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LABORATORY SOIL PHYSICAL PROPERTIES
DETERMINATION FOR HYDRGEOLOGISTS

By

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With the increase in environmental awareness and emergence of strong trends towards combining unsaturated and saturated flow and solute transport processes, numerical simulation approaches in Hydrogeology were significantly developed. However, a pronounced gap also emerged in experimental Hydrogeology. Very few universities include in their curricula field techniques in Hydrogeology, and even fewer incorporate laboratory techniques including unsaturated flow processes. As a result, no well-established relatively simple techniques are readily available for determining hydraulic conductivities of tight formations, or accurate desaturation curves, especially in the less than one bar capillary pressure ranges. It is expected that this manual on determination of selected porous media physical properties will fill this gap. Some experimental procedures were adapted or designed in the Kansas Geological Survey porous media laboratory, such as the tight formation permeability determinations and several aspects of low-tension desaturation experiments, among others, while some other procedures, such as textural analyses and particle density determinations, among others, have been adopted from well known references. It is hoped that users of this manual will provide us with feedback so that later editions of this manual will be further improved.

Laboratory Soil Physical Properties Determination

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2. Textural Analysis (Hydrometer Method)

Apparatus/Equipment

Sedimentation cyliner (1000 ml), hydrometer (ASTM 152 H model preferably) mortar & pestle, soil dispersion device (malt mixer), balance, jar bath, thermometer. (Figure 1.1)

Chemicals: Sodium hexa-metaphosphate (NaPO_3), sodium carbonate, deionized distilled water, amyl alcohol.

Procedure:

- (1) Assume you already have a soil sample received from the field and that you have oven-dried it.
- (2) Take approximately 60-70 gms of sample, break it down with mortar and pestle.

NOTE:

If the sample contains organic matter, treat it with 30% hydrogen peroxide (H_2O_2) before you start the experiment. Mix the sample with H_2O_2 and leave it sit overnight. Evaporate the soil- H_2O_2 mixture on a hot plate while stirring the sample, and then oven dry it.

- (3) Pass the oven-dried and broken sample through a #10 sieve (2mm or 0.079 inch openings) and weigh 50 gms of it.
- (4) Mix 50 gms of this sample with 125 ml of Calgon solution made up of 35.7 gm of Sodium Hexametaphosphate + 7.94 gm of Sodium Carbonate and dilute with deionized distilled water to 1000 ml solution.

- (5) Leave the soil-calgon solution mixture sit overnight. Clay soils need more time (about 16 hrs), while sandy soils much less (can leave for only one hour).
- (6) Transfer the mixture to a malt-mixture cup of an electric mixer and add deionized water until the cup is 2/3 full.
- (7) Mix for 1-2 minutes if soaked overnight, otherwise increase this time to 3-5 minutes if the mixture was soaked for a few hours.
- (8) Transfer the content of the malt-mixture cup into a 1000 ml sedimentation cylinder, being careful not to spill any material.
- (9) Add deionized water to the sedimentation cylinder to fill it up to the 1000 ml mark.
- (10) Keep ready a hydrometer (ASTM 152 H) for taking readings (Hydrometer ASTM 151 H is also available in the laboratory but do not use that).
- (11) Take a #12 rubber stopper and cap the sedimentation cylinder tightly.
- (12) Agitate the sedimentation cylinder carefully for about 1 minute (30 ups and downs).
- (13) Set the cylinder down, take out the rubber stopper immediately and insert the hydrometer.
- (14) Take readings at elapsed times of 40 seconds, 1,2,3, and 4 minutes using a stop watch. Then, take the hydrometer out of the measuring cylinder and insert it in a similar-size "working" cylinder filled with distilled water while giving it a twist.

NOTE:

- (1) You may face some difficulty while taking readings because of the presence of foam at the mixture surface in the cylinder. Add a drop

or two of Amyl Alcohol to dissolve the foam.

- (2) If you have any doubt about the first 4 or 5 readings, repeat steps (10) to (14) above.
- (15) Transfer the sedimentation cylinder to a constant temperature water bath and take readings at elapsed times of 8, 15, 30, 60 and 120 minutes. Insert the hydrometer carefully and slowly for each reading, and take it out right after the reading. Store it in the "working" cylinder with distilled water until the next reading. Note down the temperature at each reading.
- (16) Make calculations as shown in the sample calculations below.

Sample Calculations

For 40 second reading only:

From line 1 of Table 1.1 (data sheet)

$$\begin{aligned} R_c &= R_a - \text{zero correction} + C_T \quad (C_T \text{ from Table 1.2}) \\ &= 51 - 4 + 1.65 = 48.65 \end{aligned}$$

$$\begin{aligned} \text{Percent finer} &= \frac{R_c a}{W_s} \times 100 \\ &= \frac{48.65 \times 1}{50} \times 100 \quad (\text{a from data sheet}) \\ &= 97.30 \% \end{aligned}$$

Hydrometer reading corrected for meniscus only = 51 + 1 = 52

$L = 7.8$ (from Table 1.3 at $R = 52$)

$$v = \frac{L}{T} = \frac{7.8}{0.67} = 11.70$$

$K = 0.0127$ (from Table 1.4 for $G_s = 2.65$ at 26°C)

$$D = K \sqrt{\left(\frac{L}{T}\right)} = 0.0127 \sqrt{11.70} = 0.0434 \text{ mm}$$

Abbreviations:

- R_a = actual hydrometer reading
- R_c = corrected hydrometer reading
- C_T = temperature correction (Table 1.2)
- a = correction factor for meniscus
- W_s = weight of soil
- L = effective depth (Table 1.3)
- t = elapsed time
- v = velocity of falling soil particles
- K = constant for suspension (Table 1.4)
- D = diameter of the soil particles

3. Soil Density Determination

3a. Bulk density determination using the core method

A cylindrical metal sampler is pressed or driven into the soil to the desired depth and is carefully removed to preserve a known volume of sample as it existed in situ. The sample is oven-dried to 105°C and weighed. Bulk

density is the oven-dried mass divided by the field volume of the sample.

3b. Specific Gravity or Particle Density

This is the weight of soil solids compared to the weight of an equal volume of water displaced, since one cubic centimeter of water weighs approximately 1 gram.

Apparatus

Pycnometer (specific gravity flask), balance, distilled water

Procedure

- (1) Weigh an acid-washed air-dried pycnometer and record the weight.
- (2) Put about 10 grams of soil in the pycnometer, weigh on a precision balance, and record the weight.
- (3) Add about 10 ml of water to the soil in the specific gravity flask and put into a desiccator and remove the entrapped air.
- (4) Keep the vacuum sufficiently low so that, when the air is being forced out and it starts bubbling, you do not lose the soil in the flask.
- (5) When the air has been replaced, fill the pycnometer with water and cork it with the thermometer stopper attached to it.
- (6) When the soil moisture reaches a constant temperature and the flask and capillary are full, dry the outside of the flask and weigh. Record this weight.
- (7) Remove soil and water from the flask and clean it.
- (8) Refill the flask with fresh water and wipe it from outside. Then, when the temperature has reached the same point as in the previous weighing, weigh the flask with water and record the weight.

You then have the following weights:-

- 1) Weight of air-dried pycnometer, W_a

- 2) Weight of pycnometer and air-dry soil, W_s
- 3) Weight of pycnometer, soil and water, W_{sw}
- 4) Weight of pycnometer and water at temperature observed, W_w .

Sample Calculations

$$\rho_s = \frac{\rho_w (W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)}$$

where: ρ_s = Particle density

ρ_w = Density of water in grams per cubic centimeter at temperature observed

W_s = Weight of pycnometer plus soil sample = 43.4952 gm

W_a = Weight of pycnometer filled with air = 33.5101 gm

W_{sw} = Weight of pycnometer filled with soil and water = 59.4698 gm at 24.1°C.

W_w = Weight of pycnometer filled with water at temperature observed = *(Volume of pycnometer) X (water density at observed temperature -- in this case at 24.1°C).

$$= *25.303 \text{ cm}^3 \times 0.997535 \text{ gm/cm}^3$$

$$= 25.3005 \text{ gm}$$

$$\text{then } \rho_s = \frac{0.9975 (43.4952 - 33.5101)}{(43.4952 - 33.5101) - (59.4698 - 52.6211)} = 3.1757 \text{ gm/cm}^3$$

Determining the Volume of a Pycnometer

- 1) Weigh an acid-washed, air-dry pycnometer and record the weight.
- 2) Then fill the pycnometer with boiled (deaerated) distilled water and put stopper in place.

- 3) Place pycnometer in ice bath to lower the temperature to approximately 18°C. The liquid will contract, leaving part of the capillary tube empty. Fill this tube almost to the top.
- 4) Remove from ice bath and dry outside of pycnometer, place pycnometer on balance and watch liquid level rise in column. When tube is full, read temperature and weigh.
- 5) Then remove some of the liquid from the capillary tube again (about 1/16" X 1/8"); leave pycnometer on balance. When liquid is again at the top of the capillary, read temperature and weigh.
- 6) Repeat this procedure over a range of increasing temperatures (approx. 1°C. per reading).

$$\frac{\text{Wt. pycnometer + water} - \text{wt. pycnometer}}{\text{Density of water at } \underline{\quad}^{\circ} \text{C.}} = \text{Volume of pycnometer}$$

3. Some Soil-Preparation Procedures

1a. Compaction of Soil Samples to the Required Density

Apparatus/Equipment:

Metal rings, metal or solid wood cyliner, plastic cap for metal ring, hydraulic press, mortar & pestle, #10 sieve.

Sometimes we are unable to retain the original bulk density of soil samples while taking samples or transporting them. In other words, we disturb them. So we compact them in the laboratory to bring them back to their original bulk density. The orientation of soil particles changes, but we have

no control over it. The following is the procedure for compaction of disturbed samples.

Procedure

- (1) Assume you already know the natural or required bulk density of the sample.
- (2) Take the sample and break it using mortar and pestle.
- (3) Pass the sample through #10 sieve (2 mm or 0.079 inches opening).
- (4) Determine the required weight of sample to have its required bulk density ρ_b
Wt. of sample (W_s) = ρ_b X vol. of brass ring
$$= \rho_b \times \frac{\pi}{4} D^2 h$$
where ρ_b is already known and D is the inside diameter of the metal ring.
- (5) Weigh the sieved sample W_s , and divide it into 5-8 equal parts by weight (assume 5 here).
- (6) Get a metal ring and place a plastic cap on one of its ends.
- (7) Get a 4-5" round solid wood or metal cylinder (rod like) with diameter slightly less than the inside diameter of the metal ring.
- (8) Mark the round wooden piece as shown in Figure 3.1.
- (9) Bring the sample, the metal ring with its cap, an extra metal ring of the same specifications, and the solid wood or metal cylinder to the laboratory hydraulic press (available in the Ceramics Lab, KGS).
- (10) Pour one of the 5 parts of the weighed sample into the metal ring with the plastic cap at the bottom.
- (11) Place the ring on the plate (part #2) of the hydraulic press (as shown

- in Figure 3.2).
- (12) Insert the solid wood or metal cylinder into the ring (Fig. 3.2).
 - (13) Make sure that the hydraulic press valve (part #31, Fig. 3.2) is closed (turn clockwise to close).
 - (14) Turn handle (part #17, Fig. 3.2) of the hydraulic press up and down. It will move the plate (#2), loaded with the sample, upward. Keep operating on this handle until the top of the wooden piece touches the head (part #3) of the hydraulic press. This process can be speeded up with an automatic push button mounted near the gauge (#19).
 - (15) When the top of the round wooden or metal cylinder is near the head (#3), keep turning the handle (#17) up and down very slowly until the top edge of the metal ring aligns the mark A1 on the solid wood cylinder. This means that we have compacted the 1/5th quantity of the sample in 1/5th part of the metal ring.
 - (16) Turn the valve (#31) counterclockwise to release the pressure. It will bring the plate (#2) down. Take the ring with the solid wood cylinder out and close the valve (#31).
 - (17) Take the solid wood or metal cylinder out of the ring and pour the 2nd 1/5th of the sample into the ring.
 - (18) Repeat steps (14) and (15) to compress the soil up to the A2 mark of the solid wood cylinder.
 - (19) Repeat the same procedure for the A3 and A4 cylinder marks.
 - (20) For the last 1/5th part of the soil you may have difficulty because you do not have a sufficient space in the ring for it. Then get another metal ring of the same size, align it on the top edge of the metal ring, partially filled with the soil, and then pour this last 1/5th part of the soil sample.

- (21) Repeat steps (14) and (15) until the top edge of the top ring touches the mark B5 on the wooden or metal cylinder. This will fill the bottom ring up to the top edge with total soil we weighed to bring the sample to the required density. At the end remove the plastic cap from the ring.

1b. Saturation of Soil Samples

Apparatus/Equipment:

Tempe cell, desiccator, vacuum pump.

Procedure

Assume you have the soil sample ready in the tempe cell:

- (1) Fill the desiccator with water above the perforated porcelain plate.
- (2) Place the tempe cell (containing the sample) on the perforated porcelain plate, S_0 , so that it seats firmly on it. There is only one big hole in the porcelain plate, which is big enough to seat the tempe cell on it. For placing more than one tempe cell on the plate, use specially prepared acrylic rings for this purpose.

NOTE: Wrap the cell with a strong nylon tape around the two parting plates of the tempe cell to prevent any water intrusion into the outside grooves of the cell during the saturation process.

- (3) Add more water to the desiccator so that at least one inch from the bottom of the tempe cell is immersed in water.
- (4) Apply a layer of sealant grease on desiccator's rim for a good seal (it is not necessary for each run; one application remains for a long time).
- (5) Repeat steps (1) through (4) for other desiccators if you have more samples and want to saturate them at the same time (One desiccator accommodates 3 tempe cells at a time).

- (6) Check the oil level in the vacuum pump. Add oil if it is below the required level. Drain oil if it is above the level, because a bit of moisture may have intruded during the previous run. Add new oil (FISHER brand Mechanical Pump Fluid).
- (7) Close stopcock S_1 . Open stopcock S_2 for Desiccator (1) and S_3 for Desiccator (2), whichever you are going to use, or both, if using both.
- (8) Turn on the vacuum pump switch after closing all the valves.
- (9) Open stopcock S_1 very slowly while the pump is running. The process of evacuating air from the desiccator will start.
- (10) Regulate the vacuum pressure through the vacuum gauge/regulator by turning the knurled nut. Clockwise turn will increase the pressure and counterclockwise turn will decrease the pressure.

Figure 3.3: Arrangement of desicator system for saturating soil samples.

- (1) Vacuum pump
 - (2) Vacuum gauge/regulator
 - (3) Flask containing CaSO_4 as moisture absorbant
 - (4) Desicator #1
 - (5) Desicator #2
 - (6) Knurllled unit
 - (7) Ceramic plate with holes, S_0
- S_1, S_2, S_3 = stop cocks

- (11) Watch the desiccator for a few minutes. If you see bubbles in the water in the desiccator, the system is working. If not, leakage of air is suspected somewhere in the tubing joints or in the desiccator's rim. Detect the leakage with air leak detector soap solution and seal it. Maintain a vacuum pressure of 500 mmHg for a steady saturation, but this can be increased up to 700 mmHg for a quicker run.
- (12) Let the system run for 2-3 hours for complete saturation or until you see a stream of water coming out from the upper opening of the tempe cell.
- (13) After you are sure that the sample is fully saturated, shut down the power supply for vacuum pump, close stopcock S_1 , and turn the knurled nut of the vacuum gauge counterclockwise very slowly. The pointer on the gauge will come back to zero.
- (14) Open the air inlet valve of the desiccator very slowly to equilibrate the inside and outside pressure of the desiccator and slide the lid.
- (15) Remove the tempe cell and put a rubber stopper on one of the openings (brass-made opening preferably) to avoid any drainage of water or evaporation from the soil sample before you use it for further experiments. Remove the tape from the tempe cell and wipe any droplets from the outside surface of the cell. Blot the water from the upper brass opening of the tempe cell with a thin swab of wiping paper very carefully, and weigh the cell quickly.

Precautions

- (1) Oil level should be checked frequently to prevent the pump from over heating.
- (2) Pump oil should be changed occasionally or whenever you notice it to be

- a little milky, or if it is above the oil level indicator.
- (3) CaSO_4 grains are available in blue color. These grains turn to pink when they lose their moisture absorbing characteristics. Replace CaSO_4 grains in the flask when they are pink.
 - (4) Remove or slide the desiccator lid very slowly.

Note:

The Vacuum gauge/regulator has another outlet, which can be used with some other desiccators when needed.

4. Desaturation (water-characteristic) experiments

a) Sample preparation/Apparatus

- (1) Assume you received a soil sample in a metal ring of known weight (W_r) that fits into a Tempe Pressure Cell. The weight of the sampled wet soil (W_{ws}) including the weight of the ring (W_r) should be taken right after field sampling.
- (2) Put the sample with the metal ring in an oven at 105°C for approximately 24 hours. After 24 hours take the sample out of the oven and let it cool for a few minutes, and then weigh it. Record this weight as weight of dry soil (W_{ds}) + weight of the ring (W_r).
- (3) Take one Tempe Pressure Cell, open it, and wipe out any dust particles inside and outside of the O-rings. Weigh all parts of the Tempe Cell including porous plate but without the ring (because the ring to be used in this case is around the sample) and record it as W_{DTC} .
- (4) Take out the porous plate from the Tempe Cell and saturate it in a vacuum desiccator for about 2 hours. Before the porous plate is taken out from the desiccator get a paper towel, fold it, wet it and squeeze

it slightly between your hands. Take out the porous plate and wipe it with the wet paper towel so that you do not see any shining water surface on the porous plate.

- (5) Place back the saturated porous plate in the tempe cell carefully and weigh it quickly. Record this weight as W_{sTC} .
- (6) Put the sample with the ring in the Tempe Cell with the saturated porous plate. Use a soft wire screen on one end of the sample (consider this piece of wire screen as a part of tempe cell while weighing). Tighten all the screws of the tempe cell tight to prevent any kind of air leakage into the sample. Wrap 2 or 3 turns of strong nylon tape around the 2 parting plates of the Tempe Cell to prevent any water intrusion into the outside grooves of the tempe cell during the saturation process that follows.

a) Saturation of Sample

Follow the saturation procedure outlined under soil preparation procedure.

- (1) Place the tempe cell containing the soil sample in a vacuum desiccator as shown in Fig. 3.3, such that the side of the tempe cell with the outflow end (plastic) is downward.
- (2) Fill the desiccator with water up to about one inch above the tempe cell wall.
- (3) Turn on the vacuum pump after closing all the valves. Open the valves slowly while the pump is running.
- (4) Run the vacuum pump for about 3 hours to saturate the sample completely. More clayey soils may take more time to saturate. Maintain a vacuum pressure of 500 mmHg for a steady saturation, but this can be increased up to 700 mmHg for a quicker run. A continuous stream of water will be coming out of the upper opening of the tempe

cell when the sample is fully saturated.

- (5) Take the tempe cell out of the desiccator, put a rubber stopper on one end, remove the tape and wipe any droplets from the outside surface of the tempe cell. Blot the water from the upper brass opening of the tempe cell with a thin swab of wiping paper very carefully. Weigh the tempe cell quickly with the rubber stopper of known weight and record this weight as $W_{SS+TC+RS}$ and then subtract the weight of rubber stopper to obtain W_{SS+TC} .
- (6) Calculate the net amount of water in the sample. This is a quantity of water at 100% saturation.

c) Low-suction desaturation (hanging column method) (Fig. 4.1)

- (1) Hang a burette with a stand at low elevation. Attach about 8 feet of plastic tubing to the burette outlet. Fill the burette about 1/3 with water. Let the water flow through the plastic tubing by opening the stop cock of the burette. When all the plastic tubing is filled with water, close the stop cock.
- (2) Connect the other end of the plastic tubing to the lower outlet opening of the tempe cell with the saturated sample in it and a rubber stopper on the upper (inlet) end of the tempe cell (to reduce evaporation losses) being careful that no air bubble is trapped at the end of the tubing.
- (3) Hang the tempe cell on a stand about 10 cm above the water level in the burette. The tempe cell stand should be at least 8 feet high above the floor. Note down the water level reading in the burette.
- (4) Remove the rubber stopper and open the stop cock of the burette. Water will start draining from the sample and you will notice water rising very slowly in the burette.

- (5) Let the water drain from the sample until it achieves equilibrium. Equilibrium is attained when there is no change in the water level in the burette with time. Allow about 8-24 hours to equilibrate. At the point of equilibrium, note down the water level reading in the burette, and the elevation difference between the water level in the burette and the top of the sample. This elevation difference is the applied capillary pressure in terms of centimeters of water.
- (6) Put the rubber stopper on the tempe cell and increase its elevation by 10 cm. Remove the rubber stopper and let it equilibrate.
- (7) Repeat step #5 until the sample's height reaches to the maximum available height of the stand.
- (8) Put a rubber stopper on one end, remove the tempe cell from the stand, and weigh it immediately. Record this weight as $W_{TC+RSS1}$. Calculate the amount of water left in the sample and record it as W_{RS} (see sample calculation for this).
- (9) Calculate the accumulated water collected during the desaturation process, add this amount to W_{RS} , and compare it to the amount of water in the soil sample when it was fully saturated (W_S) (assume 1 ml = 1 gm of water). This will determine if you lost any water from the sample through any leakage or evaporation (see precautions how to reduce evaporation).
- (10) Calculate saturations, S , of the soil sample at all pressure heads, P_C , taken during this process and plot these data points as a P_C vs S relationship on a semi-log graph paper.

d) High Pressure Desaturation

- (1) Set up the apparatus as shown in Figure 4.2. It consists of a 5-bar

pressure vessel, burette, pressure gauge and a compressed air supply source. We have different options to start with high pressure desaturation.

- (2a) (i) If you want to continue the same sample you have from step #8 of the low-suction pressure process, (in order to compile the P_C vs S curve for higher pressure ranges,) convert the last (maximum) applied in the low-suction desaturation procedure pressure head in terms of bars.
- (ii) Place the tempe cell with the sample in it on an especially designed acrylic plate stand in the pressure vessel.
- (iii) Fill a burette (having a double stop cock which facilitates the drainage of the burette when it is about to overflow) with water and connect the burette nozzle to one of the four outlets of the pressure cell (while the other three outlets are closed air tight) through a plastic tubing (Fig. 3).
- (iv) Fill the plastic tubing up to the end by opening the stop cock of the burette to remove any air bubble in the water stream from the tempe cell to the burette. Close the stop cock of the burette.
- (v) Connect the other end of the plastic tubing to the lower end of the tempe cell in the pressure vessel in such a way that you do not introduce any air bubble to the water stream from the tempe cell to the burette.
- (vi) Remove the rubber stopper from the tempe cell. Put the lid on the pressure vessel and tighten the nuts and bolts carefully to make the pressure vessel air tight. Take the burette's water level initial reading.

- (vii) Follow the procedure of operating the pressure system (described separately below) and apply the same pressure calculated in step (2a(i)). Open the stop cock of the burette. Watch any increase in the water level of the burette and wait for a couple of hours for equilibration.
- (viii) Theoretically there should be no increase in water level of the burette, because the soil is subjected to the same pressure it had during the last step of the low-pressure desaturation process. However, the pressure gauge divisions in the soil moisture manifold are not so precise as to achieve the same pressure as in the hanging column method, and you may observe some increase in water level if the pressure is slightly more than that we want to operate on.
- (ix) Note down various intermediate readings of water level in the burette with time intervals of 1-2 hours. Consider the last reading as the final reading, when it is not different from the last two or three readings. When there is no difference in the last 2 or 3 readings, we assume that the sample has achieved an equilibrium and no more water will drain out at this pressure.
- (x) The difference of final and initial readings will give the volume of water collected at the operating pressure.
- (xi) Increase the pressure and repeat steps (9) and (10) to get the next P_C vs S data points.
- (xii) Successive pressure increments will produce a number of P_C vs S data points.

Note:

- (1) Pressure increments of 0.05 bar can be given conveniently. The scale

on the pressure gauge is not so fine to read more precisely.

- (2) Maximum pressure applied depends on the porous plate in the tempe cell used. With one bar porous plate, maximum pressure applied should not be more than one bar. Porous plates of 3 bars and 5 bars may be available, but the range of the fine-division pressure gauge is 0-4 bars.
- (xiii) After reaching the maximum desired pressure, take out the tempe cell from the pressure vessel observing the pressure system's operating instructions and weigh it and record it as $W_{TC+RSS2}$.
- (xiv) Calculate the weight of water left in the sample at the end of the run and record it as W_{RSS2} (follow the sample calculations).
- (xv) Calculate all P_C vs S curve from the low-suction pressure process.

(2b) Four fully saturated samples can be operated at a time following the procedure described in (2a) starting with 0.05 bars pressure with increments of 0.05 bars. One burette is used for each individual sample through the 4 outlets of the pressure vessel (Fig. 4.3).

Note: (i) this process may not be able to provide too many data points at high saturation and low pressure ranges, as the divisions on the pressure gauge are not so fine.

- (ii) This multiple sample procedure can be adopted by achieving the same pressure for each of 4 samples from low-pressure desaturation process in the following way:

Assume you have 4 samples with the last pressure applied during the low-pressure desaturation process being 0.16, 0.15, 0.19, and 0.18 bars, respectively. Operate each sample individually in high-pressure desaturation

process as explained in (2a) up to the pressure of 0.20 bar (which is nearly the maximum pressure of the 4 samples). Save each sample from any drainage or evaporation by putting a rubber stopper in the tempe cell during this process. After each sample has been drained with pressure up to 0.20 bars, then continue the multiple sample procedure (2b) to speed up the process.

Precautions

- (1) Avoid any drainage or evaporation from the soil sample by putting a rubber stopper on one opening of the tempe cell, when the sample is not in use (Fig. 4.4)
- (2) Close the burette tops with stretchable plastic sheet and make a small hole with a needle in it to minimize the evaporation from the burette.
- (3) While increasing the pressure on the pressure gauge, never exceed the desired operating pressure. It will shoot water out of the sample quickly at a pressure more than the desired one. So before applying the pressure, close the stop cock of the burette. When you set the correct pressure, open the stop cock.

Table 4.1

Sample Weights at Various Stages of the Capillary Pressure vs
Saturation Data Run

(A) Wt. of empty ring # (W_r)	=	gms
(B) Wt. of field wet soil (W_{ws}) + wt. of ring (W_r)	=	gms
(C) Wt. of oven dry soil (W_{ds}) + wt. of ring (W_r)	=	gms
(D) Wt. of field wet soil (W_{ws}) = (B) - (A)	=	gms
(E) Wt. of oven dry soil (W_{ds}) = (C) - (A)	=	gms
(F) Wt. of assembled tempe cell (include dry porous plate, wire screen; exclude brass ring) (W_{dTC})	=	gms
(G) Wt. of tempe cell with porous plate saturated (W_{sTC})	=	gms
(H) Wt. of tempe cell with saturated porous plate, dry soil and ring ($W_{sTC+ds+r}$); (G) + (C)	=	gms
(I) Wt. of tempe cell with saturated porous plate, saturated sample and ring ($W_{sTC+sS+r}$)	=	gms
(J) Amount of water in saturated soil sample (W_g) = (I) - (H)	=	gms
(K) Wt. of tempe cell with residual saturation (after low-pressure desaturation run); ($W_{sTC+RsS1}$)	=	gms
(L) Wt. of residual water (W_{RsS1}) = (J) - [(I) - (K)]	=	gms
(M) Wt. of tempe cell with residual saturation (after high pressure desaturation run) ($W_{sTC+RsS2}$)	=	gms
(N) Wt. of residual water (W_{RsS2}) = (L) - [(K) - (M)]	=	gms
(O) Total water released (J) - (N)	=	gms
(P) Actual water collected (cumulative)	=	gms
(Q) Water loss in evaporation, etc. (O) - (P)	=	gms

Diameter of soil sample (D) =

Length of soil sample (L) =

Volume of soil sample (V) $\frac{\pi}{4} D^2 * L =$

Porosity (ϕ) = $\frac{J}{(J) + (E)} =$ %

Bulk density (ρ_b) = $\frac{(E)}{V} =$ gm/cm³

Residual saturation (S_r) = $\frac{(N)}{(J)} =$

Table 4.2
Low Suction Pressure (Hanging Column) Data

Sample # _____

Date/Time	<u>Burrett Readings</u>			Volume	Head	Remarks
	Initial	Intermediate	Final	Water Collected (ml)	(cm)	
<hr/>						

Table 4.3
High Pressure Data

Sample # _____

<u>Date/Time</u>	<u>Burette Readings</u>			Volume	Head	Remarks
	Initial	Intermediate	Final	Water Collected (ml)	(cm)	
<hr/>						

Table 4.4

Calculations of Pressure vs Saturation Data

Pressure	Water Released	Cumulative Water Released	Saturation	$S_e = \frac{S - S_r}{1 - S_r}$	$\theta = \phi \cdot 5$	$WC = \frac{\theta}{\rho_b}$
Bars	cm of Water (ml)	(ml)	$S = 1 - \frac{\text{cumul. water released}}{J}$		cm^3/cm^3	gm/gm

Operating the Pressure System

Assume the soil samples are set in the pressure plate extractor. The out-flow tubings of the extractor are connected to burrettes with their valves closed. The extractor is made air tight by tightening the screws properly. All the valves of the pressure system are assumed to be closed initially.

5 Bar Pressure Plate Extractor

- (1) First close the "connecting hose valve #1030." (item (8) in Fig. 4.5).
- (2) Open nullmatic regulator valve (make several turns clockwise to allow free flow of air).
- (3) Open regulator #3 (turn clockwise) until pressure as indicated by test gauge is 3 psi above the equilibrium desired pressure.
- (4) Leave regulator #3 at this setting and close nullmatic valve (turn knob counter-clockwise). When the nullmatic valve is closed, all the air in the system beyond the regulator #3 is drained from the system.
- (5) Open the "connecting hose valve #1030" very slowly.
- (6) Open the nullmatic valve very carefully until pressure builds up in the pressure plate extractor to the equilibrium pressure desired (as indicated by the gauge).
- (7) Open the burette valves very slowly one by one. The water will start flowing from the soil samples to the burrettes and you will notice the rise of water in them.
- (8) The regulator #3 will maintain the pressure set in step 6. Observe and record the changes of water level in the burrettes separately until you achieve an equilibrium. The equilibrium is said to be achieved when you notice no change in water level in the burette for 3-4 hours at the particular pressure.
- (9) Increase the next desired pressure repeating step 6.

At the End of the Run

- (10) Close the burette's valves to prevent backflow of water from the burettes to the samples.
- (11) Close the nullmatic regulator (turn counter-clockwise very slowly). This will drain the air of the pressure plate extractor to drain through the regulator.
- (12) The dial gauge arm will indicate the drainage of the pressure in the extractor when it reaches zero.
- (13) Unscrew the bolts of pressure extractor and remove the samples.

How to Start the PM Compressor Pump

For the first time:

- (1) Close all air line valves.
- (2) Turn the starting switch to the "on" position (Fig. 1).

The compressor will start only if the timer knob is closed. (To close the timer knob, simply turn the knob clockwise until the compressor motor starts.)

Observations

First Cycle:

The timer will permit the compressor to run for 5 minutes and the pressure will build up to 140 psi.

Second Cycle:

After 1 hour the timer will turn the compressor on again and will raise the pressure up to 220 psi.

Third Cycle:

For the third cycle, the pressure will build up to 270 psi.

Fourth Cycle:

A 4th cycle will probably be required for the tank pressure to reach the maximum value required for the pressure switch to open. Thereafter the compressor will run only when required to maintain tank pressure within the operating limits as demanded by the pressure switch and timer.

Completing cycles 1-4 will take about 3-4 hours.

Note:

To speed up the process of going through the various cycles after the first cycle, turn the timer knob (Fig. 1) clockwise until the switch again closes. Repeat this procedure until you reach about 300 psi (close to maximum capacity of the compressor). If this procedure is followed, be sure to allow 15 minutes between runs to permit the compressor and motor to cool off so as to avoid problems of overheating. For maintenance of compressor, see the manual.

5. Hydraulic Conductivity Determinations

a. Constant Head Method

Special Apparatus

A simple apparatus for measurement of permeability of saturated soil samples by a constant-head method is shown in Figure 5.1 in cross-section. The apparatus may be arranged to hold a number of soil cores in a row.

Procedure

(1) Assume you already have a soil sample taken in a metal ring (of a tempe cell) and it is oven dry.

(2) Cover both ends of the sample with circular pieces of cloth screen. Use a rubber-band or a plastic ring to stretch the cloth screen on one end of the sample.

Put an about 9 inches long piece of transparent acrylic cylinder on the other end of the sample so that it could stretch the cloth screen. Make sure it is very tight on the brass ring and there should be no leakage of water through the contact of acrylic cylinder and the brass ring.

(3) put the sample (prepared in step 2) upright in a tray filled with water, so that the bottom end of the sample is dipped in the water. Keep the sample dipped in water for a few of hours, preferably overnight, to make sure that it is fully saturated.

(4) Set up the arrangement as shown in Figure 5.1. A porcelain funnel with a built-in screen is suspended over a graduated cylinder with the help of a stand. Another plastic funnel with an outlet near the edge is suspended on another stand near a water tap. The funnel's lower opening is connected to a water tap through plastic tubing.

(5) When the sample is fully saturated, put it in the porcelain funnel in the upright position. Open the inlet of the plastic funnel to let water overflow through the upper opening of the funnel. This will keep the water surface in the funnel at constant level. Keep the water tap on.

(6) Make a siphon through a plastic tubing between the plastic funnel filled with the constant level of flowing water and the acrylic cylinder over the sample.

(7) Water will start flowing through the sample under a constant head ΔH as shown in Figure 5.1. Let the water flow through the sample for 10-15 minutes to reach its steady state.

(8) Collect the out-coming water from the sample into a graduated cylinder and note down the time of that amount of water using a stop watch. Repeat this step for 5-10 times to achieve an averaged value of hydraulic conductivity.

Sample Calculations

Hydraulic Conductivity Test (Constant Head Method)

Date: July 16, 1984

Operator: N. Shaukat

Sample #3, Location: Behind Foley Building

Diameter of the sample (D) = 5.390 cm

Length of the sample (L) = 2.900 cm

x-sectional area of the sample (A) = $\frac{\pi}{4} D^2 = \frac{\pi}{4} (5.390)^2 = 22.817 \text{ cm}^2$

Hydraulic head difference (ΔH) = 17.3 cm

#	Reading on Graduated Cylinder		Volume of Water Collected (Q) (Final - Initial) (ml)	Time (t) (sec)	K = $\frac{Q}{At} * \frac{L}{\Delta H}$		
	Initial (ml)	Final (ml)			cm/sec	cm/hr	cm/day
1	10	20	10	82.56	8.899×10^{-4}	3.204	76.88
2	20	30	10	82.34	8.992×10^{-4}	3.212	77.09
3	40	50	10	81.75	8.987×10^{-4}	3.235	77.65
4	15	25	10	81.04	9.066×10^{-4}	3.264	78.33
5	30	40	10	81.75	8.987×10^{-4}	3.235	77.65
6	10	20	10	82.04	8.955×10^{-4}	3.224	77.37
7	25	35	19	82.45	8.911×10^{-4}	3.208	76.99
8	40	50	10	81.95	8.965×10^{-4}	3.227	77.46
9	10	20	10	82.25	8.932×10^{-4}	3.216	77.17
10	25	35	10	81.83	8.978×10^{-4}	3.232	77.57

$$\begin{aligned} \text{Avg. } K &= (K_1 + K_2 + K_3 + \dots + K_n)/n \\ &= 77.42 \text{ cm/day} = 2.360 \text{ ft/day} \end{aligned}$$

$$\text{Permeability (k)} = K_{\eta} / \rho g$$

(9) Measure the hydraulic head difference ΔH and the temperature of water.

Sample Calculations

Calculate the hydraulic conductivity using the following formula

$$K = \left(\frac{Q}{At} \right) \frac{L}{\Delta H}$$

where K = hydraulic conductivity (L/T)

Q = volume of water passed through the sample in time t (V)

A = cross sectional area of sample (L^2)

L = length of the sample (L)

ΔH = hydraulic head difference (L)

Permeability is calculated by the following relationship:

$$k = K\eta/\rho g$$

where k = permeability (L^2)

η = fluid viscosity at temperature T°

ρ = fluid density at temperature T°

g = acceleration due to gravity.

b. Falling Head Method

Special Apparatus

An arrangement for measurement of hydraulic conductivity of saturated soil samples by a falling-head method is shown in Figure 5.2 in cross section. It consists on a tempe pressure cell to hold the soil sample and a burette, attached to a water source.

Procedure

- (1) Assume you already have a soil sample taken in a brass ring and it is oven dry.
- (2) Put the sample in a tempe pressure cell with the porous plate taken out, replacing it with a cloth screen, and saturate the sample in a dessiccator as described in the method of obtaining the capillary pressure vs saturation curve.
- (3) After the sample has been fully saturated, hold the tempe cell on a stand and connect the lower opening to a burette through a plastic tubing as shown in Figure 5.2.
- (4) The upper opening of the tempe cell is connected to a glass tubing bent at right angle for the overflow. The bent glass tubing is held horizontal in a fixed position. The plastic tubing connected to the glass tube should be initially close with a clamp to avoid draining the saturated sample.
- (5) Note down the initial water level in the burette and measure its height from the center of the horizontally held glass tube with a centimeter scale attached to the burette and call this height H_1 .
- (6) Remove the clamp from the plastic outlet tubing and open the outlet of the burette to let water go into the sample. The water level in the

- burette will start decreasing. Record a certain drop in water level to H_2 and note down the time required for this drop in water level.
- (7) Fill the burette with water again and repeat step #6 several times (about 10 times) to get a good average value of hydraulic conductivity.

Calculations

Calculate the hydraulic conductivity using the following formula

$$K = (aL/At) \ln(H_1/H_2)$$

where

a = inside cross-sectional area of the burette (L^2)

L = length of the sample (L)

A = cross-sectional area of the sample (L^2)

t = time for the hydraulic head difference to decrease
from H_1 to H_2 (T)

K = hydraulic conductivity (L/T)

Sample Calculations

Hydraulic Conductivity Test (Falling-Head Method)

Date: July 18, 1984

Operator: N. Shaukat

Sample: #3; Location: Behind Foley Building

Diameter of the sample (D) = 5.390 cm

length of the sample (L) = 2.900 cm

X-sectional area of the sample (A) = $\frac{\pi}{4} D^2 = \frac{\pi}{4} (5.390)^2 = 22.817 \text{ cm}^2$

Inside diameter of the burette (d) = 1.049 cm

Cross-section area of the burette (a) = $\frac{\pi}{4} d^2 = \frac{\pi}{4} (1.049)^2 = 0.86425 \text{ cm}^2$

#	Initial Head	Final Head	Time (t)	K = (aL/At) ln(H ₁ /H ₂)		
	(H ₁) (cm)	(H ₂) (cm)	(seconds)	cm/sec	cm/hr	cm/day
1	40	30	36	8.778x10 ⁻⁴	3.160	75.841
2	38	28	37	9.066x10 ⁻⁴	3.264	78.328
3	40	30	35	9.028x10 ⁻⁴	3.250	78.004
4	40	30	36	8.778x10 ⁻⁴	3.160	75.841
5	40	30	37	8.540x10 ⁻⁴	3.075	73.788
6						
7						
8						
9						
10						

Avg K = (K₁ + K₂ + K₃ + ... + K_n)/n
 = 76.360 cm/day = 2.3275 ft/day

Permeability (k) = kn/ρg

c. Tight Formation Constant Head Method

When soils are very tight, too clayey, or shales, it is difficult to apply a long constant pressure head in the laboratory. The problem of maintaining a high pressure head is solved by using our 5-bar pressure vessel. Follow the following steps:

Procedure

- (1) Compact the sample in a brass ring to the required density (follow instructions for compaction).
- (2) Place the brass ring filled with the compacted soil sample in the tempe pressure cell.
- (3) Saturate the sample with water in the dessicator for 5-6 hours (follow instructions for saturation of soil samples). After saturating the sample, take it out from the dessicator and put a rubber stopper on one end of the tempe cell to prevent any leakage.
- (4) Bring the saturated sample into the pressure vessel (5-bars) and place it on a small tripod.
- (5) Take a 500 ml conical flask with a side opening, and pass a plastic tubing through the opening, as shown in the Figure.
- (6) Fill the flask with deaired water, and pass the water through the plastic tubing. When the tubing is free of any air bubble, close the flask with a rubber stopper so that the water stays in the tubing up to the outer end of the tubing.
- (7) Place the flask on the horizontal plate in the pressure vessel.
- (8) Mount a burette (having a 2-way stopcock) on a stand. Attach a plastic tubing to the burette's opening and connect it to one of the four outlets of the pressure vessel.

- (9) Extend the black tubing with a plastic tubing so that it can fit over the tempe cell's brass opening.
- (10) Fill the burette with water and let the water pass through the tubing to take out all air from the tubing and burette. Close the stopcock of the burette so that the water remains in the tubing.
- (11) Take out the rubber stopper from the tempe cell and connect it to the water-filled plastic tubing coming from the burette.
- (12) Connect the other opening of the tempe cell to the water filled plastic tubing coming from the conical flask, and take out the rubber stopper from the flask.
- (13) Put the lid on the pressure vessel and tighten all bolts; make the pressure vessel air tight.
- (14) Follow the operating instructions of pressure supply system, and increase the pressure by 0.5 bar increments.
- (15) Open the stopcock of the burette. You will notice a little rise of water level in the burette.
- (16) Increase the pressure from 2.5 bars to 3.5 bars very slowly depending on the density of the sample (low density - low pressure, high density - high pressure), and keep it constant. Wait for a few minutes.
- (17) Water will start flowing from the flask to the burette through the sample.
- (18) Measure a certain increase in volume of water in the burette by noting down the initial and final readings of the water level in the burette. Record the time in seconds on stop watch for this increase.
- (19) Take several readings of volume of water increase in burette vs time in seconds.
- (20) Convert the pressure in terms of centimeters of water (1 bar = 1019.7267

cm of water).

- (21) Calculate the hydraulic conductivity following the "constant head method" calculation procedure.
- (22) At the end of the run, close the stopcock of the burette and release the vessel's pressure using the nullmatic valve of the pressure supply unit. The burette's stopcock is closed first to prevent any backflow.
- (23) When the pressure inside the vessel reaches zero, open its lid and remove the sample.

Precautions

- (1) the plastic tubing from the conical flask to the burette should be free of any air bubble, and filled with water completely before you pressurize the system. Care must be taken while connecting the plastic tubing to the tempe cell not to introduce any air into it.
- (2) all the connections must be air sealed and the sample in the tempe cell should be well tightened to prevent any intrusion of pressurized air into the water flow. If there is any leakage, you will see air bubbles coming into the burette from the pressurized vessel. If it is so, discontinue the process and open the pressure vessel following step #22, and make the system free of air-leakage. Sealant grease can be used in the start at the suspected points of leakage (especially around the brass ring of the sample).
- (3) air pressure should be increased very slowly, otherwise the water will come out abruptly from the open end of the burette.
- (4) Drain the burette using a 2-way stopcock, when the water level is near the open end of the burette during successive readings.

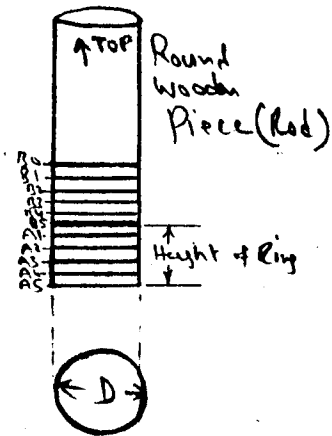
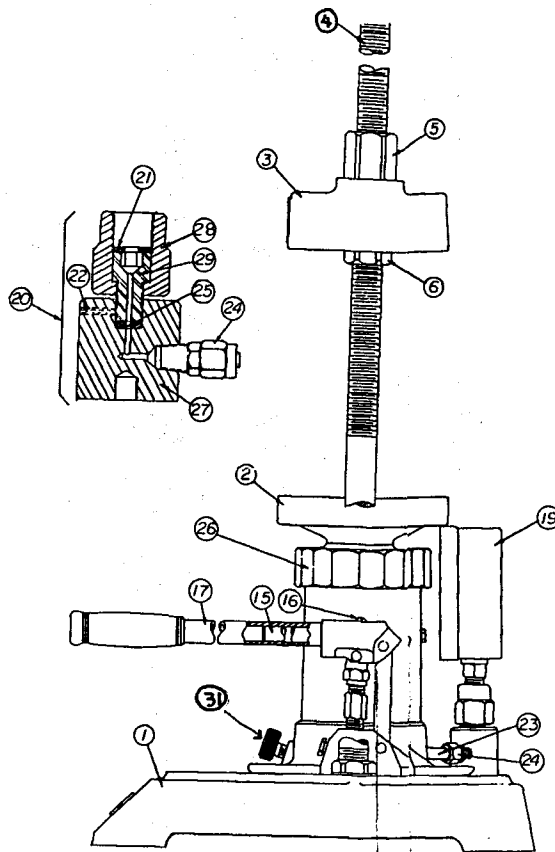
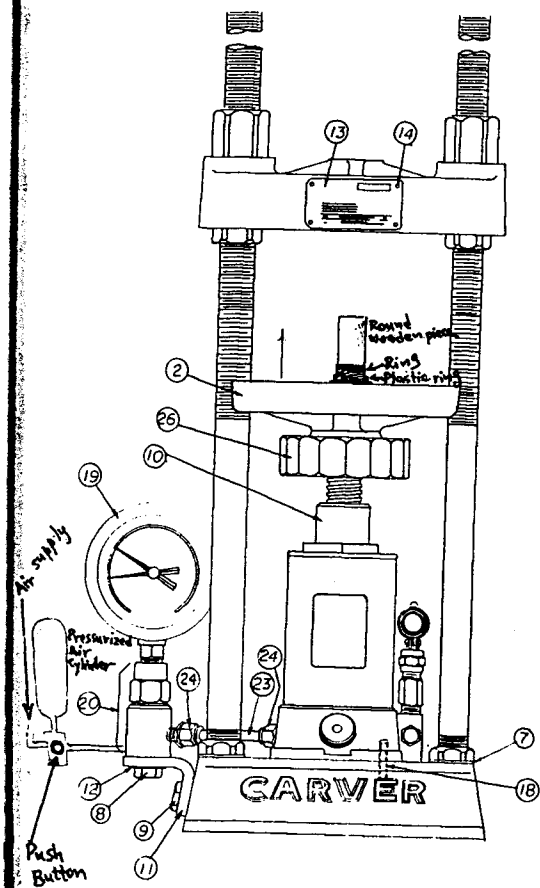


Fig. 3.1



*NOTE: SEE DRAWING D-31001 HYDRAULIC UNIT ILLUSTRATED IDENTIFICATION

EFFECTIVE RAM DIA. 2.031
 EFFECTIVE RAM AREA 3.236 SQ. IN.
 PUMP PISTON DIA. .437
 PUMP PISTON AREA .150

ITEM NUMBER	PART NUMBER	QTY	DESCRIPTION
30	311005	1	HYDRAULIC UNIT PACKING REPAIR KIT
29	369003	1	COUPLING SCREW
28	369002	1	COUPLING SWIVEL
27	369001	1	COUPLING BASE
26	214001	1	STEM ADJUSTING CAP
25	843002	1	COUPLING BASE SEAL
24	983001	2	HYDRAULIC FITTING
23	367019	1	GAUGE CONNECTION TUBE
22	917001	1	COUPLING SET SCREW
21	843001	1	GAUGE SEAL-COPPER
20	368001	1	GAUGE UNION COUPLING ASSEM.
19	381005	1	GAUGE - 24,000-LBS. CAT. NO. 2085-9
19	381004	1	GAUGE - 10,000-LBS. CAT. NO. 2085-7
19	381003	1	GAUGE - 5,000-LBS. CAT. NO. 2085-5
19	381002	1	GAUGE - 2,000-LBS. CAT. NO. 2085-3
19	381001	1	GAUGE - 1,000-LBS. CAT. NO. 2085-1
18	914002	4	UNIT BASE SCREW 10-24 x 1"
17	245001	1	PUMP LEVER LONG
16	914001	1	PUMP LEVER SCREW 10-24 x 3/4"
15	262001	1	PUMP LEVER SHORT
14	914045	4	DRIVE SCREW 1/4" U-SIZE 2 X 1/8"
13	973006	1	NAME PLATE
12	921008	1	FLAT WASHER
11	251001	1	BRACKET
10	311001	1	HYDRAULIC UNIT ASSEM.
9	913001	2	HEX. HD. CAPSCREW - 1/8" x 1 1/2"
8	913002	1	HEX. HD. CAPSCREW - 1/8" x 1 1/4"
7	922001	2	COLUMN LOCK WASHER
6	241002	4	COLUMN LOCK NUT
5	241001	2	COLUMN TALL NUT
4	241003	2	COLUMN
3	212003	1	HEAD
2	212002	1	PLATEN
1	212001	1	BASE

ITEM NUMBER	PART NUMBER	QTY	DESCRIPTION
31			valve

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FRED S. CARVER, INC.
 STEELTON, PA.
 HYDRAULIC LAB. PR

Fig. 3.2

Sample saturation

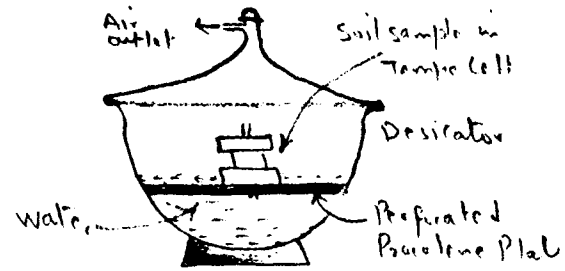


Figure (3.3)

Fig. 3.3 a

SATURATION OF SOIL SAMPLES

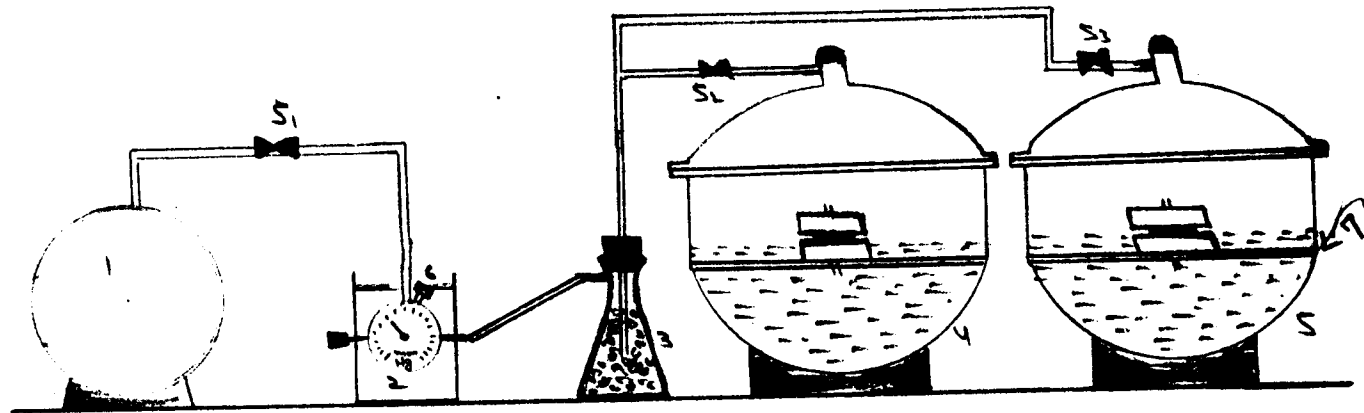
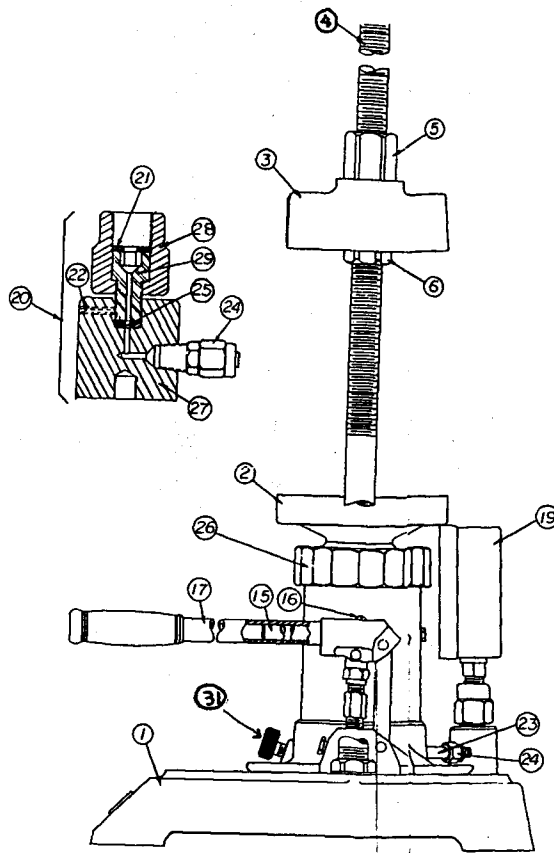
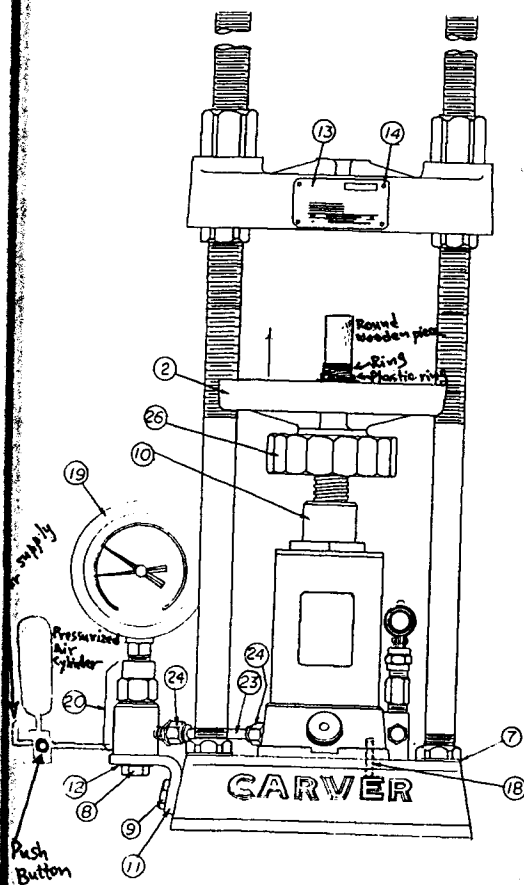


Figure: (3.3) . Arrangement of Desiccator system for saturating the soil samples.

- (1) Vacuum pump
 - (2) Vacuum gauge/regulator
 - (3) Flask containing $CaSO_4$ as moisture absorbent.
 - (4) Desiccator # 1
 - (5) Desiccator # 2
 - (6) Knurled nut
 - (7) Ceramic plate with holes
- S_1, S_2, S_3 — Stop cocks.

Fig. 3.3b



XNOTE: SEE DRAWING D-311001 HYDRAULIC UNIT ILLUSTRATED IDENTIFICATION

EFFECTIVE RAM DIA. 2.031
 EFFECTIVE RAM AREA 3.236 SQ. IN.
 PUMP PISTON DIA. .437
 PUMP PISTON AREA .150

31 valve

ITEM NUMBER	PART NUMBER	DESCRIPTION
30	311005	1 HYDRAULIC UNIT PACKING REPAIR KIT
29	369003	7 COUPLING SCREW
28	369002	1 COUPLING SWIVEL
27	369001	1 COUPLING BASE
26	214001	1 STEM ADJUSTING CAP
25	843002	1 COUPLING BASE SEAL
24	965001	2 HYDRAULIC FITTING
23	367019	1 GAUGE CONNECTION TUBE
22	917001	1 COUPLING SCREW
21	843001	1 GAUGE SEAL - COPPER
20	368001	1 GAUGE UNION COUPLING ASSEM.
19	381003	1 GAUGE - 25,000-LBS. (CAT. NO. 2085-9)
19	381004	1 GAUGE - 10,000-LBS. (CAT. NO. 2085-7)
19	381003	1 GAUGE - 5,000-LBS. (CAT. NO. 2085-5)
19	381002	1 GAUGE - 2,000-LBS. (CAT. NO. 2085-3)
19	381001	1 GAUGE - 1,000-LBS. (CAT. NO. 2085-1)
18	914002	4 UNIT BASE SCREW 10-24x1
17	245001	1 PUMP LEVER LONG
16	914001	1 PUMP LEVER SCREW 10-24x1/2
15	262001	1 PUMP LEVER SHORT
14	914045	4 DRIVE SCREW TYR U SIZE 2X1/8"
13	973006	1 NAME PLATE
12	921008	1 TAIL WASHER
11	251001	1 BRACKET
10	311001	1 HYDRAULIC UNIT ASSEM.
9	913001	2 HEX. HD. CAPSCREW .75-18 x 1"
8	913002	1 HEX. HD. CAPSCREW .75-13 x 1/2"
7	922001	2 COLUMN LOCK WASHER
6	241008	4 COLUMN LOCK NUT
5	241001	2 COLUMN TALL NUT
4	241003	2 COLUMN
3	212003	1 HEAD
2	212002	1 PLATEN
1	212001	1 BASE

ITEM NUMBER PART NUMBER NO. REQ. DESCRIPTION
 FRED S. CARVER, INC.
 11500 E. 11TH AVE.
 DENVER, CO. 80202
 (303) 733-1111

Fig. 3.2

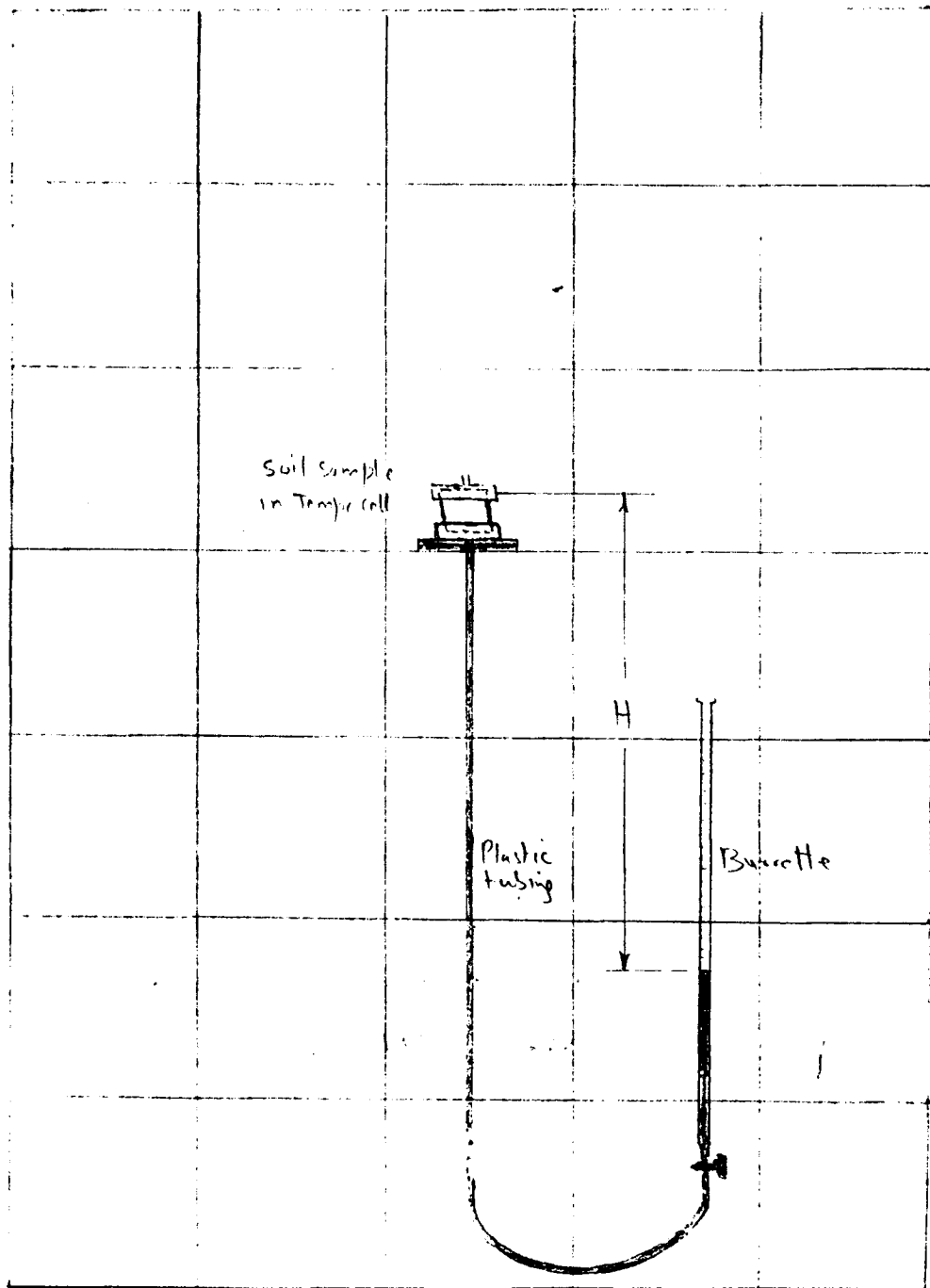


Figure: (4.1) Arrangement for desaturation of sample with a hanging column method.

Fig. 4.1

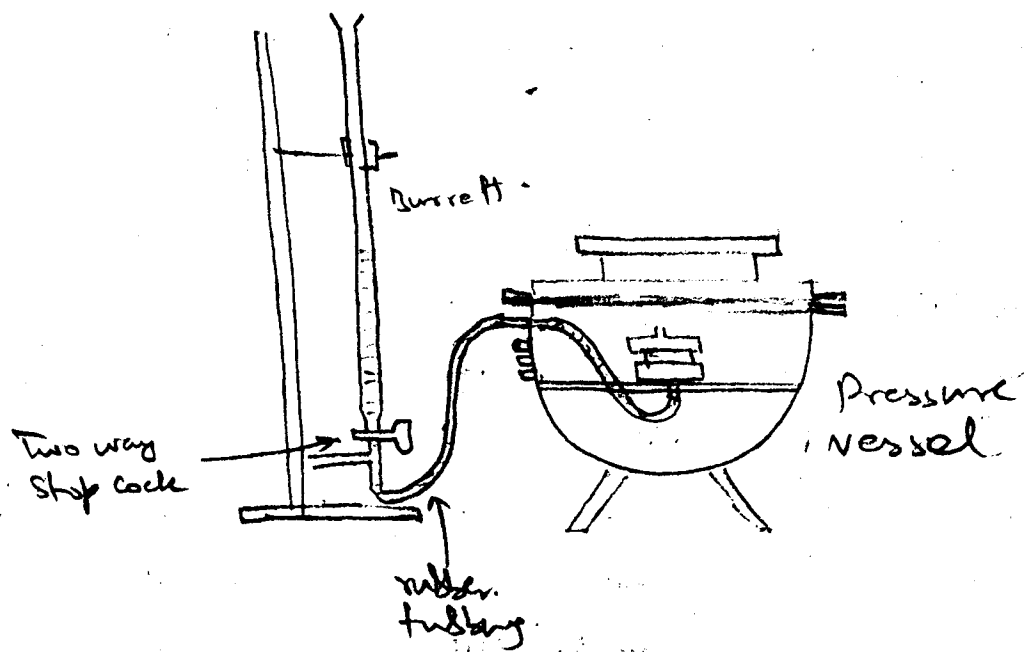


Fig. 4.2

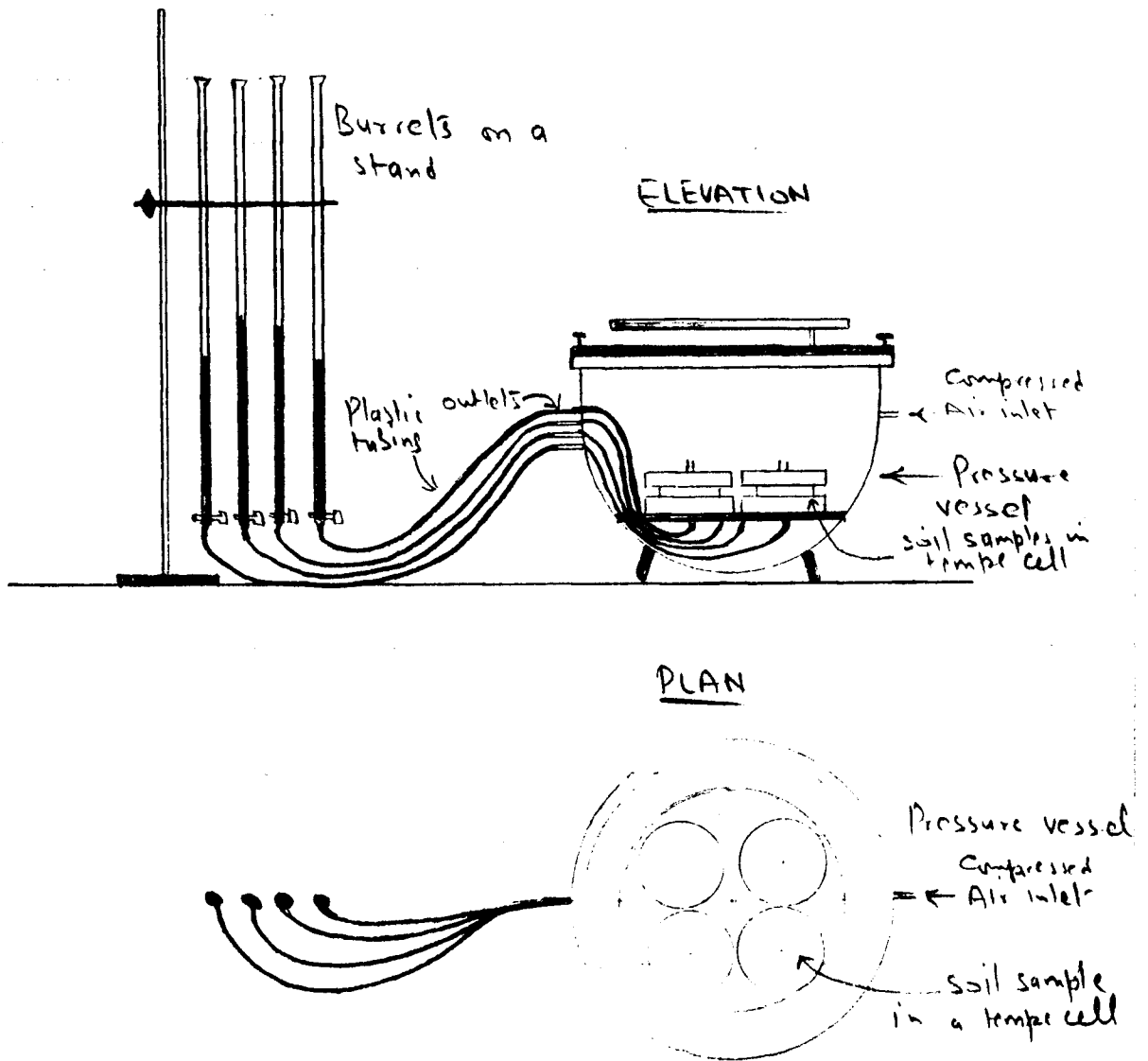
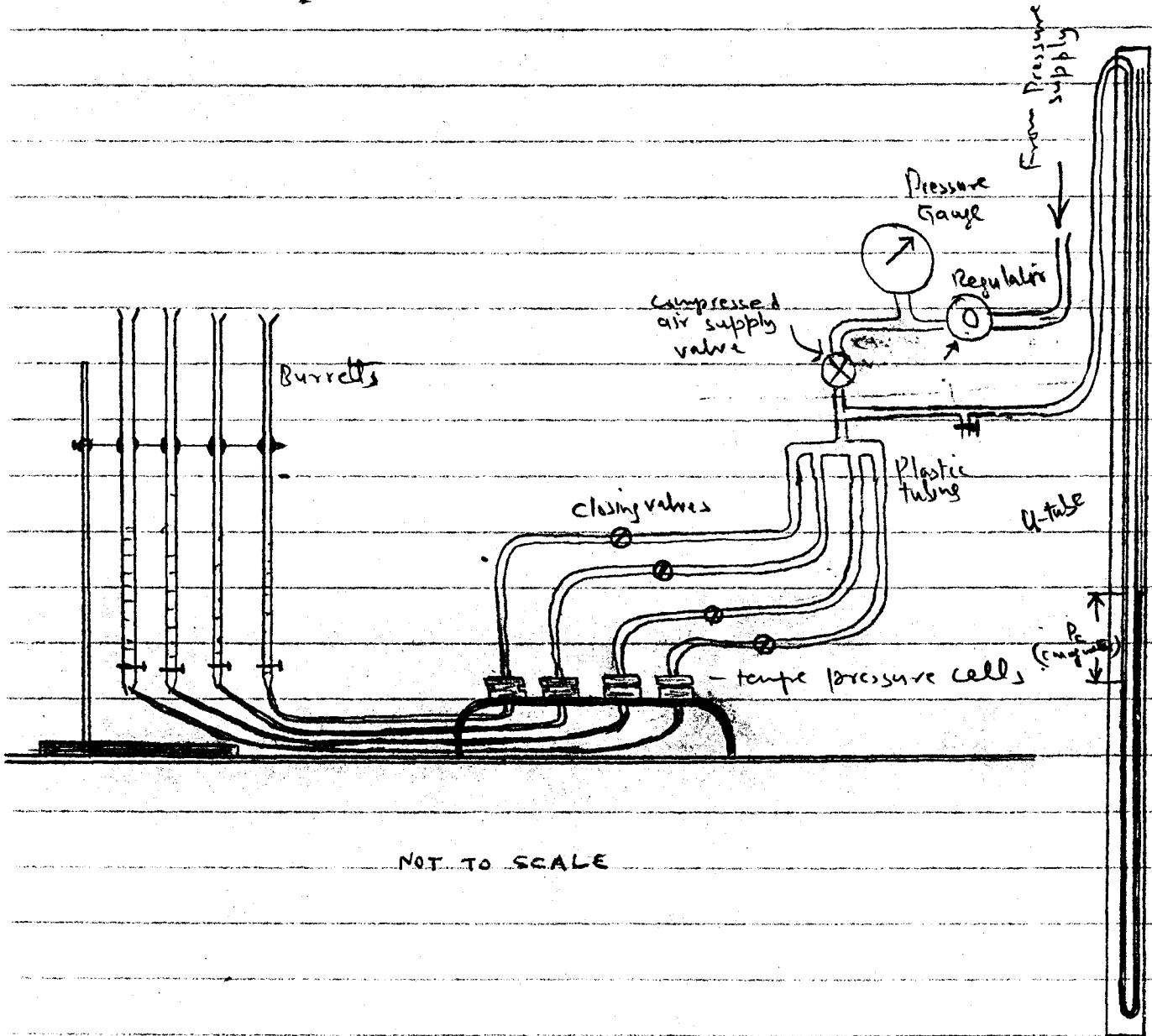


Figure: (4.3) Arrangement for multiple sample procedure for high-pressure desaturation.

Fig. 4.3 a

Fig. 4.3 b.



NOT TO SCALE

Figure 4.3 b

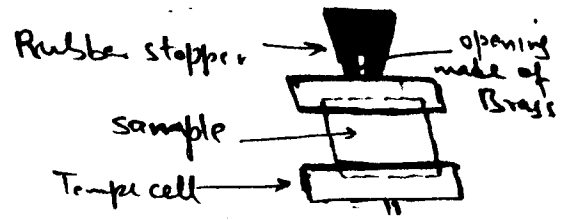


Fig. 4.4

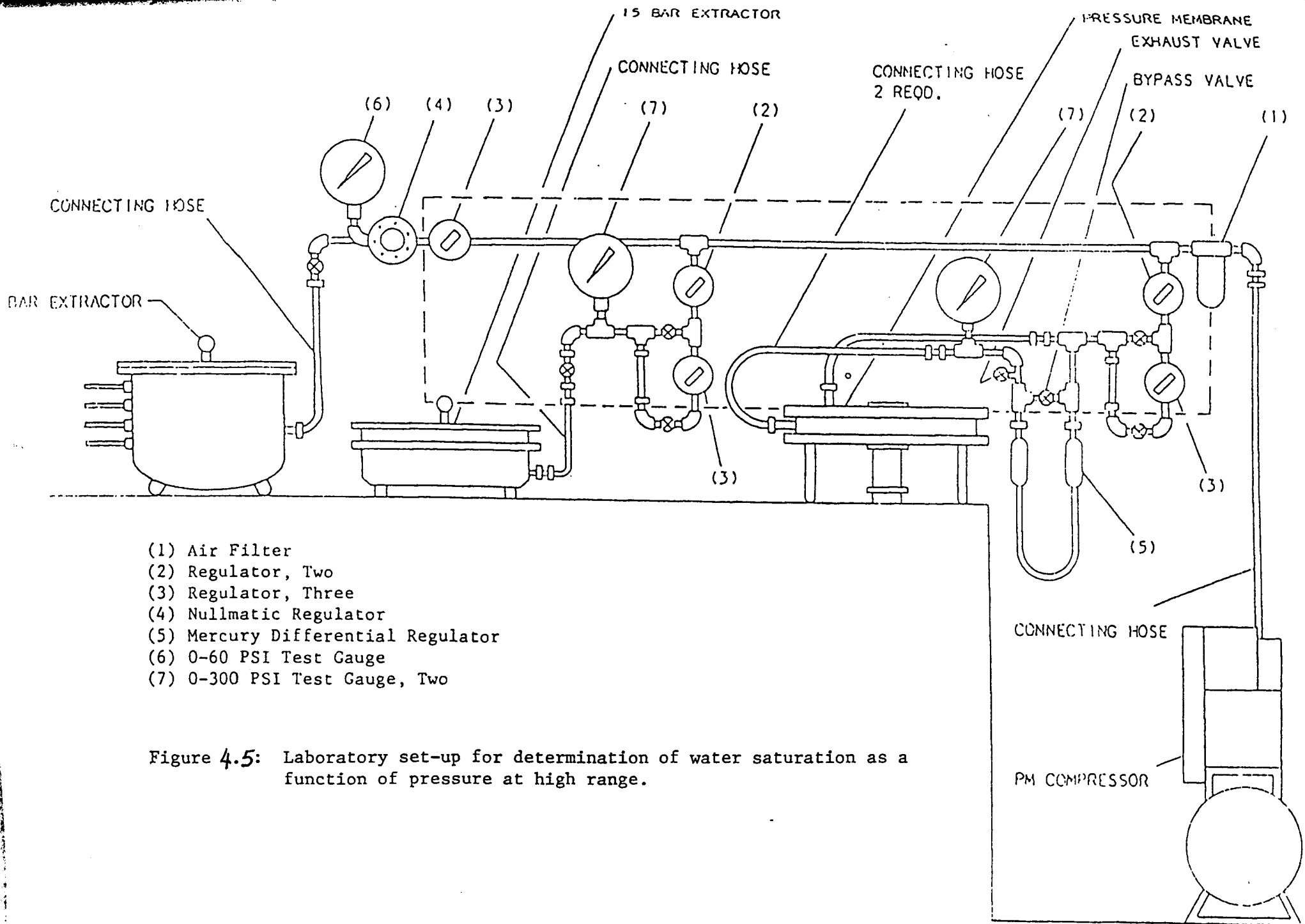


Figure 4.5: Laboratory set-up for determination of water saturation as a function of pressure at high range.

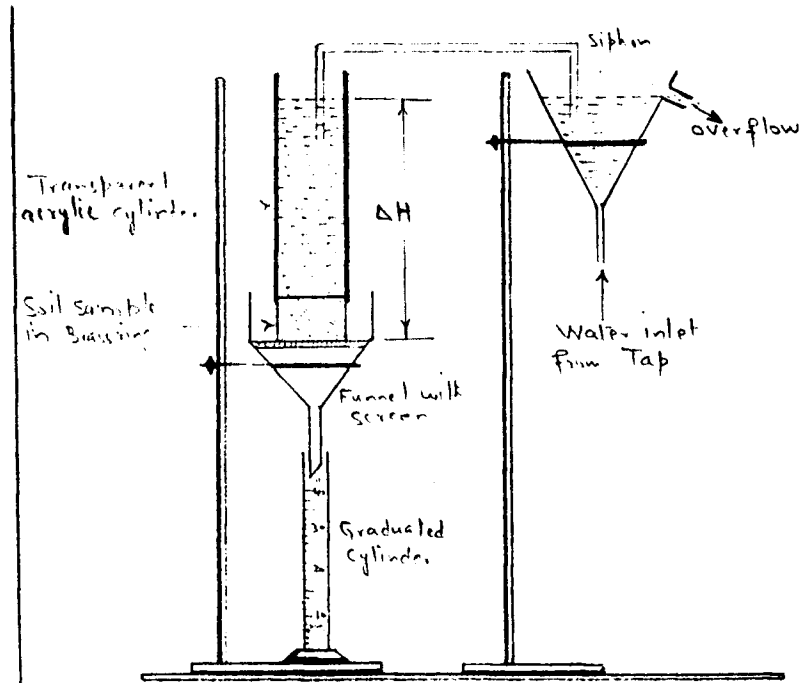


Figure 5.1 : Constant head system for permeability measurement of soil samples

Fig. 5.1

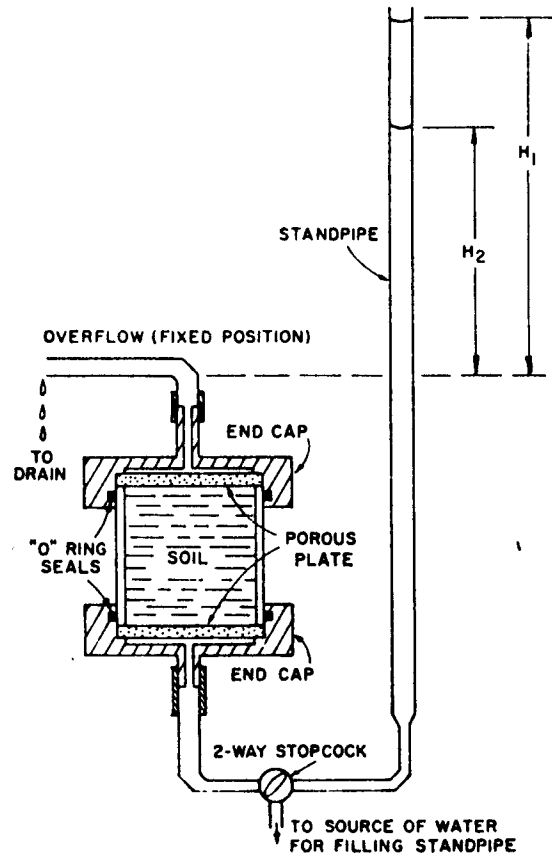


Figure 5.2 : Falling-head system for permeability measurement of soil samples

Fig. 5.2

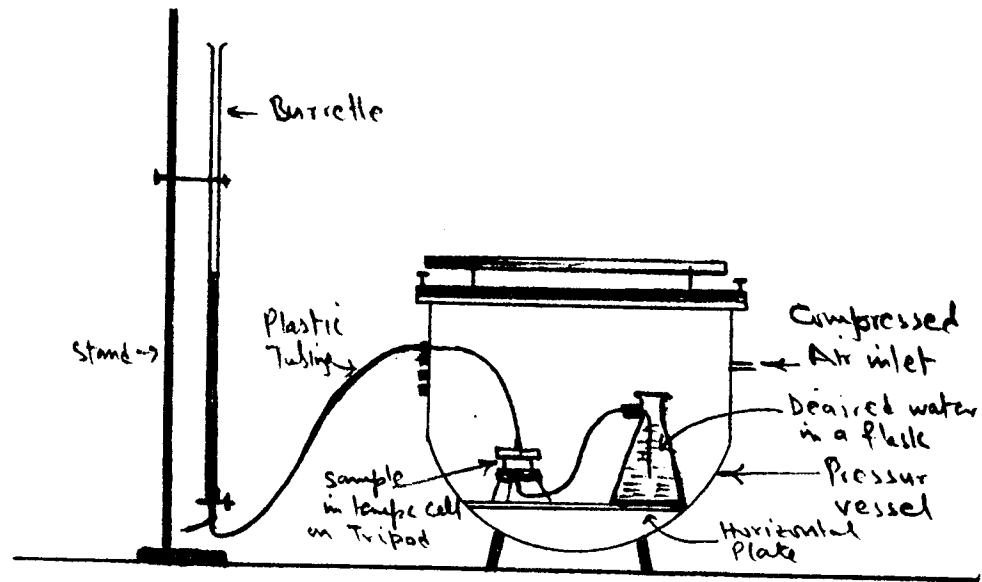


Figure : Arrangement for Permeability Test at high pressure head.

Fig. 5.3

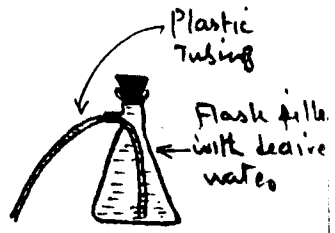


Fig. 5.4

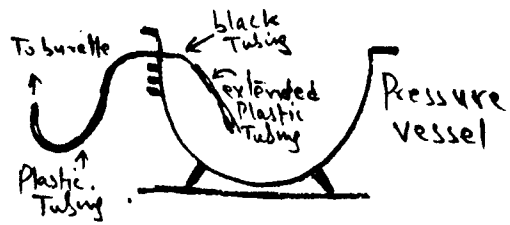


Fig. 5.5