g h_k$. Since the pressure difference across the interface UV is, by definition, the capillary pressure (P_c) of the system, it follows that $P_c = P_a - P_w = \rho g h_k$.

The pores in the upper layers of the sample will constitute a complicated "labyrinth of voids" and therefore, for h_k, a more complicated relation holds[1].

$$h_k = 0.45\ \frac{1-\phi}{\phi} \cdot \frac{1}{d_{10}}\ \text{cm (for sands)} \qquad (1.4)$$

where ϕ = porosity, %

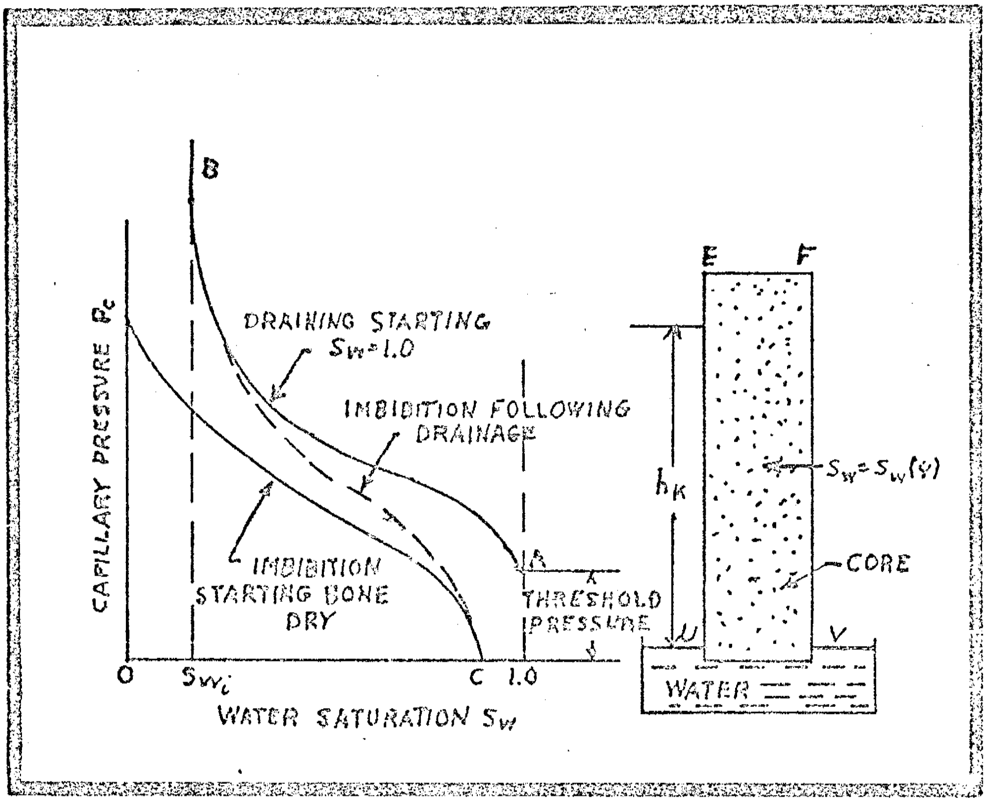

Figure 1.5 Capillary rise in a sand filled pipe

d_{10} = effective diameter (90% retained by weight) of soil particles, cm

A table of values for h_k is included in the Appendix (see Table 1.5). For the material used in this study, d_{10} = 0.000795 cm giving h_k = 13.86 meters = 45.5 feet. It should be noted that our material contained more fines than the samples in Table 1.5.

Also shown in Figure 1.5 is the concept of threshold pressure. This shows that, to drain capillary water, there is a certain pressure differential that must be applied before the water will be forced out of the pores by air. The threshold pressure observed in the experiments ranged from 0 for the compacted samples to 5 psi for the rock cores.

The phenomenon of capillarity plays an important role in the flow of fluids with a free surface. Consider a leach dump containing a surface pond (see Figure 1.6). The dotted line corresponds to the free surface without capillairty, the smooth line to that with capillarity[1]. With capillary forces acting, the area of wetting widens and the flowrate increases.

The pregnant solution held in the capillaries acts according to the laws of physics and all water above the irreducible saturation will be flushed out when a new leaching cycle takes place. The new fluid injected into the dump may raise the local dump water table, thus allowing

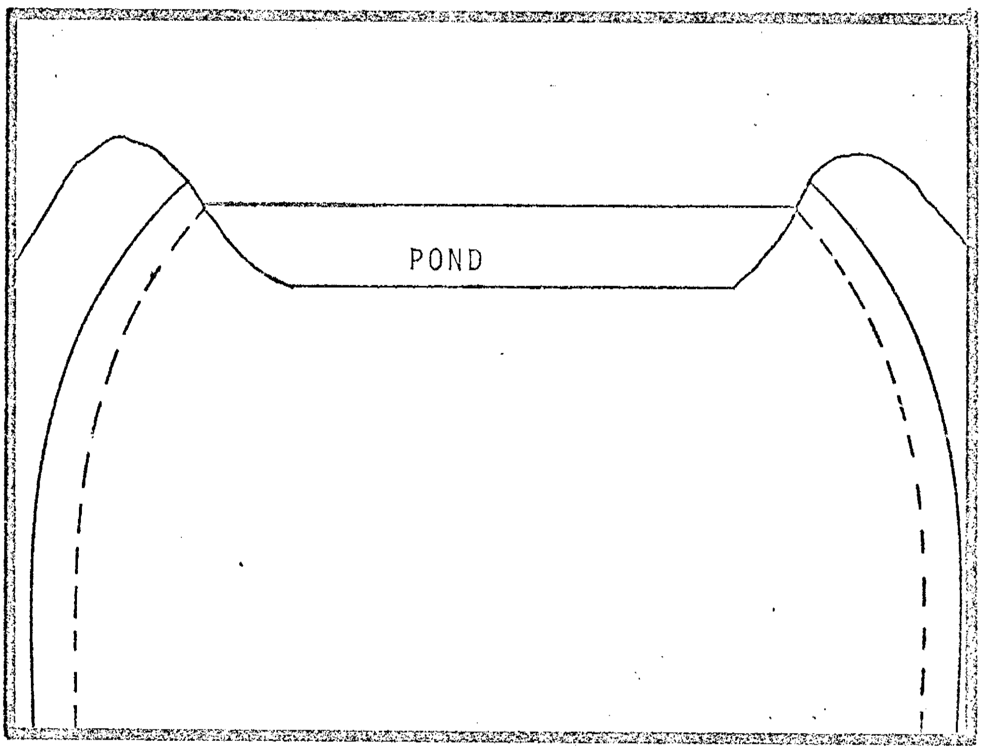

Figure 1.6 How capillarity increases the area of wetting in a leach dump

the capillary water to rise. When the dump is drained, the local dump water table falls, draining most of the capillaries back to their original configuration. This flushes some of the pregnant solution into the drainage channels. The irreducible water saturation in the pores of the rocks and in the capillaries between the rocks can not be displaced by flow or by application of a pressure gradient. However, the new leach solution and the pregnant solution mix by diffusion; a process that requires time. Allowed sufficient time for diffusion to take place, the mixed solutions are displaced by further infiltration of the new leach solution, thus flushing more mineral from the flooded zones. This does not mean that the most effective leaching takes place. The zones filled with the capillary water and the area below the local dump water table will be continuously saturated with solution. Oxygen may be less available to ore in these zones and the oxidation of the ore could be retarded resulting in lower recoveries.

(Section 1.5)

PERMEABILITY AS RELATED TO CAPILLARITY

Capillarity and permeability are interrelated. The reason for this is that they both use the same capillary tubes. A capillary path extends from the water table to the surface. It makes a perfect channel for fluid flow acting under either a water head and the force of gravity or by the force of gravity alone. It can be seen from Poiseuille's equation

$$Q/t = \frac{Vr^2 \Delta P}{8 \mu L^2} \qquad (1.5)$$

that the rate of flow varies directly as r^2. Because capillary pressure varies inversely with r, it follows that permeability is proportional to $(1/P_c{}^2)$[1].

This means that in a leach dump, the larger capillaries will be the major flow channels and so on down to the extremely small capillaries. While the flow through the small capillaries is said to be insignificant compared to the total flow, it is important to realize that flow does occur and in conjunction with other events (see last paragraph, Section 1.4) acts to flush the pregnant solution out of the dump.

(Section 2)

SCOPE OF THE STUDY

The purpose of this study was to determine the effect of capillary pressure on fluid retention in a leach dump. One of the main areas of interest in this study is a discussion of the phenomenon of the "perched water tables"[5]. A perched water table is a large mass of fluid retained in a dump, even after the drying and/or aerating cycle. This retained fluid is of economic importance to the mineral industry because unless it can be recovered, its mineral values will be lost.

If perched water tables exist in a dump, they can greatly affect the economics of leaching. The fluid retained in the perched water table becomes saturated with the desired mineral but is difficult to drain. A small amount of fluid may be swept from the extremities of the mass by flowing water but will be insignificant compared to the total mass.

A second area of study in this paper is that of fluid flow through unconsolidated porous media containing significant amounts of clays. Flow takes place in pores and channels with fluid saturation above the irreducible saturation. By definition irreducible water can not flow nor is there any flow within the fine pores of the ore.

Many of the studies conducted on flow through porous media used non-clayey material[6]. Those that used clayey materials used a bactericide to nullify the effects of bacteria growth[7]. A detailed study should be undertaken on the migration of clays in dumps. Clays are present in nearly all dumps and generally make up a large proportion of the size distribution of an actively leached dump. This study has examined only one-dimensional flow, clays included in their natural state, and the change in one-dimensional flow due to compaction.

(Section 3)

APPARATUS USED IN THE STUDY

The apparatus used in this study consisted of an electric drying oven, scale and weights, hollow brass cylinders screened on one end, a hydraulic press, a degassed water supply, a moisturized, regulated air supply, a vacuum pump, sieve analysis equipment, and a Core Lab capillary air-water pressure apparatus.

The electric oven was bottom vented and regulated within a temperature range of 120°F to 130°F to dry the clays contained in the samples without alteration. The scale and weights used were accurate within 0.1 gram and could be interpolated to 0.01 gram. The hollow brass cylinders were screened on one end with 200 mesh screen to retain the samples and were coated on the inside with Dupont Silicone Adhesive to prevent "channeling" from occuring along the sides of the cylinder. The hydraulic press was used to compact the samples in the cylinders. The vacuum pump was used to evacuate the compacted samples prior to their total saturation with degassed water. The sieve analysis equipment was used to obtain the histogram of the material used and in the make-up of all samples used. The air supply was regulated at 50 psi and passed through a water bath to moisturize the air.

The Core Lab capillary pressure apparatus consisted of a main control panel (A) and a high pressure bomb (B), (See Figure 3.1). The main control panel contained the

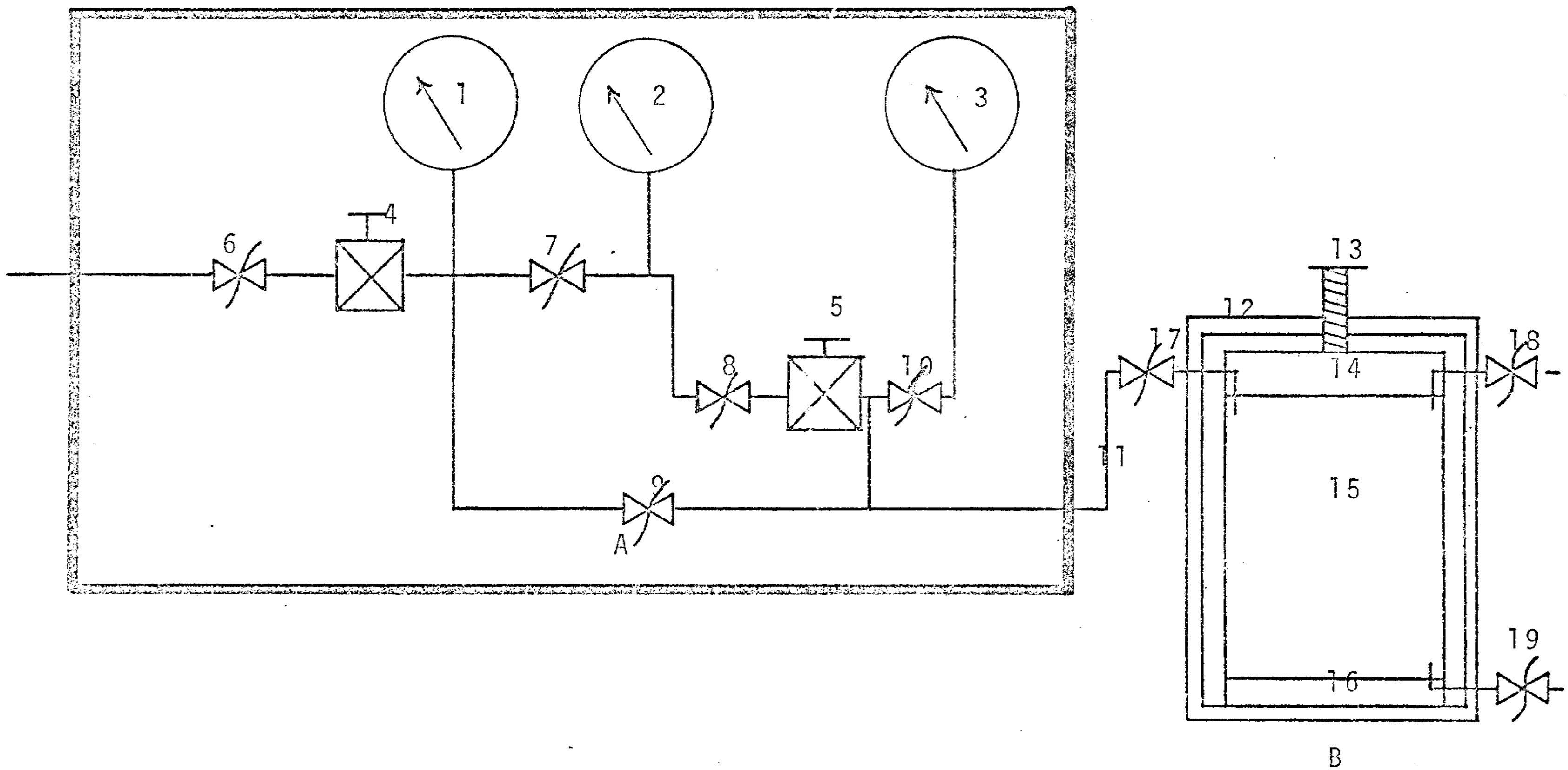

Figure 3.1 Core Lab capillary (air-water) pressure apparatus

high pressure gauge (0-50 psi) (1); the medium pressure gauge (0-15 psi) (2); the low pressure gauge (0-2.5 psi); the high pressure regulator (4); the low pressure regulator (5); the air inlet valve (6); the gauge inlet valve (7); the low pressure shut off valve (8); the high pressure air outlet valve (9); and the low pressure air outlet valve (10). The main control panel was connected to the bomb by a high pressure air line (11). The bomb was set in a yoke (12) and contained by a screw stop (13). The bomb consisted of three main parts: the top (14), the cylinder (15), and the base (16). The top contained two valves and was machined to receive the screw stop. The valves in the top were the air inlet valve (17) and the air outlet valve (18). The cylinder was machined to hold an O-ring in each end to provide for effective seals. The base (See Figure 3.2) had the water outlet valve (19) and was machined to receive the O-ring on which the porous ceramic plate (20) rested. The plate was held in place by a stainless steel restraining ring (21) held in place by six set screw clamps (22).

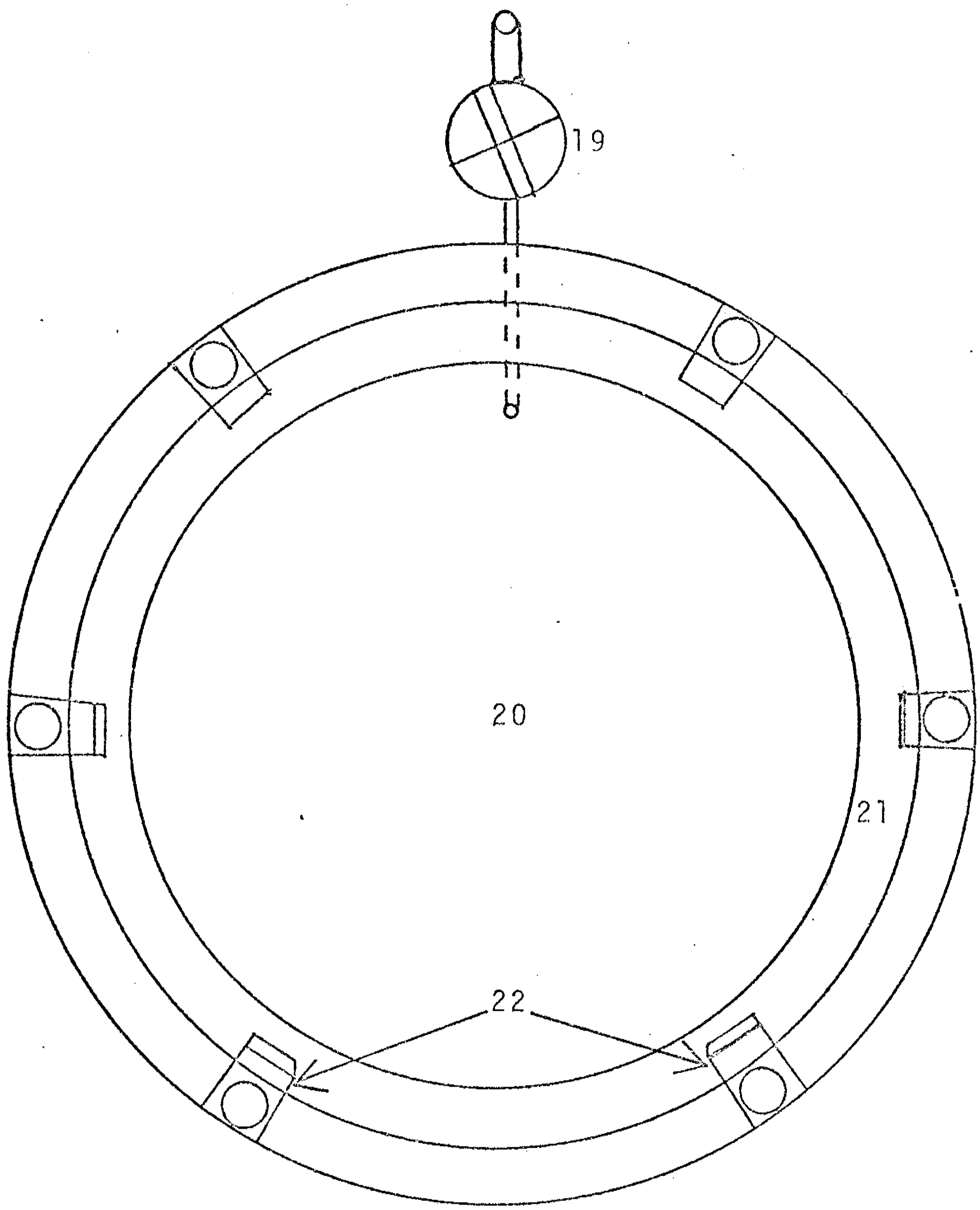

Figure 3.2 Plan view (base) high pressure bomb

(Section 4)

PREPARATION OF SAMPLES USED

The material used in this study came from Kennecott Copper's Chino Mines Division "G" dump. The sample was first dried then sieved in a roto-tap machine. A histogram was obtained showing weight percentage distribution for all minus one inch (-1") material in the sample (see Figure 4.1). All samples used were made up from the sieved material and the same distributions were retained (see Figures 4.2 and 4.5, sample 6 contained -48 +65 mesh material only). Each sample, with the exception of sample 5, was compacted to 100 psi. Sample 5 was compacted to 400 psi to determine what effect, if any, a change in compaction would have on the capillary pressure curve obtained. The dry weights and total volumes were determined after compaction. The samples were then evacuated and totally saturated with degassed water. They were again weighed and the porosity (ϕ) determined as well as the weight of water retained at total saturation. A thin base pad of diatomaceous earth was applied to the bottom of the sample to insure capillary contact between the sample and the porous ceramic plate. The sample was then placed in the bomb and the bomb sealed.

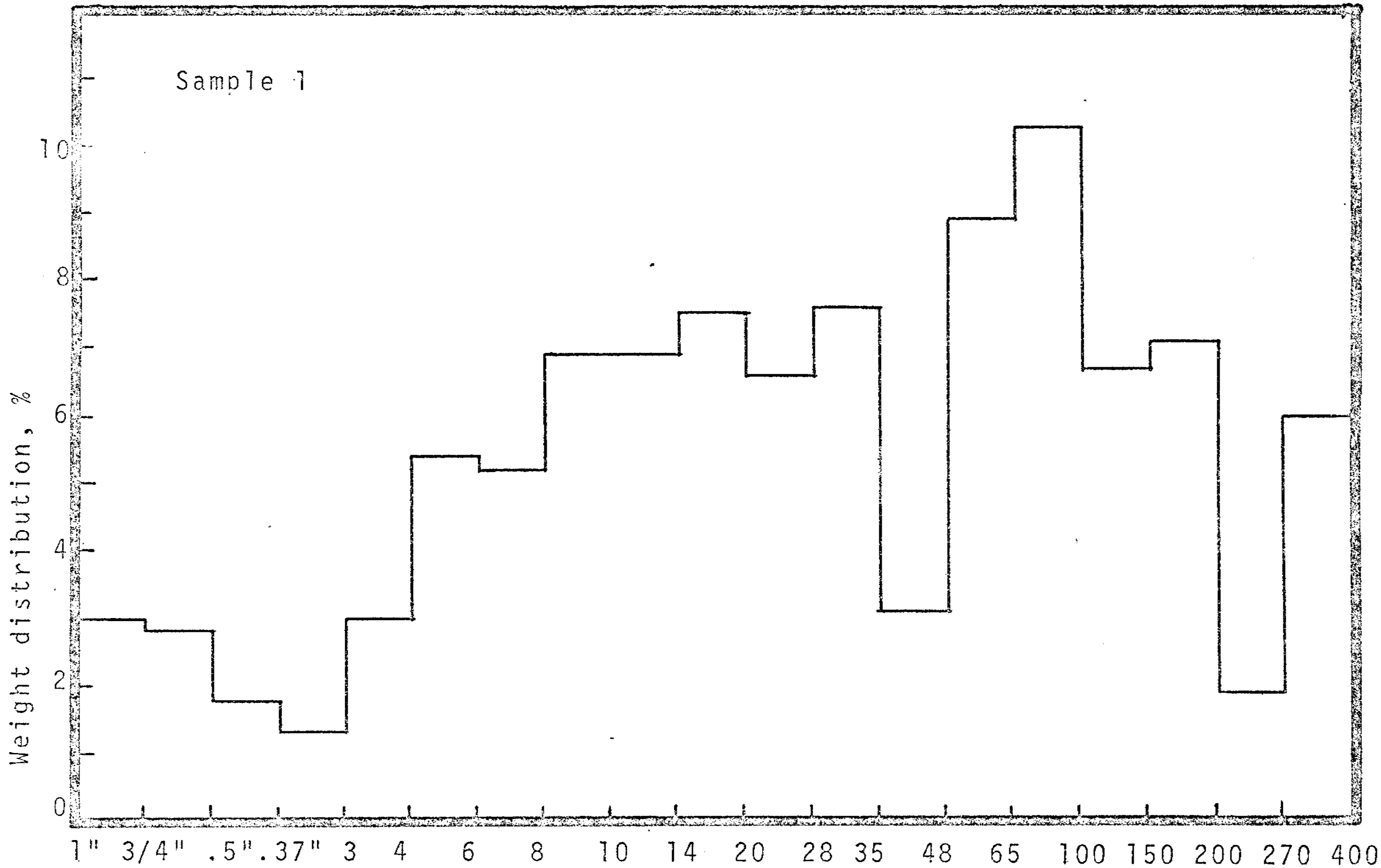

Figure 4.1 Histogram of the composite sample using the Tayler Standard Sieve analysis

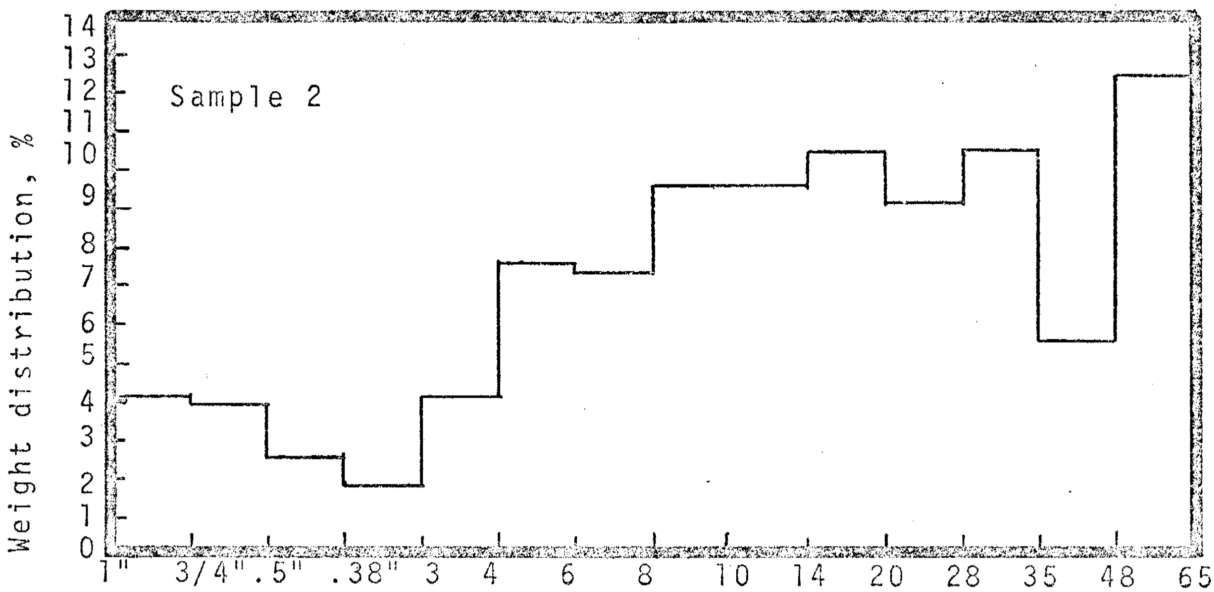

Figure 4.2 Histogram of +65 mesh material (100 psi compaction)

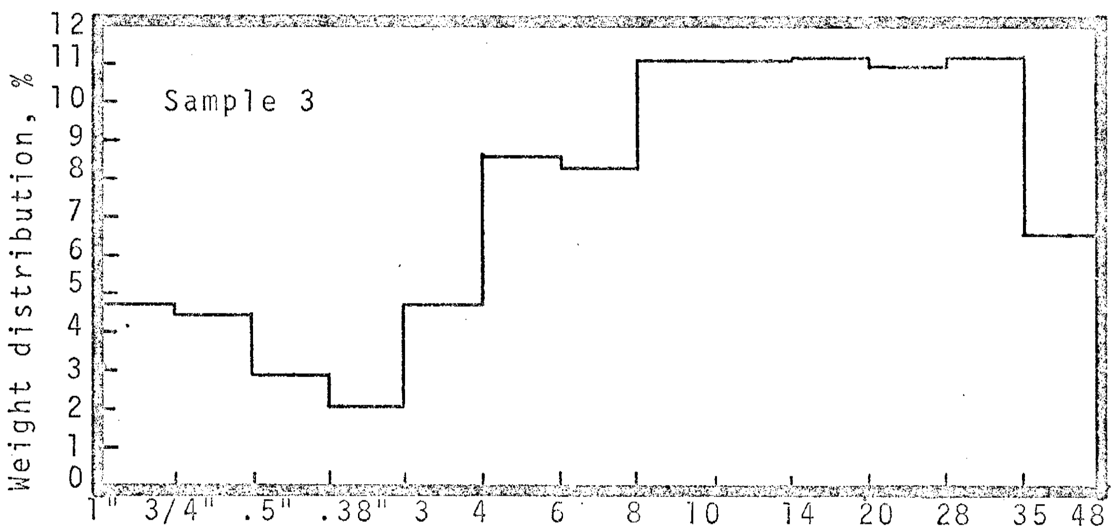

Figure 4.3 Histogram of +48 mesh material

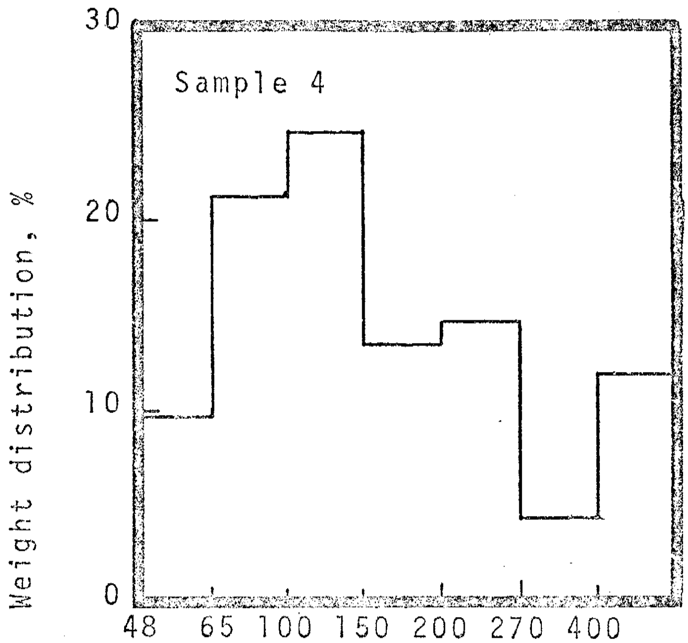

Figure 4.4 Histogram of -48 mesh material

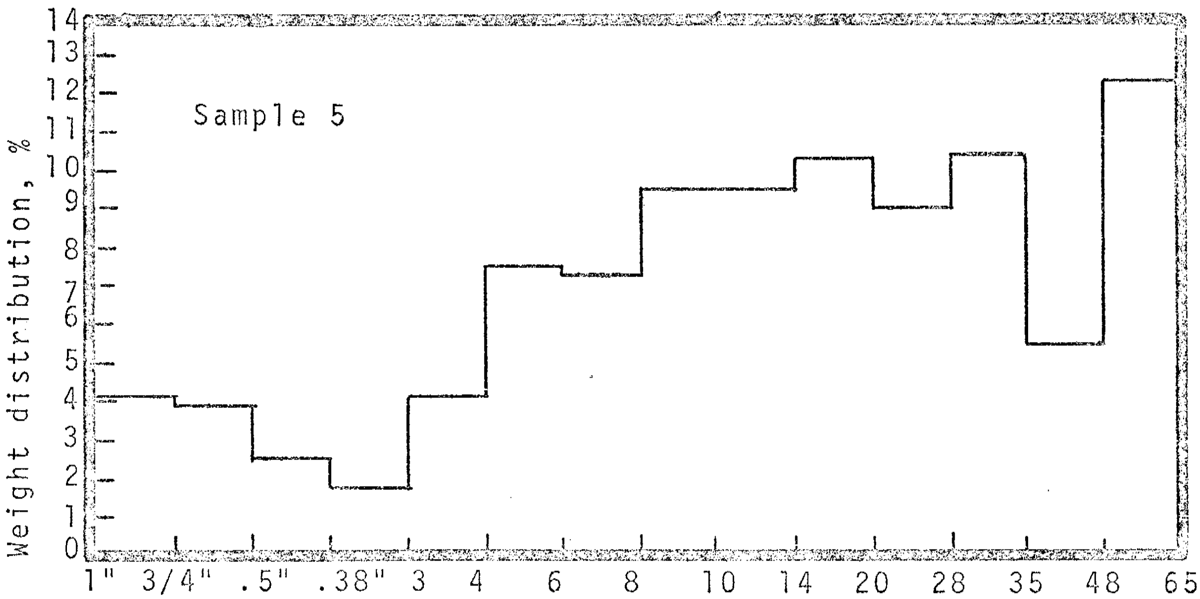

Figure 4.5 Histogram of +65 mesh material (400 psi compaction)

(Section 5)

PROCEDURE FOLLOWED IN EXPERIMENTAL WORK

With all valves closed and both regulators backed off, the sample was placed in the bomb. The bomb was then sealed in the yoke using the screw stop. The following procedure was then followed. (a) Open the air inlet valve on the control panel; (b) open the gauge inlet valve; (c) using the high pressure regulator obtain a reading of 4 psi on the medium pressure gauge; (d) open the low pressure air inlet valve; (e) using the low pressure regulator obtain a reading of 1 psi on the low pressure gauge; (f) open the low pressure air outlet valve; (g) on the bomb, open the water outlet valve; (h) open the air outlet valve on the bomb; (i) open the air inlet valve on the bomb slowly until air can be detected leaving the air outlet valve on the bomb; (j) close the air outlet valve on the bomb.

This allows the air pressure inside the bomb to build up slowly thus protecting the ceramic plate from being forced down on its O-ring by a sudden surge of air pressure which may cause it to break, ruining the experiment. After the air pressure has had time to build up, the valve is then opened fully. Water will now be observed leaving the water outlet valve. When the flow of water ceases entirely, depressurization takes place.

In depressurizing the bomb: (k) close the air inlet valve on the bomb; (l) slowly open the air outlet valve on the bomb until air can be detected escaping, thus protecting the ceramic plate. (If the pressure is released too fast, the rubber O-ring may snap the plate into the restraining ring and crack the plate.) (m) As soon as the flow of air stops, the bomb is depressurized and is released from the yoke using the screw stop; (n) remove the diatomaceous earth pad completely from the sample and weigh the sample; (o) place a new diatomaceous earth pad on the sample and reseal the sample in the bomb; (p) using the low pressure air regulator obtain a reading of 2 psi on the low pressure gauge; (q) repeat steps (f) through (o); (r) back off the low pressure air regulator until the low pressure air gauge reads 0 psi to protect the gauge; (s) close the low pressure air inlet valve; (t) close the low pressure air outlet valve; (u) open the high pressure air outlet valve; (v) repeat steps (h) through (o); (w) using the high pressure air regulator, obtain a reading of 8 psi on the medium pressure air gauge; (x) repeat steps (h) through (o); (y) using the high pressure air regulator obtain a reading of 15 psi on the medium pressure air gauge; (z) repeat steps (h) through (o); (aa) back off the high pressure air regulator until all gauges read 0 psi; (ab) close the gauge inlet valve; (ac) using the high pressure air regulator, obtain a reading of 25 psi on the high pressure air gauge; (ad) repeat steps (h) through (n). The change in weight corresponds directly to the change in water saturation. This can now be plotted to give the capillary pressure curve of the sample. (See Figures 6.1 and 6.2).

(Section 6)

DISCUSSION

The material used in this study consisted of the minus one inch material from five samples taken from the "G" dump at Kennecott's Chino Mine. The "G" dump is one of the older dumps at Chino. It has been inactive since June 1971. This dump had been trenched in several places in an effort by Kennecott to learn more about the mechanics of dump leaching. Three of the samples were taken from the top of the dump, one from the side of the dump, and one from a fifteen foot deep trench in the dump. The weight distributions of these samples were calculated and the average used in this study. Material larger than one inch could not be used as it would have made the samples too large to handle with the existing laboratory equipment. This limitation on size is not thought to be too severe, since if only very coarse material is present almost all of the retained fluid will be in the pores of the rock. Thus the capillary pressure curves in Figure 6.3 would apply. It should be noted that the histograms were taken before the material was compacted. Compaction is normally associated with crushing and grinding. The effect of compaction can be seen by comparing samples 2 and 5 in Figures 6.1 and 6.2. Sample 2 was compacted under 100 psi while sample 5 was compacted under 400 psi. The histogram for these samples is shown in Figures 4.2 and 4.5. Note that the material is all coarser than 65 mesh. As might be

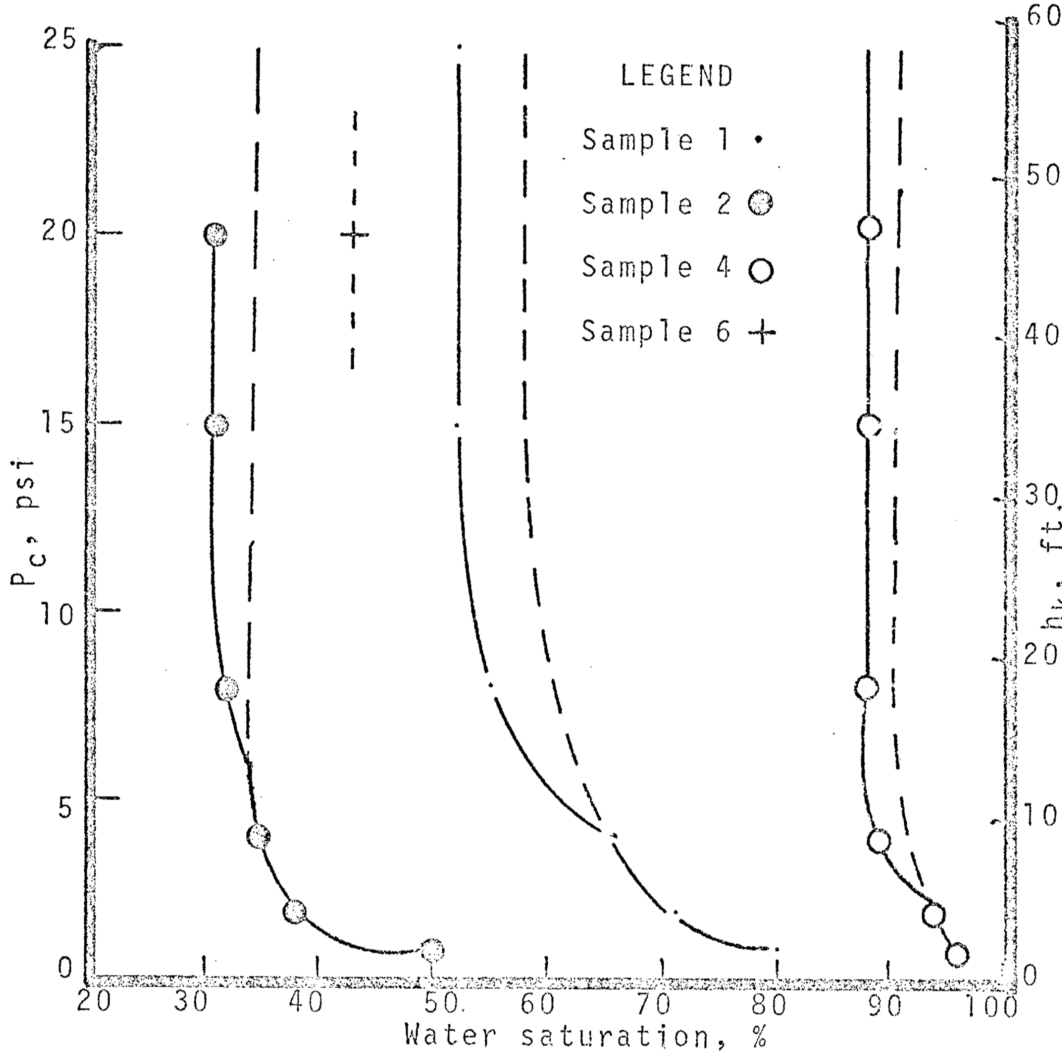

Figure 6.1 Capillary pressure curves on Chino material

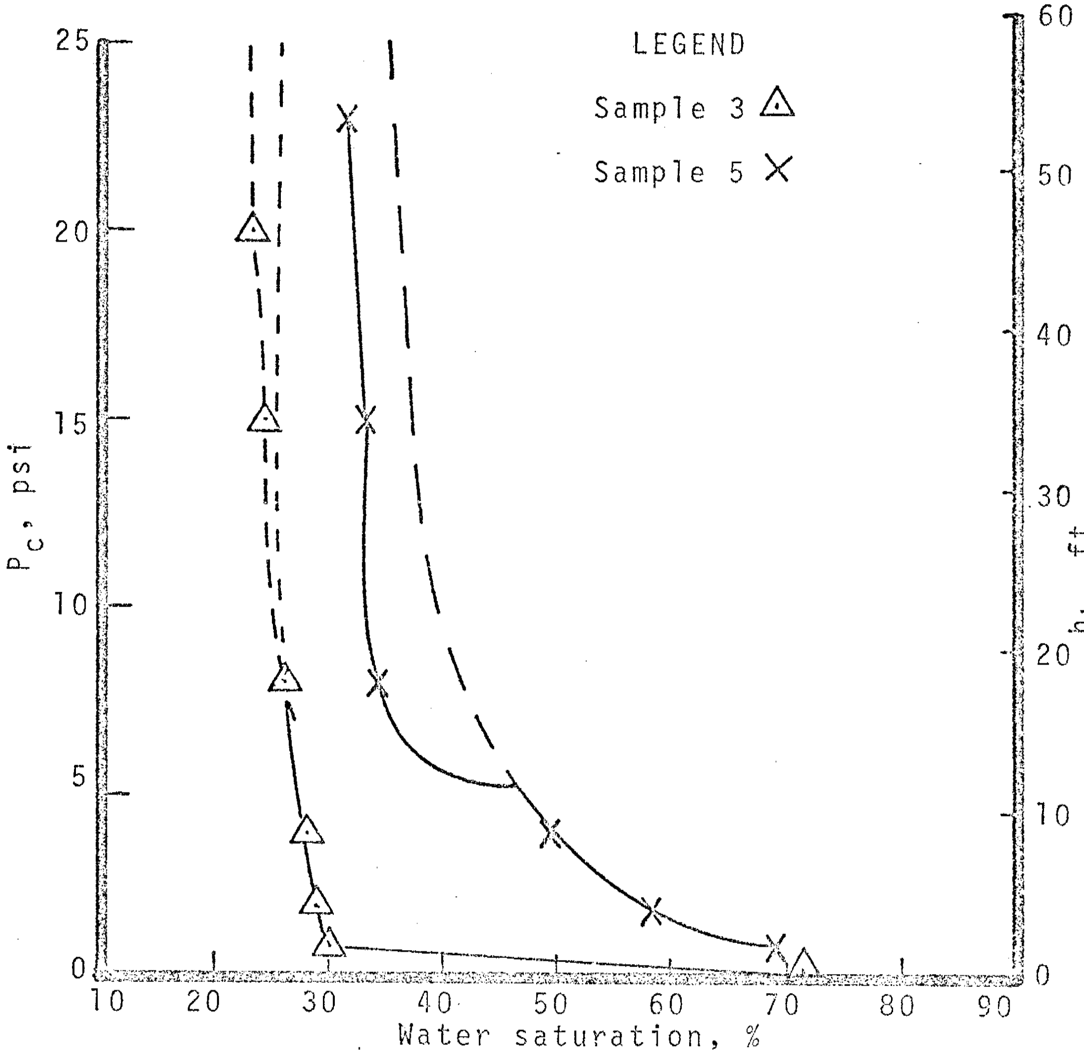

Figure 6.2 Capillary pressure curves on Chino material

expected, the coarser particles in sample 5 show some crushing as demonstrated by the somewhat greater amount of water held at low capillary pressures. Above a capillary pressure of 8 psi, the curves are essentially identical showing no change in the number of fine particles. It is probable that little crushing of the large particles occurs at 100 psi and this compaction pressure was used in preparing all of the other aggregate samples for capillary pressure tests. Two difficulties were encountered in repeating the histograms after all of the capillary pressure tests were completed: 1) some of the fines (-200 mesh material) could have been carried out of the sample during the tests, and 2) some of the material is imbedded in the silicone adhesive used to coat the sides of the cylinders and can not be recovered after the capillary pressure run. For these reasons, the histograms were prepared on the samples before compaction to provide a constant model to work with, within reasonable limits of accuracy.

Sample 1, shown in Figure 6.1 (See Figure 4.1 for histogram) is a composite of the 5 samples taken from G dump. The entry pressure appears to be at or near zero psi. At one psi (2.31 ft. up in a dump) the sample contains 80 percent water saturation which decreases to an irreducible water saturation of 52 percent at 15 psi (34 ft.). This indicates that a layer of this material in a dump would retain 52 percent water saturation after wetting irrespective of the height to which the layer extends above the point of zero capillary pressure. This irreducible water in the aggregate would eventually be removed by evaporation but this would take a very long time in a large mass of rock aggregate. In any case, water would be maintained within the dump as long as it was in contact with water at its base. Thus water would not retreat below the value of h_k (capillary rise) for the particular aggregate.

Sample 1 (as well as several of the other curves) appear to show the development of a "double" capillary curve. A double curve results from the existance of two separate and distinct pore size distributions in a porous media. That is, a coarse set of pores and a much finer set of pores with very few pores of intermediate size. A typical example of such a pore system is a vuggy limestone or dolomite which also has in addition to vugs a fine intercrystalline porosity. Note that the capillary curve for sample 1 has both a solid and a dashed portion. The dashed portion represents the irreducible water saturation that would exist if the rock fragments were solid. But they are porous as we have seen in Table 1.2. Figure 6.3 illustrates the capillary pressure curves obtained on five rock samples. Note that three of these rocks had typical capillary pressure curves and had entry pressures of about 5 psi. Now looking at Figure 6.1, we note that the capillary curve appears to shift to the left at about 5 psi. Several other samples do

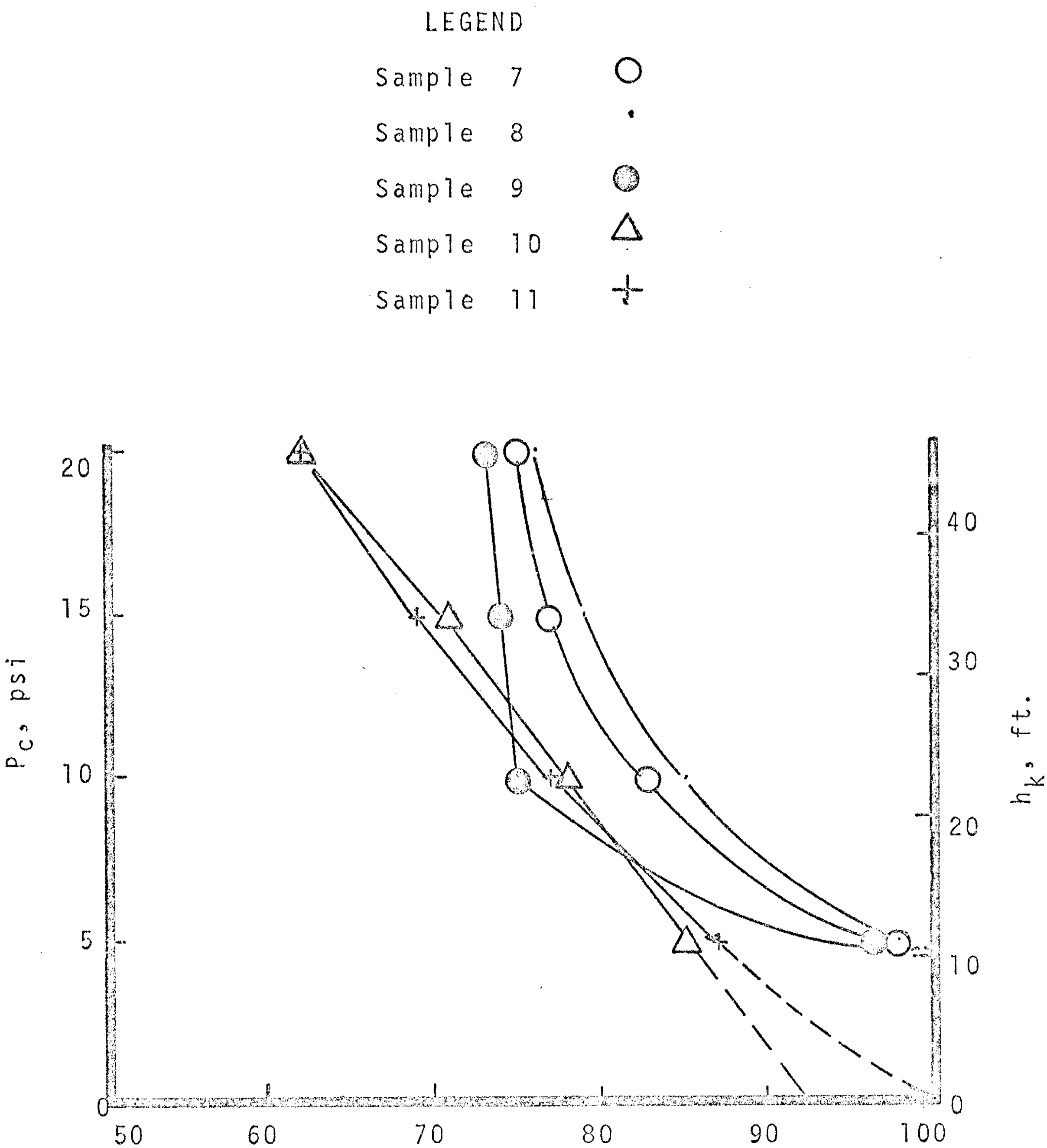

Figure 6.3 P_c curves on rock found in samples

also. We believe that this shift in the curve is real and represents the dewatering of pore space in the rock fragments.

The average porosity of the rock was determined with evacuation to be 12.6%. The average porosity determined without evacuation was 9.6% (lower because of trapped gas which remained in the pore space). The rocks used in the porosity tests ranged in size from 1" to 6" in diameter. Table 1.2 in the appendix gives the porosity obtained on 31 samples of Chino dump material which yielded an average porosity of 12%. The rock samples retain roughly 80% water as irreducible. This water is free to flow if the saturation in the pores is above the irreducible saturation. Water held in the pores of the rock fragments is not free to flow in the dump because the rocks have very low permeability. Attempts were made to measure permeabilities on the Chino rocks. Table 1.6 shows that the highest permeability found was 4.8 md to air and a water permeability of only 0.26 md was obtained. Clearly there is no flow through the rocks although they may have 10% porosity and be almost saturated with water.

Water permeability tests were run on each of the compacted samples. This was done by measuring the time required to pass a measured amount of water through the sample at a pressure differential of one atmosphere. The permeabilities ranged from 130 millidarcys to 800 millidarcys.

Although it has been stated earlier that the permeability is proportional to $1/P_c^2$, no relationship appeared to exist between capillary pressure and the measured water permeabilities. This may be due to plugging of one or both of the ends of the samples with fines during compaction or later during the capillary pressure measurements. A separate sample was made up and subjected to compaction pressures from 0 to 250 psi in 25 psi increments. The permeability was measured on the sample after each compaction. Figure 6.4 shows that although permeabilities are erratic at low compaction pressures, they decrease with increasing compaction and tend to establish a smooth curve relationship. Permeabilities range from 71 to 5 millidarcys. (Table 1.7)

Sample 3 was composed of particles between 1 inch and 48 mesh and is thus quite coarse. An irreducible water saturation of 23 percent is indicated from the capillary pressure curve, Figure 6.2. This material has zero entry pressure and actually drained to a water saturation of 73 percent after saturation and before being placed in the capillary pressure cell. Nevertheless, this coarse sample will retain appreciable water in the coarse capillaries between the particles of rock. This water will remain in the dump during rather long periods if the dump is allowed to stand idle. The dump cannot dry out rapidly by evaporation because of its great mass and the difficulty with which air

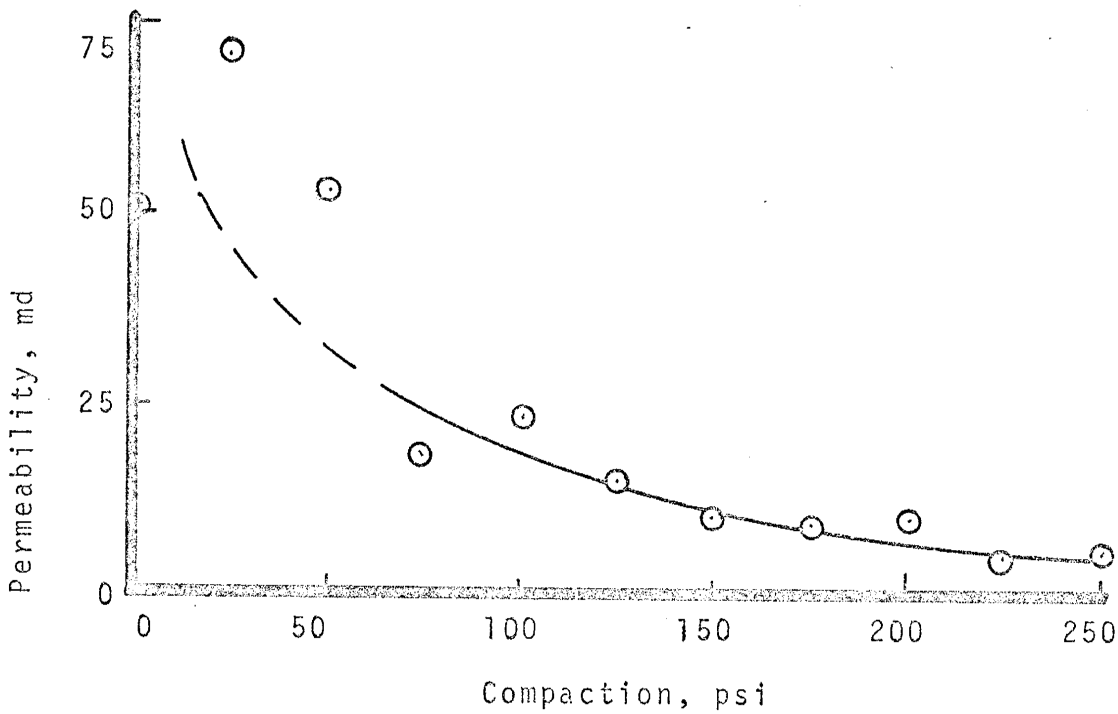

Figure 6.4 Compaction effect on sample permeability using a random sample containing fines

circulates through it. The low irreducible water saturation shows that there is appreciable pore volume to permit fluid flow (permeability of sample 3 was 796 md). Sample 4 is composed of very fine particles as can be seen in the histogram, Figure 4.4. Again the entry pressure for the aggregate is probably zero. This material, however, has a very high irreducible water saturation of about 88%. Therefore, fluid flow would be restricted through its very fine pores.

Sample 6 was closely sized material, i.e. minus 48 to plus 65 mesh. This material retains an irreducible water saturation of about 43 percent.

Going back to Figure 6.3, samples 10 and 11 yield essentially straight lines and may have zero entry pressure. Figure 6.5 is a plot of one of each type of capillary curve shown in Figure 6.3. Figure 6.6 shows the frequency of pore space distribution occupied by air versus saturation. We would like to represent this frequency as a function of the radius of the pores in the samples. This can be done for sample 9 if we remember that

$$r = \frac{2 \gamma \cos \theta}{P_c}$$

where γ = air-water interfacial tension, dynes/cm

θ = the contact angle

P_c = capillary pressure in dynes/cm^2

and r = capillary radius in cm.

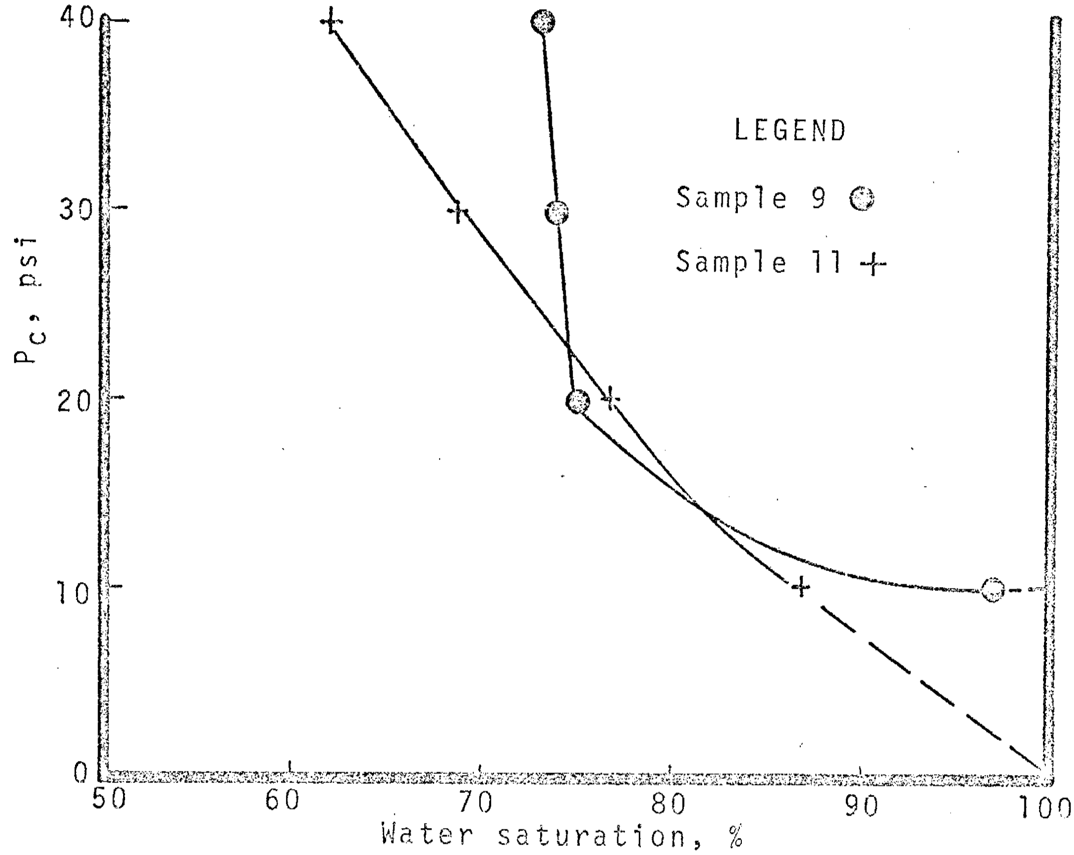

Figure 6.5 Capillary pressure curves on rock type found in Chino samples

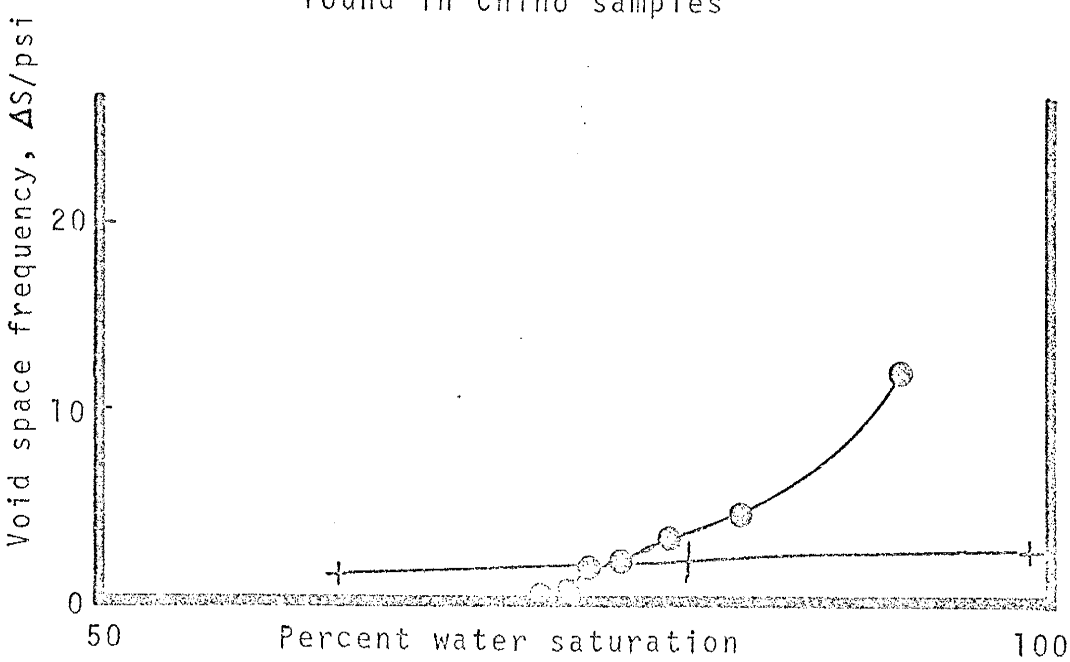

Figure 6.6 Void space frequency versus percent saturation in rock taken from samples

Since we have not made measurements of γ and θ in this study, let us assume γ = 70 dynes/cm and θ = 30°. An error in these values will shift the curve but the curve will remain qualitatively the same. Figure 6.7 shows the graph of frequency versus capillary radius. The radius, r_d, corresponding to the first pore displaced with air at the entry pressure, is 0.00035 cm. Note that air has not displaced much water from pores smaller than 0.00017 cm. Most of the water driven out of the rock was held in pores with radii between 0.00017 and 0.00035 cm. Note that there is only one mode or group of pores in this rock. Sample 11 in Figure 6.5 is essentially a straight line. Note the frequency versus saturation plot for this curve in Figure 6.6. It is also almost a stright line inclined very slightly to the left. This indicates a uniformly decreasing pore size distribution which is quite atypical of rock pores. The most likely explanation is that this represents a rock containing one or more minute fractures which overshadow the fine pores in the rock.

Figure 6.8 is the capillary curve for sample 1 and Figure 6.9 represents the void space frequency versus fluid saturation. Figure 6.10 is a plot of this pore space frequency versus the pore radii. Note that the radii of the pores of the aggregate vary from 0.0003 to 0.0018 cm. The radii of the pores of the rock are less than 0.0003 cm. Two pore size distributions are readily apparent in Figure 6.10 and account for the double capillary curve of sample 1.

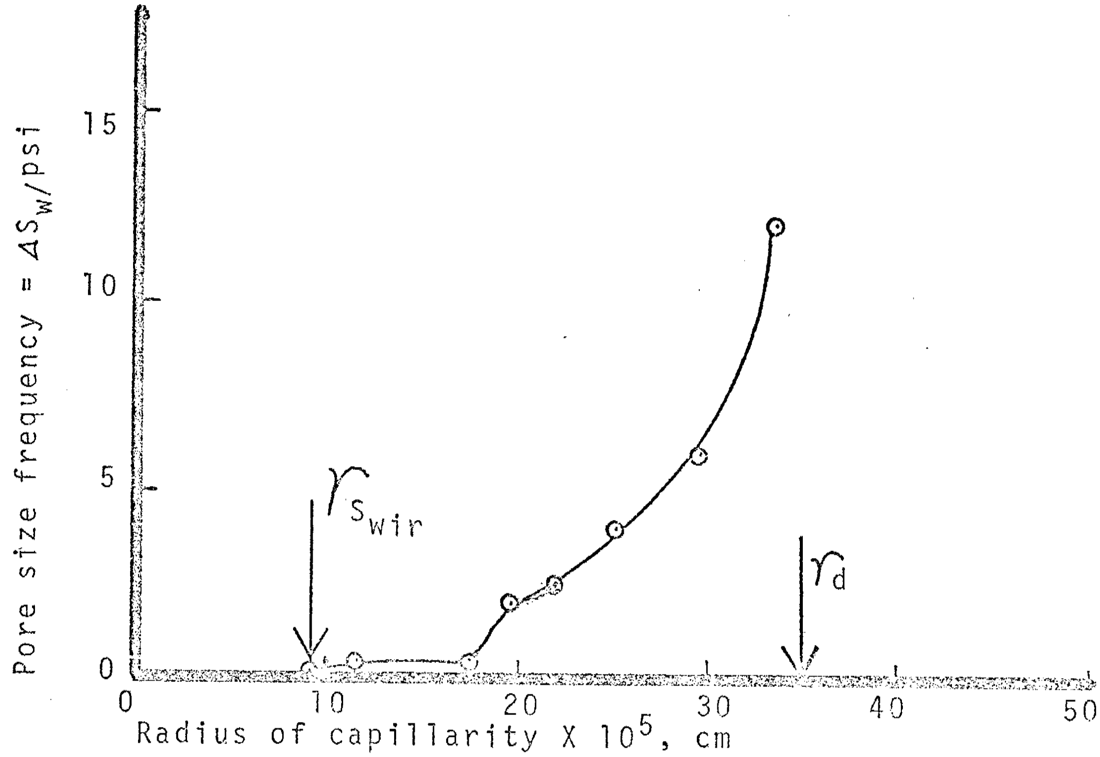

Figure 6.7 Void space frequency versus radius of capillaries

Note: 73% of the water is held in pores smaller than 0.000177 cm in diameter

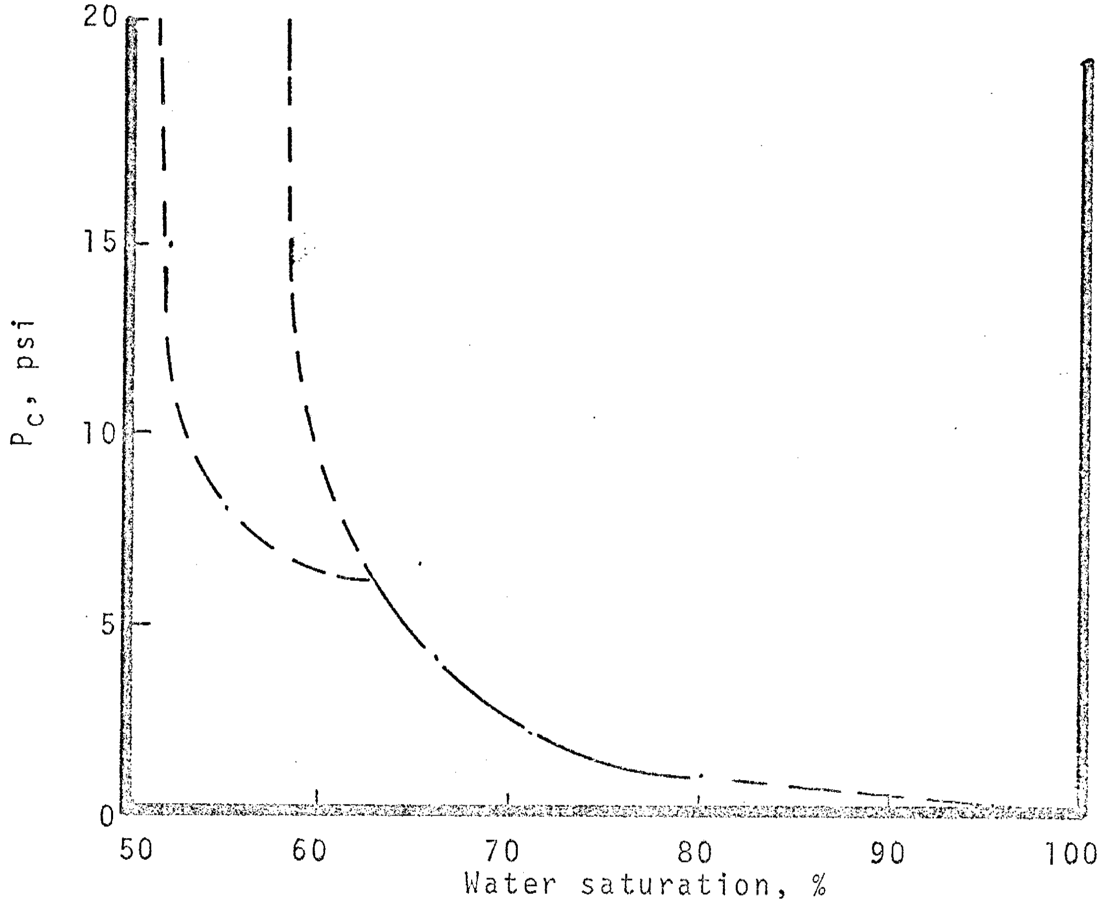

Figure 6.8 Capillary pressure curve for composite sample (sample 1)

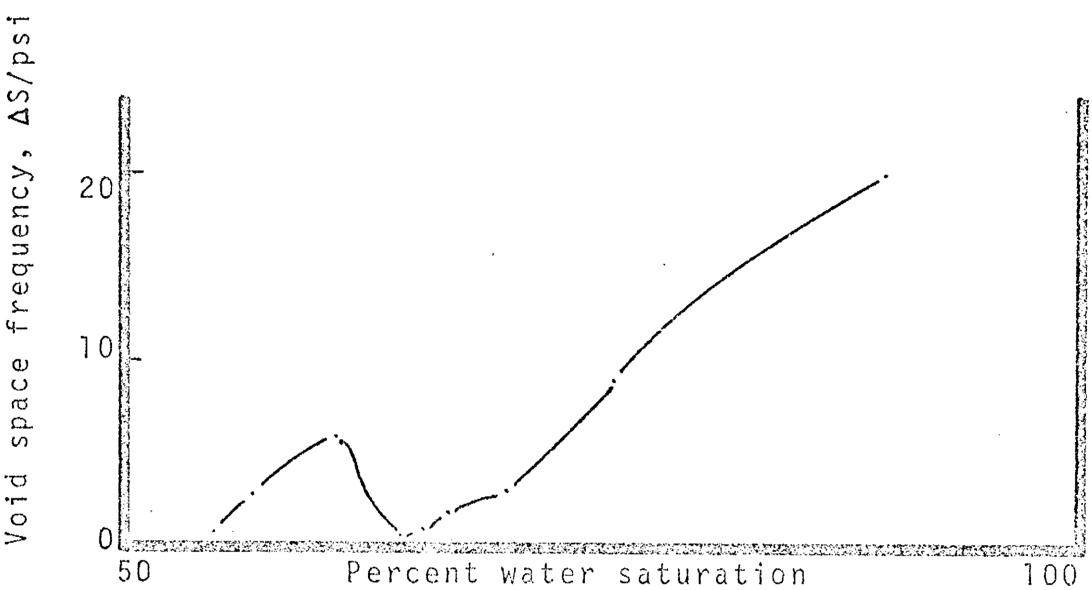

Figure 6.9 Void space frequency versus percent saturation in composite sample

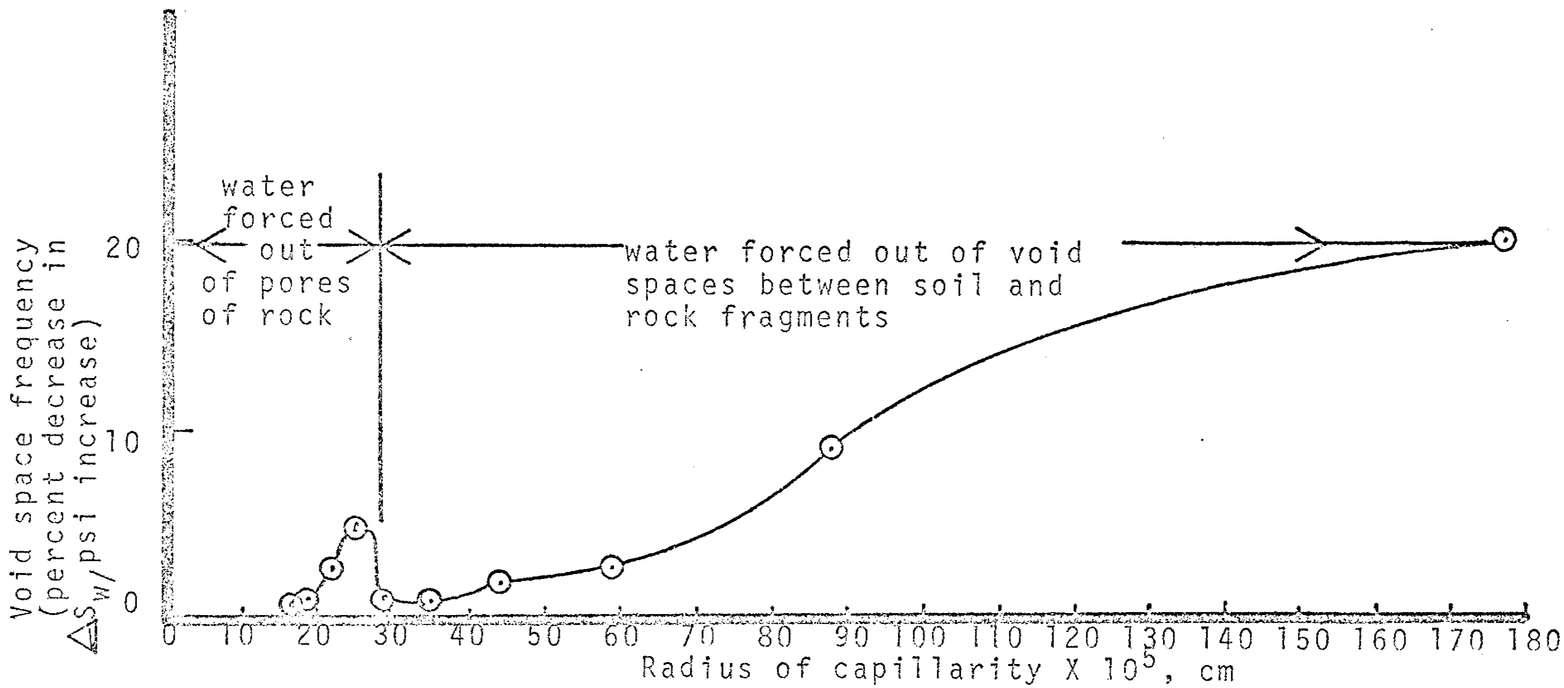

Figure 6.10 Void space frequency versus Radius of capillarity

The manner in which water is retained in a dump is of considerable importance. First, after the final leach cycle has been completed, the mineral values in the water retained in the dump are lost. Second, a high water saturation in the pores during a drying cycle may retard aeration by reducing the permeability of the dump to air. And third, if large masses of free water are dammed up in the dump by impermeable layers, the stability of the dump may be threatened. In addition to perched water tables (which probably can not last over long periods of time) water will be retained in porous media through which it has flowed at its irreducible saturation. In addition, a capillary rise of h_k will be maintained as long as there is a source of water at the base of the layer to replenish it. Even without a source of water, the capillary water would remain in the porous media over very long periods of time. The height to which water rises by capillarity is a function of the pore size distribution and this in turn for the aggregate is a function of the stratification or layering in the dump. It should be remembered that the rock is also a porous system and will retain its own capillary water to much greater heights than the coarse pores of the aggregate permit. Figures 6.11 and 6.12 are photographs taken at a trench in "J" dump at Kennecott's Chino mine. The stratification in a leach dump depends on the method of construction. Typically, trucks are used to haul the leach material to the edge of the dump and it is dumped over the side, coming to rest at

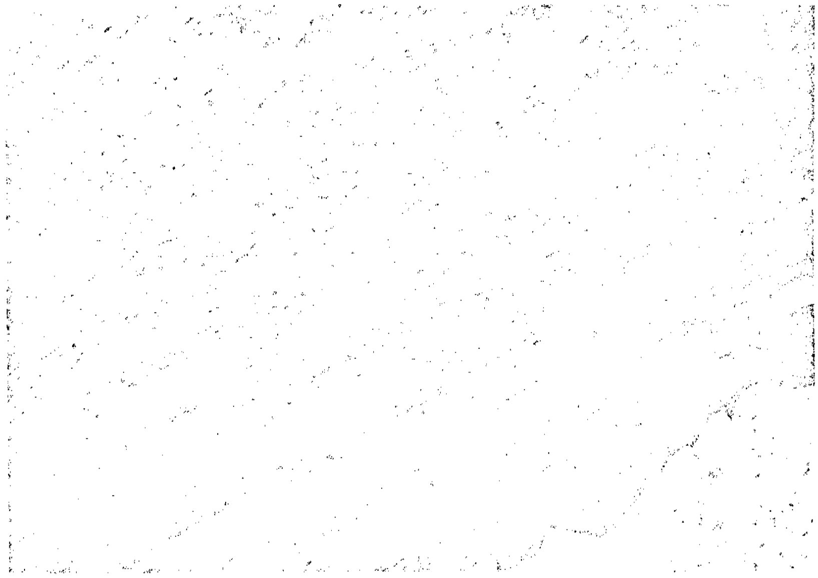

Figure 6.11 Photograph showing dump layering taken at "J" dump Kennecott's Chino Mine

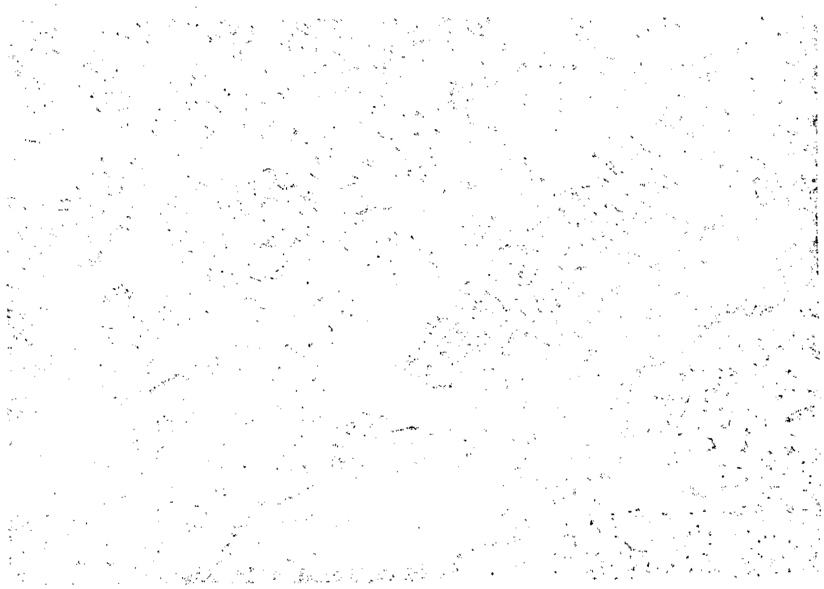

Figure 6.12 Photograph showing dump layering taken at "J" dump Kennecott's Chino Mine

its angle of repose. Coarse material tends to roll to the base of the dump with finer material near the top. Distinct layers of coarse and fine material are deposited. Haulage across the surface also crushes coarse material at the surface of each lift and although this is often ripped to loosen it and increase permeability, it still is composed of a large number of fines. Figure 6.13 depicts a much simplified and idealized section through a lift of a dump showing alternating layers of coarse and fine material. A perched water table could not exist in the center of the lift although it might exist at its base where the old haulage surface might act as an impermeable barrier. If the pore size distribution is as shown in Figure 6.13, a distribution of water saturation would result from capillary forces as shown in Figure 6.14. Note that there is an apparent perched water table between 19 to 35 feet. This zone of high water saturation would appear on the logs run to detect perched water tables. The existance of a perched water table could be verified or refuted by coring the dump and running capillary pressure curves on the cores. If the water saturation distribution from the capillary pressure data matched the water saturation distribution calculated from the log, the water held is clearly capillary water and not a perched water table. On the other hand, if a well is drilled into the perched water table and the water is drained off, then the water is clearly not capillary water.

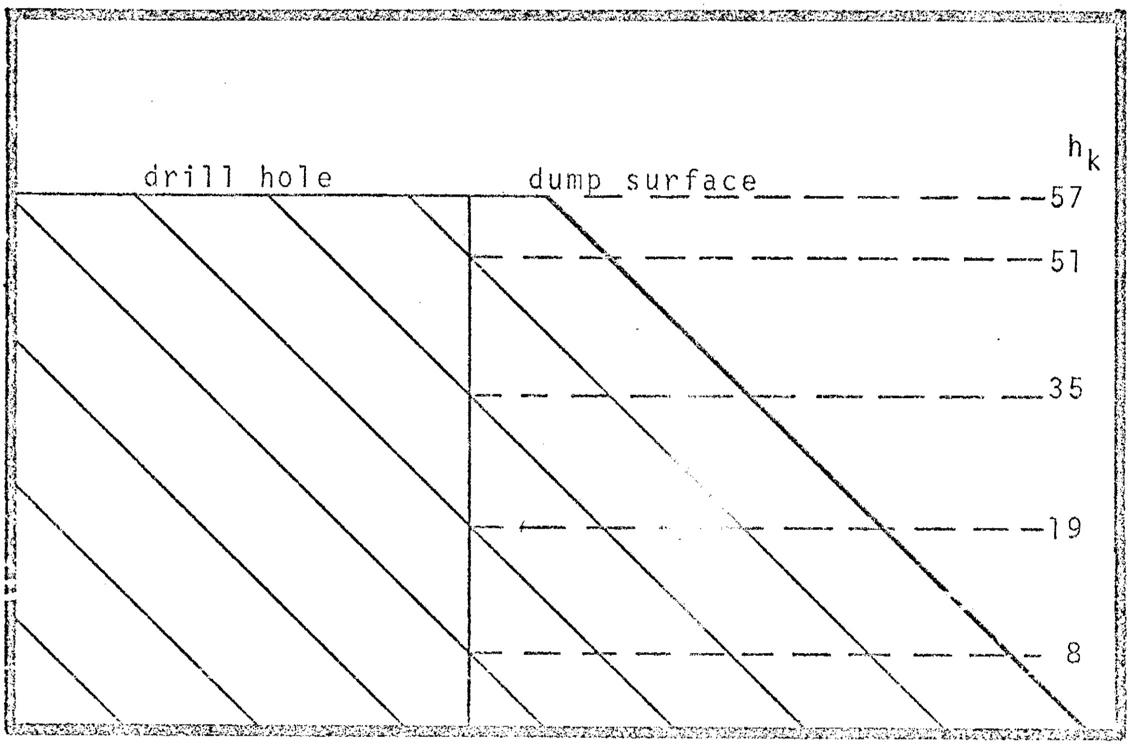

Figure 6.13 Idealized dump cross section showing layering

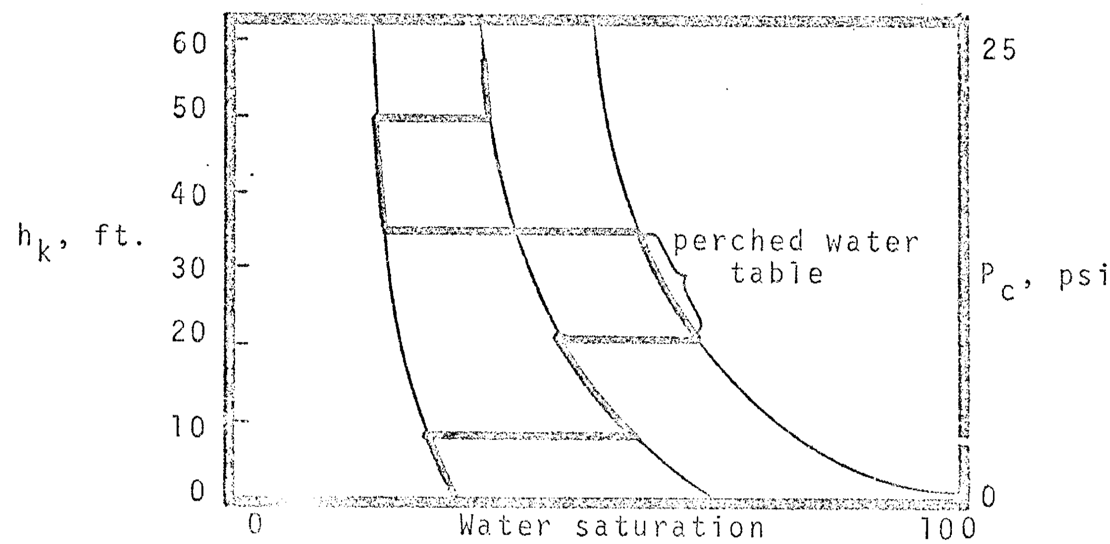

Figure 6.14 Hypothetical capillary curves showing a perched water table caused by capillary action

Logs can be run during drainage of the zone to detect a fluid draw down close to the wellbore.

(Section 7)

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Large amounts of water can be retained in dumps due to capillary suction.
2. Two distinct and separate capillary pressure systems exist in the Chino dump material tested. One system results from the rocks having intercrystalline porosity which gives rise to capillary phenomena within the rock mass. The entry pressure of Chino mine rocks tested in this study was about 5 psi which corresponds to a capillary rise of about 11.5 feet. If fractured, the rocks exhibit a zero entry pressure due to displacement of fluid from the fracture. The second capillary system is attributed to the pore space between the rock fragments. The aggregate has a zero entry pressure and a sample composed of coarse material may be partially desaturated at zero capillary pressure. Most of the water displaced from a core of dump aggregate comes from the coarse capillary system. The rock capillary system contains much less water and retains about 80 percent of it as irreducible water. The presence of two separate and distinct pore size distributions in a sample can produce recognizable

double capillary curves as illustrated by sample 1 in Figure 6.1.

3. The permeability of the aggregate decreases with increasing degree of compaction. Dry fine grained material naturally has alow permeability to air, but when the fine grained material is wet it will have an even lower permeability to air. Note sample 4 which has an irreducible water saturation of almost 88 percent. Therefore, since 2% desaturation is in the rock where no flow takes place, air can flow through only 10 percent of the pore space of this sample. By definition irreducible water is that water which cannot be displaced from the pores by fluid flow.

4. The Chino mine rocks have very low permeabilities and no fluids flow through their pores in the dumps. The highest air permeability measured was 4.8 md and the highest water permeability measured was 0.26 md. Most samples had no detectable permeability. The pores of the rock are interconnected as demonstrated by the capillary pressure data and also by the ready imbibition of water. This indicates that minerals within the rock can be leached only by diffusion processes.

5. High degrees of compaction can alter the capillary curves by fracturing and breaking down the larger particles. This produces smaller particles but apparently not many more fines. This can be seen by comparing sample 2 which was compacted under 100 psi with sample 5 which was compacted to 400 psi. Note the higher water retention at low capillary pressures in sample 5. (See Figures 6.1 and 6.2.)

6. It is possible for a zone of high capillarity to appear as a perched water table. Field and laboratory tests can be used to determine whether it is a perched water table or a zone of high capillary water saturation.

APPENDIX

Table 1.1 Porosities derived from various packing arrangements for uniform spheres

Grain stacking arrangement	ϕ
Simple Cubic	48
Body Centered Cubic	32
Face Centered Cubic or Cubic Close-Packed	26
Rhombohedrol or Hexagonal Close-Packed	26
Tetrahedral Close-Packed	66
Tetrahedral	87.6

Table 1.2 Porosities of typical Chino rocks

Thin Chalcocite or Pyrite on Altered Sediments

Sample #	φ
C-14	12.1
C-15	9.1
C-16	6.9
C-17	4.5
$\bar{\phi}$ =	8.2

Quartz Monzonite Porphry

Sample #	φ
C-11	31.4
C-12	10.0
C-13	8.7
C-19	9.5
C-20	18.9
C-22	17.0
C-23	17.1
C-24	18.8
C-25	8.5
$\bar{\phi}$ =	15.5

Altered Quartz Monzonite with Chalcocite

Sample #	φ
C-26	9.8
C-27	12.6
C-28	10.9
C-29	13.5
C-30	10.7
$\bar{\phi}$ =	11.5

Altered Quartz Monzonite

Sample #	φ
C-31	11.3
C-32	11.4
C-33	7.9
C-34	10.1
C-35	10.1
C-36	11.4
C-37	7.2
C-38	12.7
$\bar{\phi}$ =	10.3

Rock Sample Used

Sample 7	6.3
Sample 8	14.5
Sample 9	14.8
Sample 10	14.1
Sample 11	13.1
$\bar{\phi}$ =	12.6

Table 1.3 Porosity of soils similar to samples used[1]

Soil	ϕ
Gravel (with particle diameter from 2 to 20 mm)	30-40
Sands (with particle diameter from 0.05 to 2 mm)	30-45
Clayey Soil	40-55

Table 1.4 Porosity and bulk volume of samples used

	ϕ	B.V.	cc water
Sample 1	29	340	98.2
Sample 2	41	302	104.74
Sample 3	42	419	176.1
Sample 5	36	348	122.3
Sample 6	31	218	120

Table 1.5 h_k for soils similar to samples used[1]

Soil	h_k (cm)
Clay	400-200
Sandy Soil	150-100
Sandy Upper Soil	100-50

Table 1.6 Permeability values on samples used

Specimen	k_w, md	k_a, md
C-12	0.265	4.80
Sample 1	145	
Sample 2	128	
Sample 3	796*	
Sample 4	**	
Sample 5	139	
Sample 6	***	

* contained no fines
** plugged during permeability run
*** plugged during run

Table 1.7 Permeability versus compaction on random sample containing fines

Compaction psi	k, md
0	52
25	71
50	53
75	18
100	23
125	16
150	11
175	10
200	10
225	5
250	7

Table 1.8 Capillary pressure data from samples used in study

Sample	1		2		3		4		5		6	
	P_c	S_w	P_c	S_w	P_c	S_w	P_c	S_w	P_c	S_w	P_c	S_w
	1	80	1	50	1	30	1	96	1	60		
	2	71	2	38	2	29	2	94	2	58		
	4	66	4	35	4	27	4	89	4	49		
	8	55	8	32	8	26	8	88	8	34		
	15	52	15	31	15	24	15	88	15	33		
	25	52	20	31	20	23	21	88	23	32	20	43

Table 1.9 Capillary pressure data from rocks of types used in preparation of samples

Sample	7		8		9		10		11	
	P_c	S_w	P_c	S_w	P_c	S_w	P_c	S_w	P_c	S_w
	5	98	5	98	5	97	5	85	5	87
	10	85	10	83	10	75	10	78	10	77
	15	79	15	77	15	74	15	71	15	69
	20	76	20	75	20	73	20	62	20	62

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