DESIGN OF A GRANULAR PRESSURE CELL TO BE USED IN SOILS.

Thesis by

Jean Maurice Meuris.

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Abstract.

In preliminary experimentation, a granular pressure cell was built and tested. From the results obtained, an improved method for the production of granular pressure cells was developed and a second pressure cell was built in order to determine the behavior of granular pressure cells, as designed, under variable external temperature conditions.

A third pressure cell was built for laboratory testing. A calibration curve was established and the pressure cell was used satisfactorily in simple laboratory testing.

Attempts were made to improve the constitution of granular pressure cells as used in the aforementioned tests. These attempts lead to suggestions intended to help in eventual further improvement of the granular pressure cells built and described in the following pages.

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I. INTRODUCTION.

1·1 General

Soils as we find them in nature are not easily investigated by our main theoretical tool, mathematics.

One seldom finds sites to be investigated which are constituted of one type of soil with constant properties throughout the site. Even when we can control the characteristics of the soils to use in construction (kind of soil, grain size, compaction, etc...) as for instance in embankment building, one cannot accurately control the behavior of such soils by means of accurate mathematical theories.

When one wants to forecast the behavior of materials like metals , one can use the theory of elasticity and determine stresses and strains in a piece of metal with good accuracy because a few properties such as the modulus of elasticity, the yield stress, and Poisson's ratio are sufficient to describe most of the features of the behavior. Also, because of its internal crystallographic structure and its properties, a piece of metal will behave in such a way that the assumptions on which the theory of elasticity stands are valid.

As far as soils are concerned, the number of properties needed for an understanding of the action of soils under load is not as limited as for metals. Perhaps one might see the difference between metals and soils in the following way.

A piece of metal is essentially a mass of atoms and molecules arranged in a pattern which can be determined. Between these atoms and molecules, atomic and molecular forces of a certain intensity are acting. Forces of valence provide primary liaisons with energies of the order of 100 Kcal./ equivalent gram (1). Intramolecular forces provide what are called secondary liaisons with energies of the order of 1 Kcal./ equivalent gram (1). Such forces, which may be said to give "cohesion" in metals are also found in individual soil particles. But not always between grains in a mass of soil. Masses of soil can:

1. Be stable by themselves as masses of sand grains in between which exist only mechanical forces such as friction forces and no intramolecular forces as in metals.

2. Possess a certain degree of "cohesion" due to intramolecular forces as masses of clay particles. But the amount of "cohesion" is variable, because the magnitudes of the intramolecular forces which are said to give "cohesion" are believed to be partly due to the bonding

water of which the properties of viscosity are variable with temperature and pressure (2, 3, 4).

Cohesion in metals is high enough to enable us to consider a metal as elastic in a large range of stresses, making the stress-strain curves independent of the stress history and constant if the stresses do not pass the yield point and have never passed it previously.

Soils can be considered elastic to only a limited degree if any. Stress-strain relationships in soils will depend on the pressure history of the soils and just this factor makes the study of soils behavior very difficult by means of mathematical tools like the theory of plasticity. The complexity of the general equations in the theory of plasticity is such that only a few particular cases in agreement with very restrictive hypotheses can be solved up to now.

As elastic theories cannot be employed but in a qualitative way, one has to resort to empirical analyses in the study of the behavior of soils. These can most usefully be investigated by, for instance, observing deflections and deducing stresses as in the case of sheetpile walls.
Such observations can be done in situ or on models in laboratories. One can also use pressure cells in the soils to be investigated. One can establish a network of pressure cells in horizontal planes and at different depths under a footing in situ or in model testing in order to establish a more accurate pressure distribution diagram than might be found by the theory of elasticity.

The use of pressure cells provides a means of checking on the much discussed degree of validity of the use of the theory of elasticity in soils (3.). The equations of the theory of elasticity are based on homogeneity and isotropy which are properties hardly found in soil masses (3, 4.).
Also, pressure cells can give information on failure in a mass of soil. Hence, one can by their use verify if the probable location of the zones of failure assumed in an analyses of the eventual failure in the soil under a footing are justified.

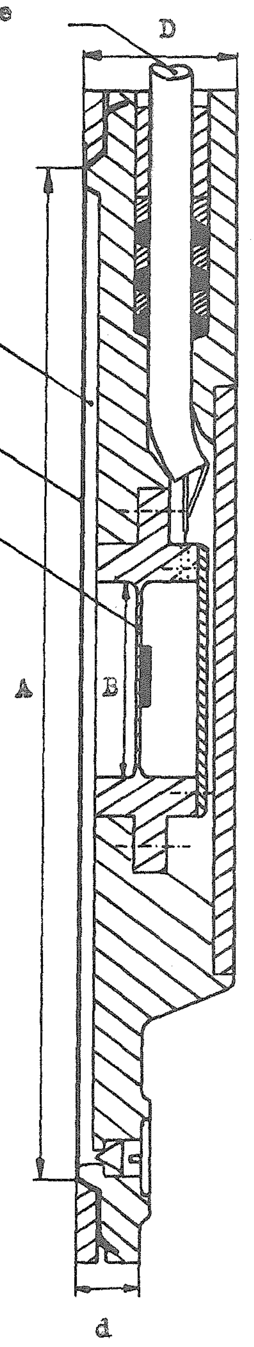
1.2 Discussion of the pressure cells used in Soil Mechanics.

Several pressure cells to be used in soils have been designed and used by various engineers (5, 6, 7, 8.), but few of them have been completely satisfactory. The points requiring improvement will be illustrated by the discussion of one of these cells.

Reference 5 gives a complete report on the design, calibration and the use of the pressure cell shown in figure 1.

One disadvantage of the pressure cell described by figure 1, is that its compressibility may be different from the compressibility of the soils to be investigated.
As Plantema (5.) points out:

> " If the cell is more compressible than the soil it recedes and indicates a value less than the prevailing pressure. On the other hand, if the cell is less compressible, it projects into the soil by a distance Z (Figure: 2.) and is thus subjected to a higher pressure than would otherwise exist at that point in the soil."



Dimensions of the pressure cells:

	Type O	Type I
A :	10 inches.	10 inches.
B :	2 inches.	2 inches.
D :	1 ½ inch .	1 3/8 inch .
d :	5/8 inch .	7/16 inch .

Figure I. Pressure cells Type O and Type I (3).

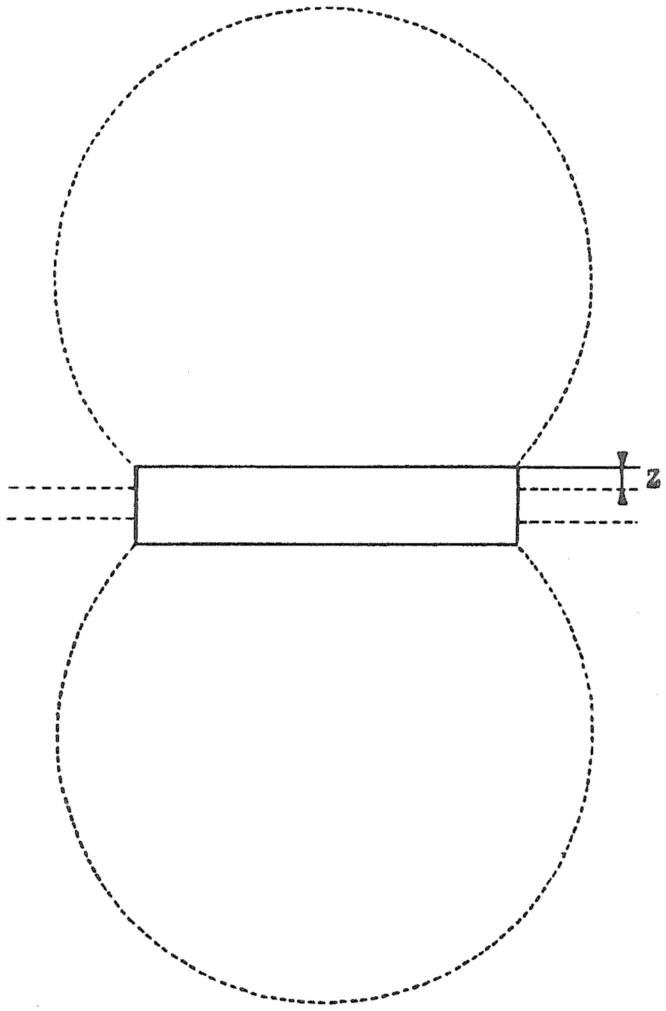


Figure 2 : Pressure cell with pressure bulbs.

(As given in reference 3.)

To control the magnitude of this additional pressure, the author makes his pressure cell as thin as possible. He also makes the pressure cell of a large diameter in order to have readings uninfluenced by local variations of pressure and because as Plantema writes :

> " The larger the diameter, the smaller is the pressure required to push the cell a distance Z into the sand."

Plantema designed two pressure cells: Type O and Type I. They both use the same compressible system (Oil and diaphragms.) (Figure : 1.) but they differ by the dimensions of their frames. Both are 10 inches in diameter but we have for Type O and Type I respectively :

$d = 5/8$ inch $D = 1\,1/2$ inch .
$d = 7/16$ inch $D = 1\,3/8$ inch .

Where d and D are thicknesses as defined in figure 1. Both cells have been calibrated as explained in reference 5.

Pressure cell Type I was found to be more compressible than dense sand. Pressure cell Type O was less compressible than dense sand (Porosity of the sand : 33 %.).

It seems that even though reference 5 does not mention how to control the compressibility of the pressure cells described, it may be possible to do so.

There is one disadvantage in the use of Plantema's pressure cells which is not mentioned but which is nonetheless important, it is the large size of the membrane of the cells Type I and Type O (10 inches.).

One can imagine that such pressure cells would be inadequate to give information on local stresses or imminent failure. Also it might be difficult with such large pressure cells to determine stress distribution curves under a footing especially when the pressure cells intersect several constant stress lines of the pressure bulb. In the case of figure 3, if the width of the footing b is 5 feet and a pressure cell is placed 15 inches below the footing as indicated in figure 3, it will intersect the lines representing the direct stresses of 0.6q, 0.5q and 0.4q, based on elastic theory and where q is load per unit area on the footing, as on figure 4. The pressure recorded might be roughly of 0.55q to 0.6q, hence there will be an error of 10 to 20 per cent in the reading of the actual stress of 0.5q at the center of the pressure cell. To be added to ,this error is also an error due to the fact that the membrane is restrained on the edges so that the pressure recorded might well be an average of the pressure distribution diagram similar to the one represented in dotted lines on figure 5.

In reference 5, Plantema gives the calibration curves established for his pressure cells Type O and Type I in water and in sand. The set-up used for the calibration of the pressure cells in sand was designed in such a way as to have constant vertical pressures on each horizontal plane through the mass of sand. Because of differences in compressibility between the sand and the pressure cells, the calibration curves in water and in sand for a pressure cell can be different

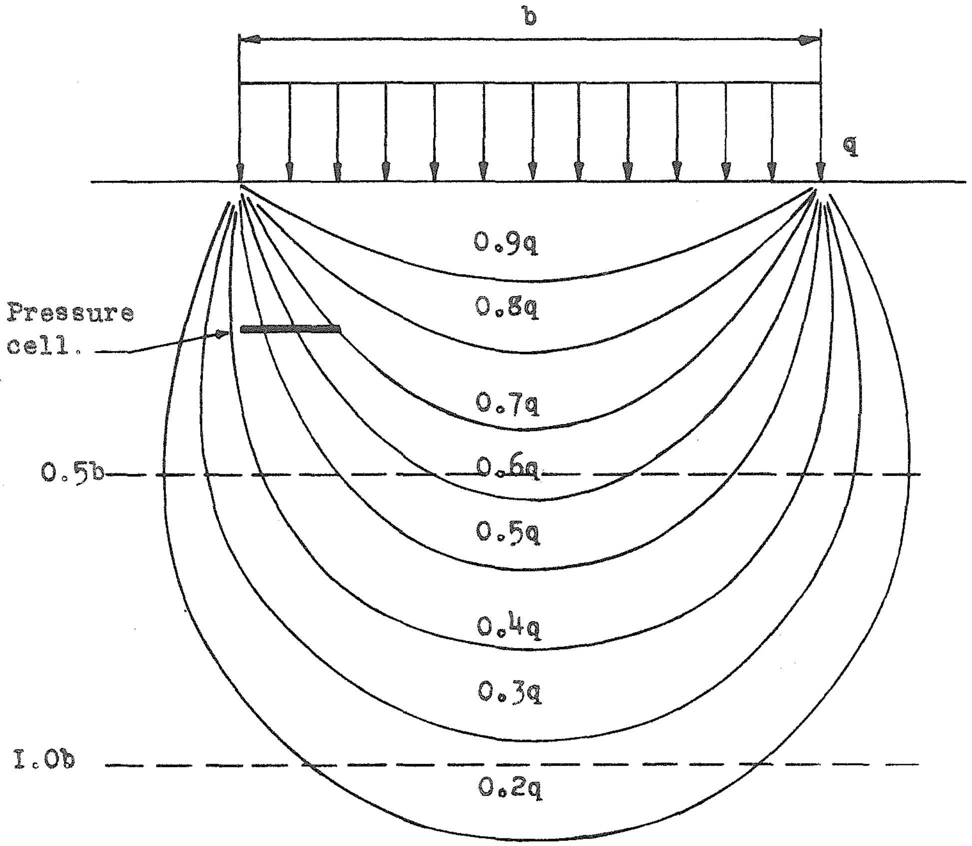
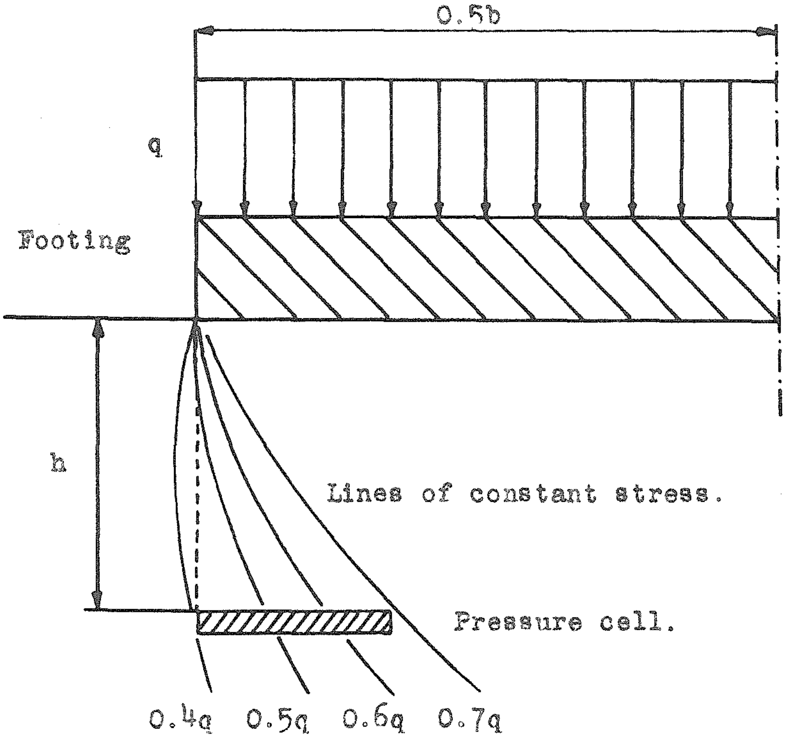


Figure 3: Pressure bulb, vertical stresses on horizontal planes under a circular footing of diameter b loaded with aload q per unit area in an elastic medium.



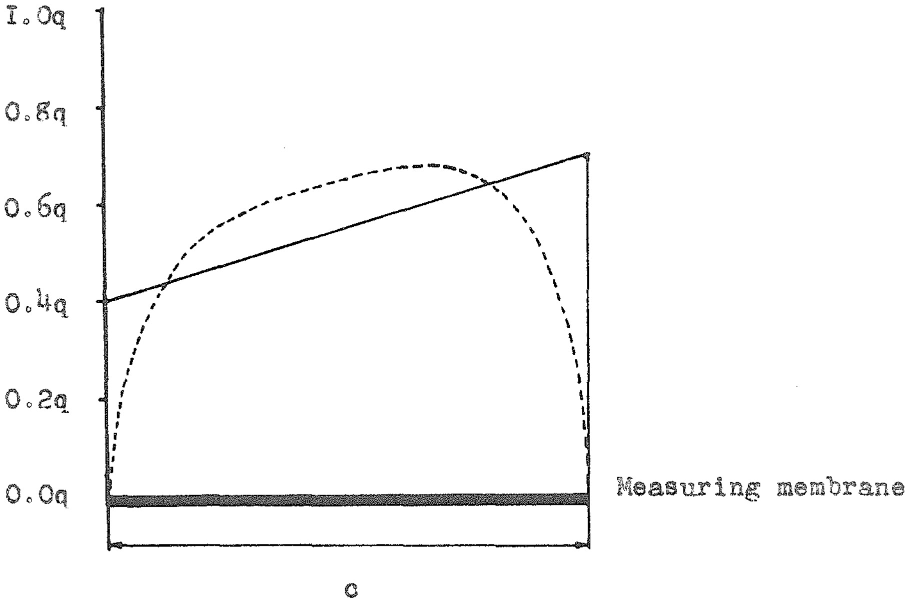
b: diameter of the circular footing. b= 60 inches

q: load per unit area on the footing.

h: depth of the pressure cell in the elastic medium. h= I5 "

Diameter of the pressure cell : I0 inches.

Figure 4 : Pressure cell intersecting the lines of constant vertical stress under the edge of a circular footing.



c: diameter of the measuring membrane. c = I0 inches

q: load per unit area.

———— Vertical pressure distribution in the elastic medium.

------ Vertical pressure distribution of which the average may be recorded.

Figure 5 : Pressure distribution on the measuring membrane of a pressure cell.

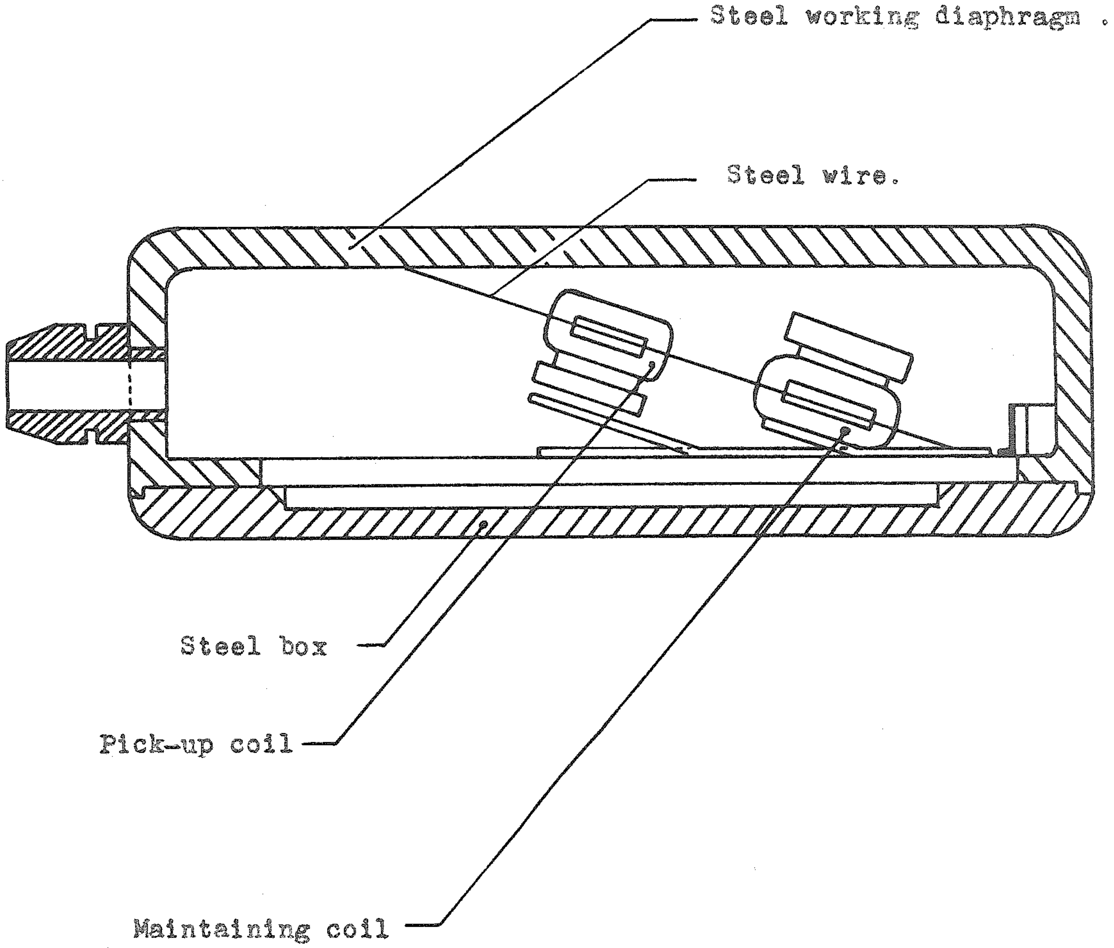
by as much as 30 per cent. Such an error has to be added to the errors due to nonuniform pressure distribution over the surface of the membrane as mentioned above and one can conclude that because of its size and nature, a pressure cell as described by figure 1 can be unreliable.

Important also is the fact that model testing is not to be overlooked in Soil Mechanics and that in this case, the pressure cells described in reference 5 will be of no use once again because of their large diameter.

In reference 6 another type of pressure cell is described (figure: 6). Such a pressure cell though smaller than the ones described by figure 1 is still big (5.5 inches in diameter) and certainly less compressible being entirely metallic. It is stated in reference 6 :

> " Pressure gauges of this type used in soils usually have an elasticity and other mechanical properties very different from the soil in which they are embedded so that errors in measuring can be expected."

In reference 7 the pressure cell of figure 7 is described. A calibration diagram is shown. The pressure cell was calibrated in water and in soil (the kind of soil is not specified). For a pressure of 1 kip per square foot, a difference in reading between the calibration curve in soil and the calibration curve in water is of about 40 per cent, which is quite appreciable. In this pressure cell, nonuniform distribution of pressure on the soil contact face may well cause the inner face of the outer disc of the cell to bear at some point against the outer edge of the inner disc. Hence, part of the load will



Overall diameter: 5.5 inches.

Overall thickness: I.5 inch.

Fundamental vibration frequency of the steel wire: 500 cycles/sec.

Thickness of the working diaphragm: $\frac{5}{32}$ inch.

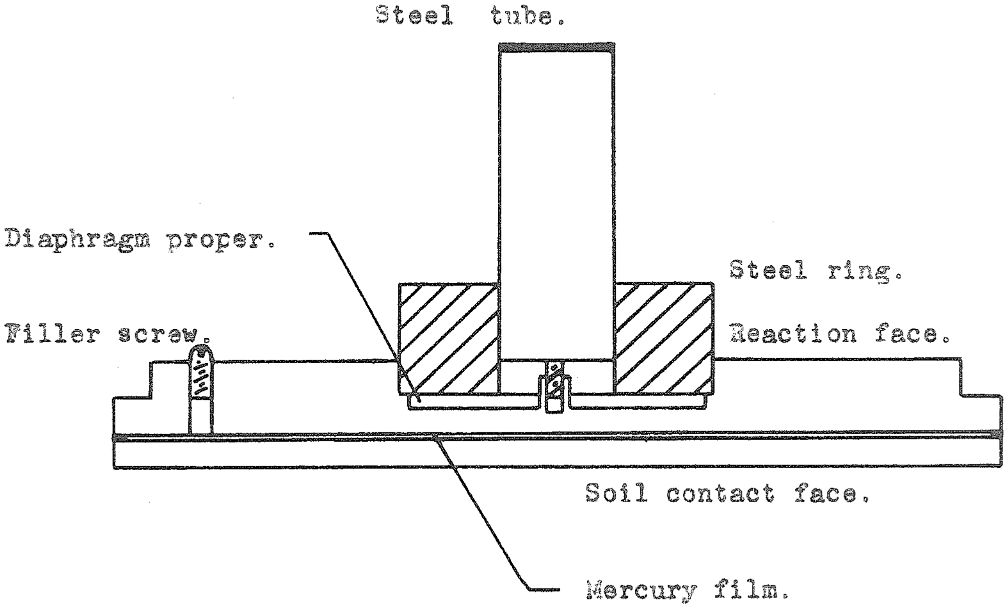
Figure 6 : A pressure cell used in soils (As given in reference 6).

be transmitted directly onto the inner disc and the pressure in the mercury film will be lower than expected. Finally again this pressure cell is of large size, the soil contact face being 7 inches in diameter. So that this cell, as all the ones mentionned in this introduction , will not be able to record local failure nor accurate pressure distribution under a loaded footing.

1.3 Conclusion.

From the above discussion, one may conclude that the main causes of inaccuracy in measuring earth pressures are due to differences in compressibility between cells and soils in which they are used and the size of the measuring element in the pressure cells.

The ability for ,a pressure cell to record stresses in the neighborhood of failure in a soil mass depends on the size of the cell. The smaller the cell the more the local failure stress will have an influence on the magnitude of the average pressure recorded by the working face.



Thickness of the mercury film : 0.012 inch.

Diameter of the soil contact face: 7 inches.

Figure 7 : A pressure cell used in soils (7).

II. DESIGN OF A GRANULAR PRESSURE CELL.

2.1 Introduction.

An ideal pressure cell to be used in soils would be a pressure cell in the form of a granular mass, because the behavior of such a pressure cell under load would be similar to the behavior of an equal mass of soil so long as the size, shape and density of the grains composing the granular pressure cell were similar to the size,shape and density of the grains composing the soil in which it would be used. As far as compressibility is concerned, as defined in reference 5, it is certain that the difference in compressibility between a granular pressure cell and the soil in which it may be used, if there is a difference between the grain size and shape in the soil and the granular pressure cell,would be much smaller than the difference in compressibility between soil and a metallic type of pressure cell.

In addition, a granular pressure cell might be much smaller than a metallic type of pressure cell. One can imagine that a pressure cell composed of grains corresponding to sand grains of medium size (Retained on 65 mesh sieve) and of cylindrical shape about 1/4 inch thick and I inch in diameter might have properties which,varying under different load conditions, would generally represent the behavior of the granular medium as a whole.

Dr. R. F. Scott, Faculty Adviser on the present research suggested that such a pressure cell be constructed of a mass of electrically conducting carbon grains. By putting electrodes on the two ends of the granular pressure cell one might be able to record the variations of electrical resistance due to the variations of surface contact between individual grains under load without the total electrical resistance being influenced by the variations of surface resistance between two particular grains only. A granular pressure cell 0.25 inch thick and 1 inch in diameter would undoubtedly give more accurate pressure readings than any of the large pressure cells described in section 1.2. It would be more sensitive to local variations of pressure in a mass of soil, but this is exactly what is wanted when one desires to have information about incipient failure in the mass of soil investigated. To be mentioned is the fact that if locally we have a transient pressure phenomenon occurring, we might have to cope with the problem of mechanical hysteresis (9, 10).

2.2 Choice of a granular material in the design of a granular pressure cell.

It seems indicated to use grains of an electrically conducting material in a granular pressure cell because it is easier to record changes of electrical properties in a granular mass of small dimensions than to measure changes in mechanical properties. The only recording equipment needed to record changes in electrical properties in a cylindrical granular mass under stress are two electrodes on the end sections of the granular pressure cell and an ohmeter.

My adviser suggested the investigation begin with an examination of the literature in the field of telephones and microphones where small granular masses of carbon have been used for a long time. In these devices, changes in pressure applied on the end sections of the volumes of carbon grains give noticeable changes in the electrical resistance of the mass as a whole.(References 9 and IO.). As is stated in reference 9:

> " One advantage of carbon over any metallic substance is that carbon is practically unoxidisable and unalterable in air."

Some experiments have been conducted in telephony to determine the relationship between the electrical resistance R and the pressure p applied to the contacts of a Blake transmitter (Reference IO.). A Blake transmitter is essentially composed of a mass of carbon granules placed in between two carbon discs. Pressure is applied on the discs and the cylindrical mass of carbon granules is thus compressed, the carbon grains bearing directly against the discs on which the load is applied. Not much information is given in reference I0 about the conditions under which the experiments were conducted, for instance how the load was applied to the Blake transmitter, but it is stated that the electrical resistance R changed from a value of 25 ohms to 2.5 ohms for a variation in force applied on the two end sections of the transmitter of 0.2 grams to I5 grams.

The change in electrical resistance is attributed to the variations in surface contact between grains in the Blake transmitter (Reference 9.). A Blake transmitter has a diameter of the order of 1 inch, hence a cross section of about 0.8 square inch. Hence the maximum pressure applied on the end sections of the Blake transmitter in the experiments described in reference I0 is of about 0.04 pounds per square inch.

The relationship between the electrical resistance R and the pressure p was found to be expressed by an equation of the form :

$$Y^{2}X = C \qquad (1)$$

In which Y is resistance, X is pressure and C is a constant. (9) It was also found that the curve represented by equation 1 was reproducible for a determined value of C so long as the degree of compaction of the granules before each test was the same.

In view of the above given information, it was decided to try to use carbon granules to make a pressure cell to be used in soils. Granular materials other than carbon, of the metallic conductor ,type or semi-conductor type might be used later on in this work or if not,it is suggested that they be investigated in further experimental work .

2.3 Choice of a matrix material.

2.31. Introduction.

It would be difficult to use a granular mass as a pressure cell if that granular mass is not held together in some way. A pressure cell has to be handled easily, carried, reused in different soil masses. It may even have to stand mishandling involving shock and vibration.

Not only must the granular mass constituting a granular pressure cell be held in the form of a volume of constant shape ,under no load, but it has to possess elasticity so that its calibration curve remains constant under identical loading conditions. In this respect it fails to simulate soil but undoubtedly much less than the pressure cells mentionned in section 1.2, for the reasons given in that same section.

A granular pressure cell must also be chemically inert if we do not want it to be deteriorated by water,gases, acids or alkalies which may be present in soils.

The best way to cope with the aforementionned conditions is to take a matrix material which can be easily incorporated throughout the mass of the pressure cell and is elastic, waterproof and chemically inert.

In order to incorporate a matrix material in the granular pressure cell it would be preferable that such a matrix material might be put in the form of a liquid so as to penetrate the entire granular mass thouroughly without leaving any air pockets. If such air pockets were left in the granular pressure cell, that cell would not be incompressible under hydrostatic pressure. Moreover, if such air pockets were big enough to contain several grains, the pressure cell would prove to be very sensitive to handling since those grains would be able to rearrange themselves if not stuck together, and the calibration curve for the pressure cell would be unreliable.

We would like also the matrix material to have a low Young's modulus under compression so as not to influence too strongly the compressibility of the pressure cell itself. If the matrix material is not compressible enough, under a load of, for instance, 5 pounds per square inch, the granular pressure cell might not compress enough to give changes in surface contact resistance recordable.

All the foregoing considerations lead us to think of rubber and polymers as possible matrix material.

2.32 Choice of a matrix material.

From references II, I2 and I3 it appears that none of the different kinds of rubbers and resins have physical and chemical properties in complete agreement with the properties we desire in the matrix material to be used for our purpose. Some resins are inert towards acids and not alkalies (I2) Natural rubber is affected by oxidation, but antioxidation compounds can be used (I2). However, of all the plastics considered, natural rubber possesses the best elastic properties.

One can think of using as a matrix material the material which presents the best mechanical or elastic properties for our purpose and then, as an outer coating, another material which because of its chemical properties satifies the condition of chemical inertness as for instance polyethelene (II, I2).

Natural rubber seems to be indicated for use as a matrix material. Some rubber compounds have moduli of elasticity of the order of I.5 IO^3 pounds per square inch at IO per cent deformation in compression (II). Natural rubber may have a modulus of elasticity even less than that figure.
The moduli of elasticity for the other resins are in the range from IO^4 up to IO^6 pounds per square inch. The elastic properties in rubber are uniformly and isotropically distributed.
Plastic properties are low ; unfortunately the references do not specify in what ranges of stresses and temperatures.
Rubber has more elasticity than any resin known. Elongations of the order of 600 per cent of its initial length can be attained without exessive plastic flow. Rubber in the liquid form also referred to as latex can easily penetrate a mass of grains put in a mold at room temperature as will be shown in further sections of this work. The composite mass of latex and granules solidifies by evaporation of the water contained in the latex which is quite convénient for possible manufacture of granular pressure cells.

Some resins have to be compounded with additives serving as polymerizing agents. The concentration of polymerizing agent in the resin has an influence on the time of polymerization. The relationship in the case of calcium acrylate, for example, is hyperbolic (14). The gel time is inversely proportionnal to the concentration of catalyst used. Figure 9 shows the relationship: gel time versus per cent of catalyst used in the case of calcium acrylate. In mixing the resin and its polymerizing agent, one has to be careful not to introduce any air bubbles in the mixture. These bubbles will modify the elastic properties of the polymerized material.

In our case, small quanties of matrix material will be used: from 3 to 5 cubic centimeters. In such a case, it will be rather difficult to control accurately homogeneous mixing of resin and polymerizing agent, so that an homogeneous polymerizing action will be rather hypothetical. The result will be that the elastic properties of the polymerized material might not be constant throughout the mass.

For all the foregoing reasons, we have chosen to use rubber as matrix in the granular pressure cells to be built. However, this choice must not be considered as completely restrictive. Some other matrix material might be used in some further development of this research work.

It is suggested that in further research, materials such as: polyethelene (12) (13),

butyl rubber (12),

vinylite resins (12, 13),

calcium acrylate (14),

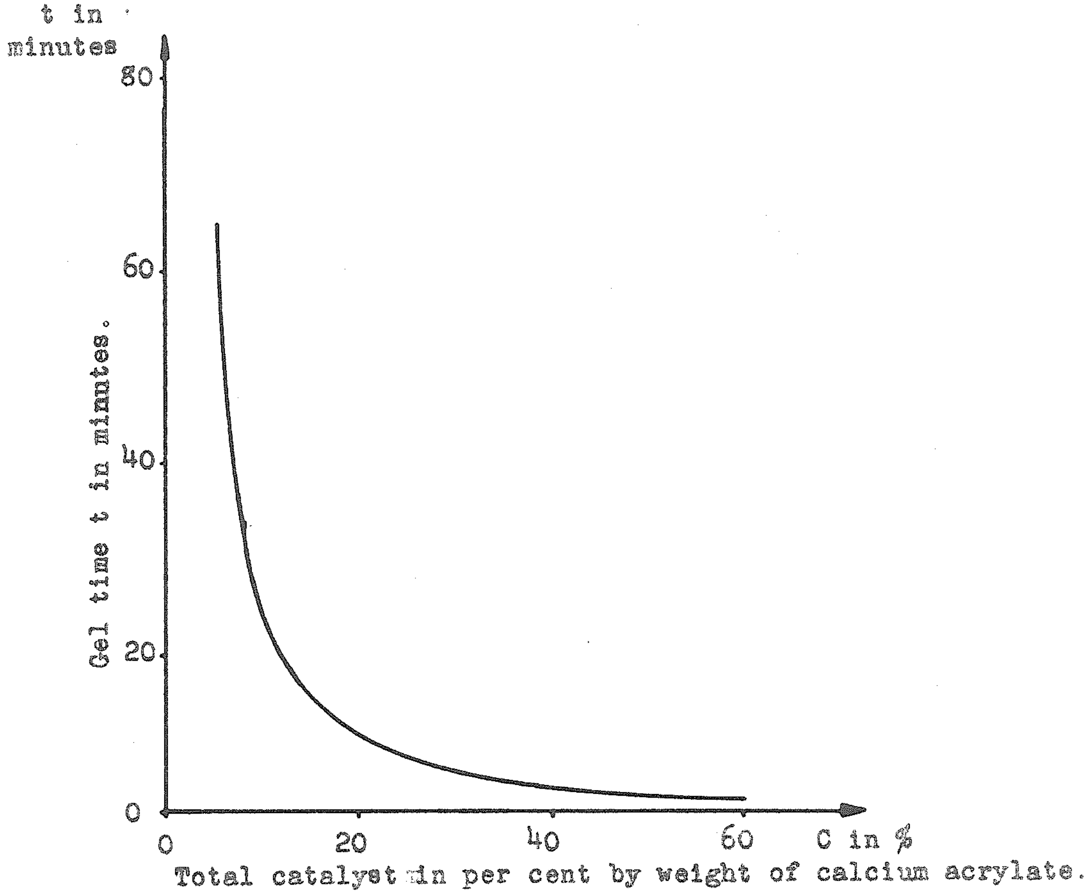
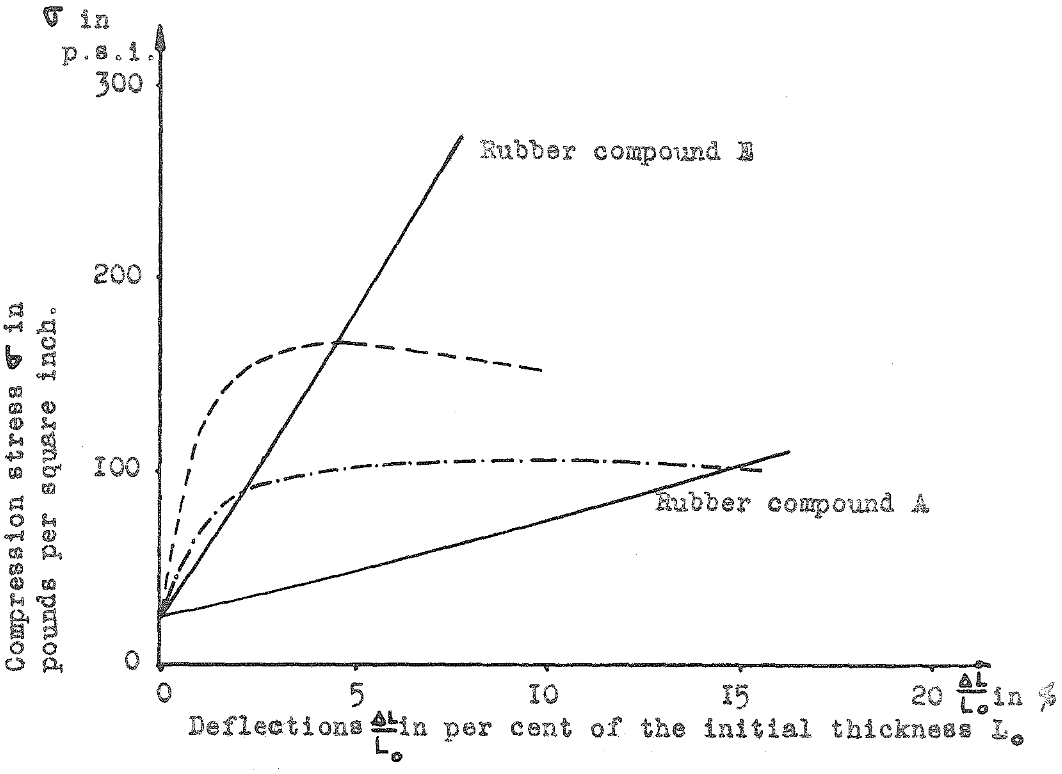


Figure 8 : Influence of the concentration in catalyst on the gel time for calcium acrylate (14).

and other resins whose properties are described in reference I3 be investigated and used. As fast progress is being made in the field of polymer resins it may be that by the time further research work is carried out, new resins will be available which might be more suitable for our purpose than any of the ones known at the present time.

To corroborate the choice of latex as a matrix material it may be interesting to look at figure IO which is a superposition of figure I4.5 in reference 3 and an adaptation of figure 2 in reference II. Figure I4.5 is an example of a stress-strain diagram one can expect to obtain for Fort Peck sand in a constant lateral pressure triaxial test. The lateral pressure σ_3 was of 30 pounds per square inch . Figure 2 in reference II is a stress-strain diagram in compression for five different kinds of rubber compounds whose nature is unfortunately not specified. The compression tests on the rubber compounds were conducted without application of lateral pressure. It is for that reason that the diagram of figure 2; reference II had to be adapted before being used in figure IO of this report.

Rubber is incompressible hence hydrostatic pressure when applied on a piece of rubber will not give any strains. So that to adapt the results of figure2; reference II to figure IO, it is sufficient to translate the stress-strain curves of reference II along the axis of stresses in order to make the origin of the considered curves coincide with the point $\Delta L = 0$; $\sigma = 30$ pounds per square inch in figure IO, where ΔL is strain and σ is stress.



Rubber compounds.

Fort Peck sand : dense $e_0 = 0.605$.

Test FP 4-2-6.

Fort Peck sand : loose $e_0 = 0.834$

Test FP 4-2-2

Constant lateral pressure $\sigma_3 = 30$ pounds per square inch.

Figure 9 : A composite stress-strain diagram for rubber compounds and sand.

So doing, the stress-strain curves for rubber in figure 10 will be similar to what one may expect to obtain in a triaxial compression test. Although the stress-strain curves for rubber represented in figure 10 do not cover the full range of stress-strain curves in compression for rubber one can expect to find, it can be readily seen that it will be possible to find a kind of rubber having appreciably more compressibility than a granular material in a range of vertical compression pressures from zero to about 100 pounds per square inch. Such a matrix material may well not influence too much the compressibility of the granular mass out of which a granular pressure cell will be mainly composed. This last statement will be verified by test.

III. PRELIMINARY EXPERIMENTS .

3.1. Check on the relationship existing between the electrical resistance and the load applied for a cylindrical mass of carbon grains mixed with rubber as matrix material.

3.11. Origin and characteristics of the carbon grains.

For preliminary testing purposes, a cylindrical sample of carbon granules mixed with rubber was prepared in the following manner.

Three carbon rods marketed by the "National Projector Co", under the catalogue number:938 , were put in a piece of cloth and crushed with a hammer. The dimensions of the rods were: diameter :3/8 inch,
length :12 inches.

The cloth was used to prevent the pieces of carbon obtained by crushing being dispersed. Once it could be felt, by touching the cloth enclosing the three carbon rods, that these had been crushed to pieces, the product of the first crushing operation was put in a "U.S. Standard Sieve series" composed of :
sieves number 10, 20, 40, 60, 140, 200.

The sieve series was shaken by hand and the grains passing through sieve number 20 but not through sieve number 40 were retained for our future experiments.

The characteristics of the sieves number 20 and 40 are as follows:

	Sieve number 20.	Sieve number 40.
Nominal opening :	0.84 millimeter.	0.42 millimeter.
	0.0331 inch.	0.0165 inch.
Nominal wire diameter:	0.42 millimeter.	0.25 millimeter.
	0.0165 inch.	0.0098 inch.

The carbon grains we retained for our experiments fall, as far as grain-size is concerned, in the class of medium sand according to the M.I.T. classification (3); we thought it desirable to use grains of about the same size as the 20 - 40 Ottawa sand we were going to use for pressure cell test purposes.

The grains passing through sieves number 40, 60, 140, and 200 were discarded. The grains retained in sieves number 10 and 20 were put back in a piece of cloth and crushed again. A succession of crushing and sieving operations was continued until no material coming originally from the three carbon rods remained in sieves number 10 and 20. After each sieving operation, the grains found between sieves number 20 and 40 were selected and retained for our experiments. A small sample of carbon grains collected on sieve number 40 were taken to room 0016 of the Thomas Engineering Laboratory at C.I.T. in order to be photographed under a microscope. The photographs were taken with equipment 230 - 5 composed of the following instruments :

Microscope : Baush and Lomb LM 4952 - P5 - 26.

Camera : Baush and Lomb P5 - 25.

Lighting source : P 5 - 95.
We used the minimum magnification obtainable (magnification: 20), and an exposure time of 10 minutes. The photographs taken are shown on figures 10 and 11. As a background for the carbon grains put under the microscope,we used millimetric paper. Figures 10 and 11 show that the carbon grains are angular. From the pictures, very little can be said about the aspect of the surfaces of the grains. No photograph of a surface could be taken because of the narrow focal depth of the microscope and probably also because of the poor reflective qualities of the surfaces of our grains. However, from looking at the contours of the grains, one can have an idea about the roughness of the surfaces (Figures 10 and 11.). If we define the roughness r* by the distance between peaks and troughs on the surface and an average plane of reference in the surface, one can say from the photographs on figures 10 and 11 that the roughness r* is of the order of 0.0025 inch or 0.064 millimeters. Figures 10 and 11 show also that the dimensions of our grains are about in the range from 0.05 to 0.025 inch or from 1.3 to 0.6 millimeter.

3.12. Matrix material and its characteristics.

As a matrix material for the grains of carbon [illegible] to be used in our first granular pressure cell, we used a liquid latex called "Lotol LX 497 - 2": Solids : 63.2 % in volume.

Control number : 111723.

Lotol LX 497 - 2 is marketed by the " Naugatuck Chemical, Division of the United States Rubber Co". This latex solidifies by evaporation

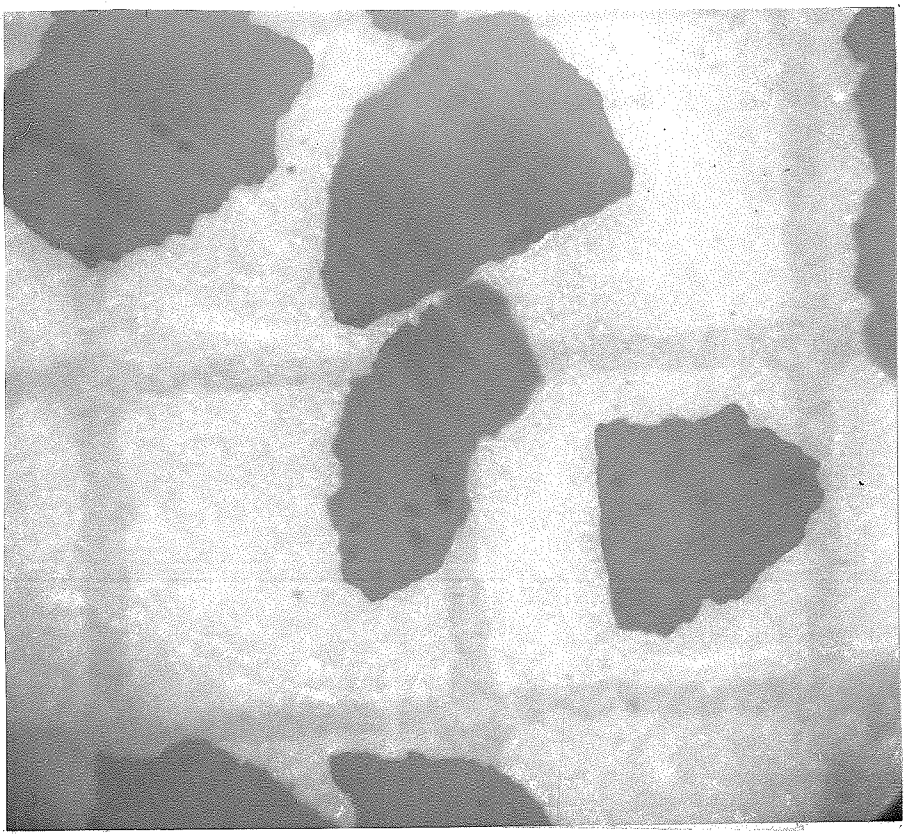


Figure 10 : Carbon grains to be used in granular pressure cells
(magnification : 20).

Figure 11 : Carbon grains to be used in granular pressure cells (magnification : 20).

of the water contained.

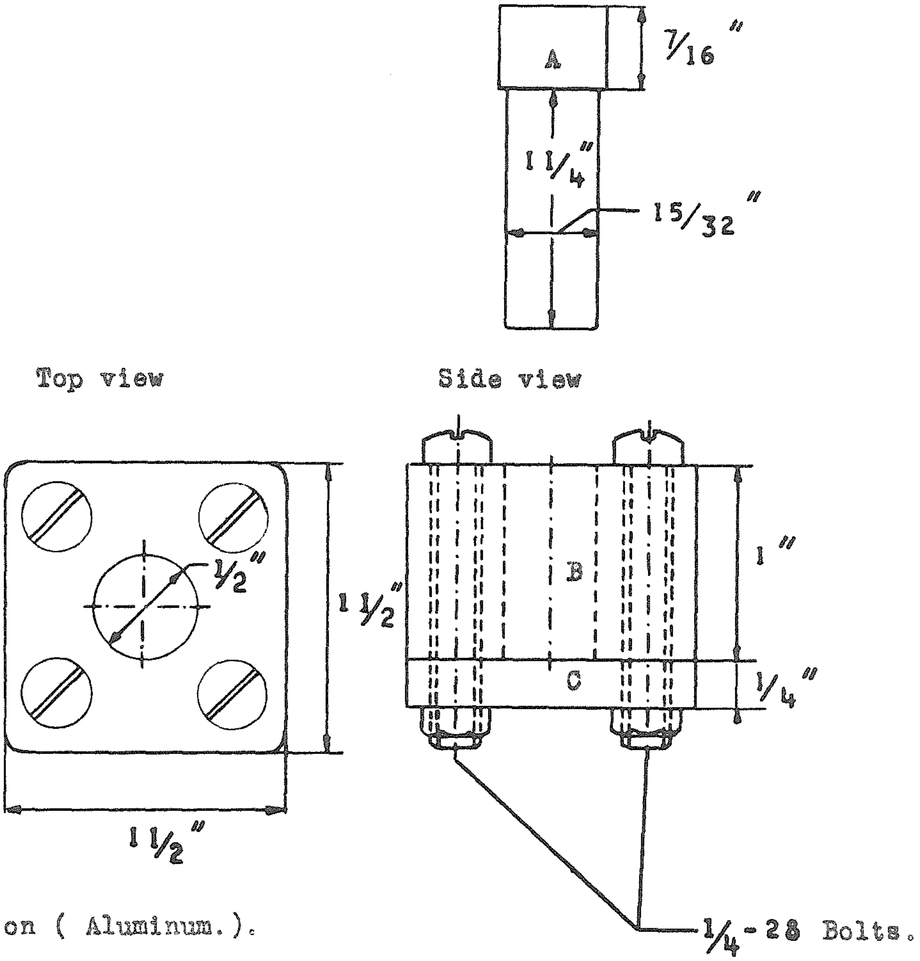
At this point it was decided to determine How much time is needed for a cylinder of carbon grains mixed with latex to dry under the atmospheric conditions existing in the Soil Mechanics laboratory.

3.121. Evaporation tests on cylindrical samples of latex-carbon grains mixtures.

A sample of latex was poured in the mold described by figure 12. A small quantity of carbon grains as described in section 3.11, about 0.5 gram, was poured over the latex in the mold. Piston A was then pressed down by hand until it was impossible to move it further down. The excess of latex flowed out of the mold through the space left between the piston and the bore constituting the cylindrical mold while the carbon grains were forced into the latex and pressed together (Figure 13).

The mold containing the piston and the latex-carbon grains mixture was then put on the balance type Braun number 3 in the Soil Mechanics laboratory. The decrease in weight, of the sample of latex mixed with carbon grains, with time was observed. The results of the observations are given in Table I. Table II is an interpretation of the results given in Table I. Figure 14 is a plot of the figures given in Table II (Curve number 1).

From figure 14 and Table II, we see that 99 per cent of the water in the sample did evaporate in about 24 hours. After 4 hours, 75 per cent of the water had evaporated even though the sample was in its mold and did not present much of its surface



A : Piston (Aluminum.).

B : Mold (Aluminum.).

C : Base plate (Aluminum.).

Figure 12 : Mold used to prepare a sample of latex-carbon grains mixture for an evaporation test.

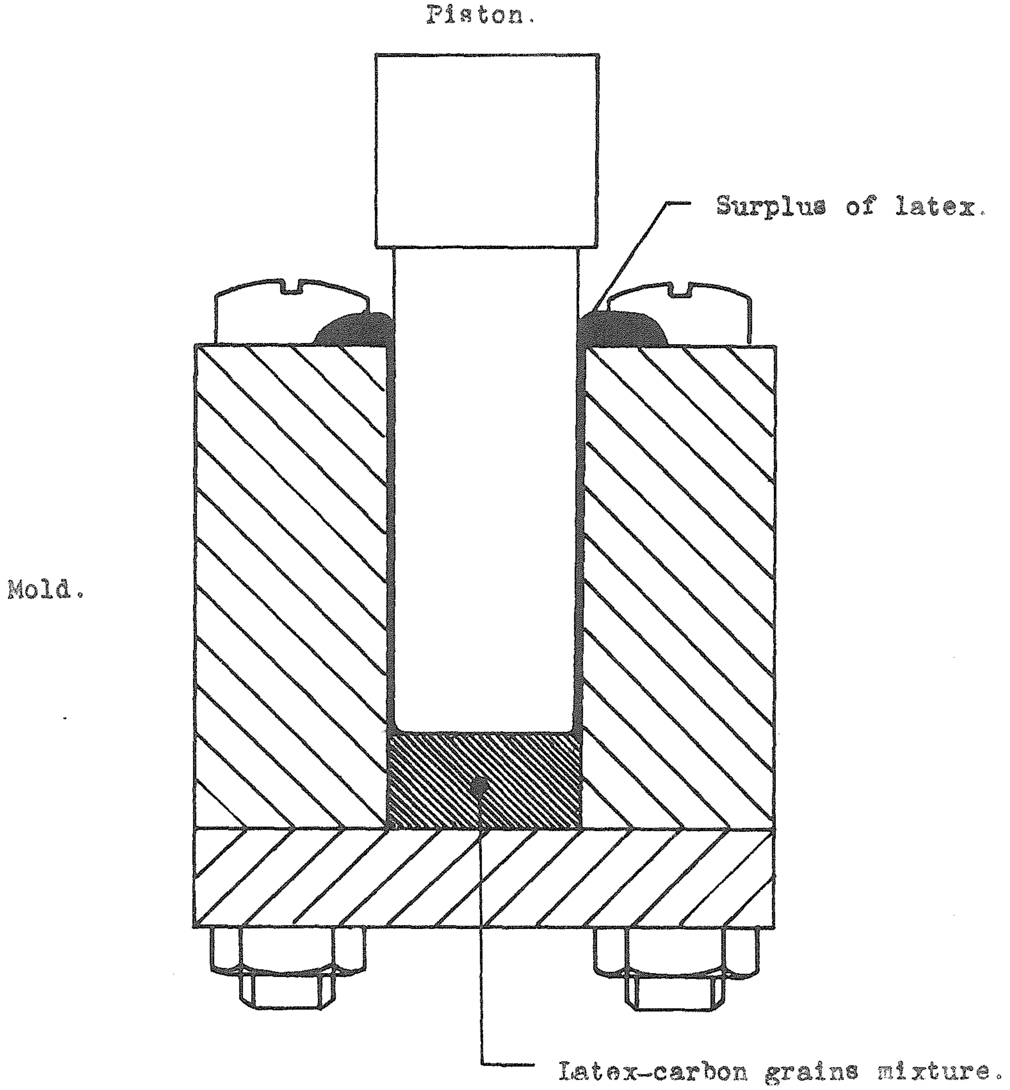


Figure 13 : Section through the mold showing how the surplus of latex can escape while making a cylinder of latex-carbon grains mixture.

Table I : Evaporation test number 1 on a cylinder of latex-carbon grains mixture.

Hour of the day	Time elapsed		Gross weight Samle+mold In grams	Gross weight Sample+mold -base plate In grams	Net weight of the sample In grams
	Hours	Minutes			
10h. 08	0	00	166.365		0.760
10h. 30	0	22	166.295		0.690
11h. 30	1	22	166.200		0.595
13h. 00	2	52	166.130		0.525
14h. 10	4	02		152.315	0.490
15h. 10	5	02		152.280	0.455
16h. 30	6	22		152.260	0.435
17h. 30	7	22			0.427
19h. 30	8	22			0.420
22h. 00	10	52			0.415
Next day					
9h. 30	22	22			0.402
11h. 15	24	07			0.402
13h. 20	26	12			0.401
16h. 50	29	42			0.400

Dimensions of the cylinder : Diameter : 0.485 inch.

Thickness: 0.14 inch.

Table II : Evaporation test number 1 on a cylinder of latex-carbon grains mixture.

Time elapsed		Water content in per cent of the initial water content
Hours	Minutes	
0	00	100
0	22	80
1	22	54.2
2	52	34.7
4	02	25
5	02	15.3
6	22	9.7
7	22	7.5
8	22	5.6
10	52	4.17
22	22	0.56
24	07	0.56
26	12	0.28
29	42	0.0

Weight of moist sample :
0.760 gram.
Weight of dry sample :
0.400 gram.
Initial water content :
0.360 gram.

Table III : Evaporation test number 2 on a cylinder of latex-carbon grains mixture.

Time elapsed		Gross weight sample + mold In grams	Weight of the sample In grams	Water content In grams	Water content in per cent of initial Water content
Hours	Minutes				
0	00	166.345	0.740	0.475	100
0	40	166.305	0.700	0.335	70.5
1	10	166.210	0.605	0.240	50.5
3	00	166.135	0.530	0.165	34.8
4	40	166.09	0.485	0.12	25.3
7	15	166.055	0.450	0.085	17.9
9	55	166.025	0.420	0.055	11.6
24	10	165.99	0.385	0.02	4.2
45	45	165.97	0.365	0.0	0.0
72	00	165.97	0.365	0.0	0.0

Dimensions of the cylinder : Diameter : 0.482 inch.
Thickness: 0.13 inch.

Weight of moist sample : 0.740 gram.

Weight of dry sample : 0.365 gram.

Initial water content: 0.375 gram.

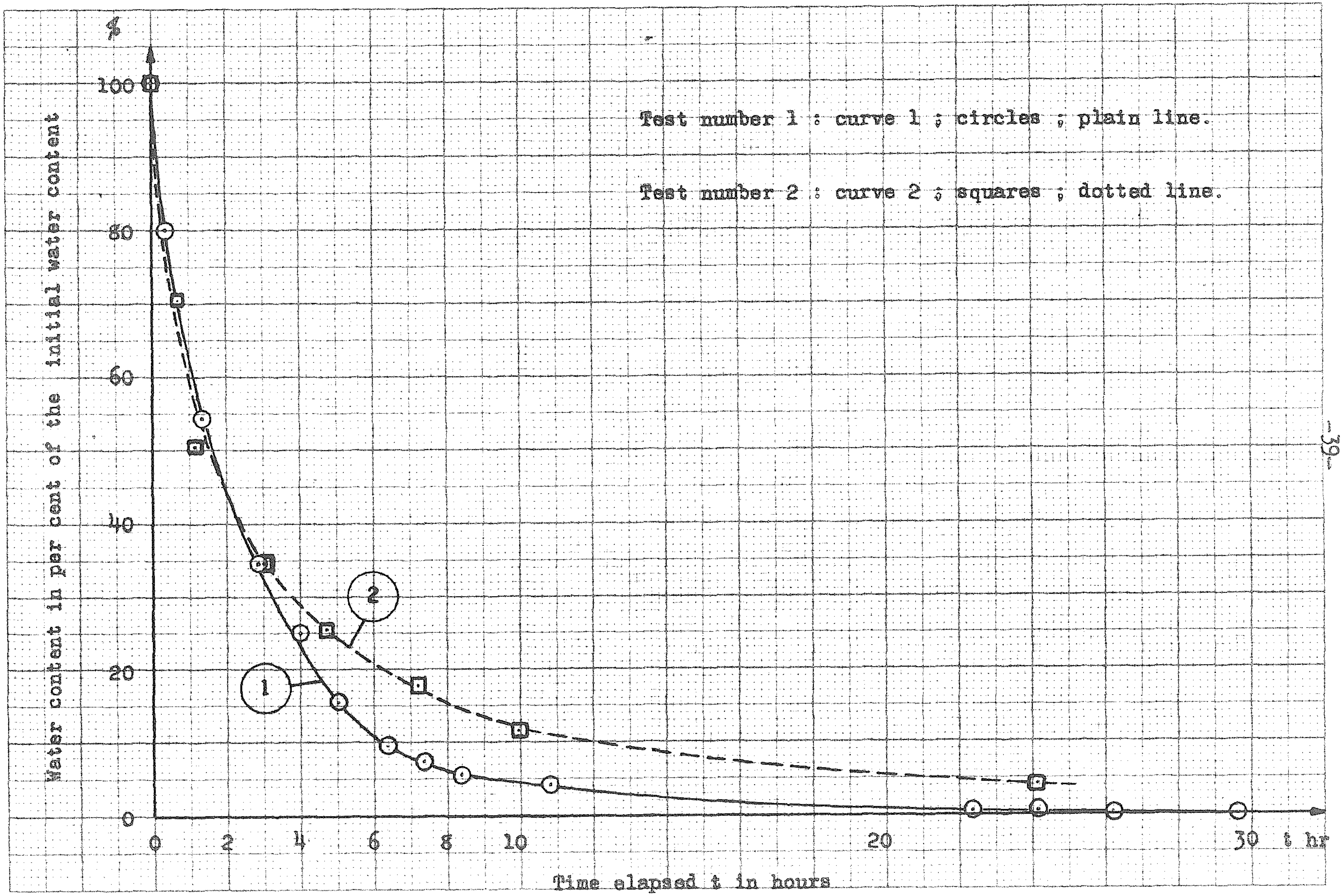


Figure 14 : Evaporation tests on cylinders of latex-carbon grains mixture.

to the air. After 4 hours, the base plate of the mold was removed. So doing the bottom end section of our sample was in contact with air. After 6 hours, the sample was extruded by pressing the piston down into the mold completely. The sample presented enough consistency to be taken up in the hand. After 29 hours, the weight of the sample stabilized at 0.40 gram. The sample was left on the balance for another 5 days during which its weight was checked upon. It proved to remain constant at the aforementioned value of 0.40 gram.

A second evaporation test was conducted. It was similar to the first test in all respects but one, instead of letting the sample of latex-carbon grains mixture dry under atmospheric conditions we put it in a vacuum chamber (figure 15). The results of this test are given in Table III and plotted on figure 14 (Curve 2).

Comparing curve 1 and curve 2, we notice that in our second test the water evaporates faster in the first hours than in our first test, but that after 3 hours, the percentage of water evaporated is about the same in both tests. From then on, water evaporated faster in our test under atmospheric conditions. In our evaporation test under vacuum it took about 45 hours for our sample of latex-carbon grains mixture to dry out although it was almost identical in volume to the sample used in our first test.(Tables I and II). One can imagine that in test number 2, the water evaporated too fast at first so that the evaporation rate was higher than the rate of diffusion of water to the surface of the sample. This situation probably caused the surface to dry out fast enough to restrain the diffusion of water to the surface. This in turn caused the evaporation rate to slow down more appreciably than in test number 1.

From the results of our two evaporation tests, we may conclude that it will be best to let our granular pressure cells to be made, to dry out under atmospheric conditions.

3.13. Triaxial compression test on a Lotol LX 497 - 2 cylinder.

A cylindrical sample of Lotol LX 497 -2 was prepared in the same way, with the same mold as was the cylinder of latex-carbon grains mixture prepared for the evaporation test described in section 3.121. The dimensions of the cylinder of latex were as follows :

Diameter : 0.485 inch.
Thickness: 0.170 inch.

It was put in the triaxial testing machine number 5 of the Soil Mechanics laboratory (Figure 15) in order to establish a stress-strain diagram for our latex in compression. In order to be able to compare that stress-strain curve with the ones on figure 9, a lateral pressure of 30 pounds per square inch was applied by means of compressed air. The vertical pressure was applied by means of weights put on the axial stressing shaft of the testing machine.

The results of the test are given in Table IV and the stress-strain curve for our test is given on figure 16, on which the stress-strain curves for sand of figure 9 are also given.

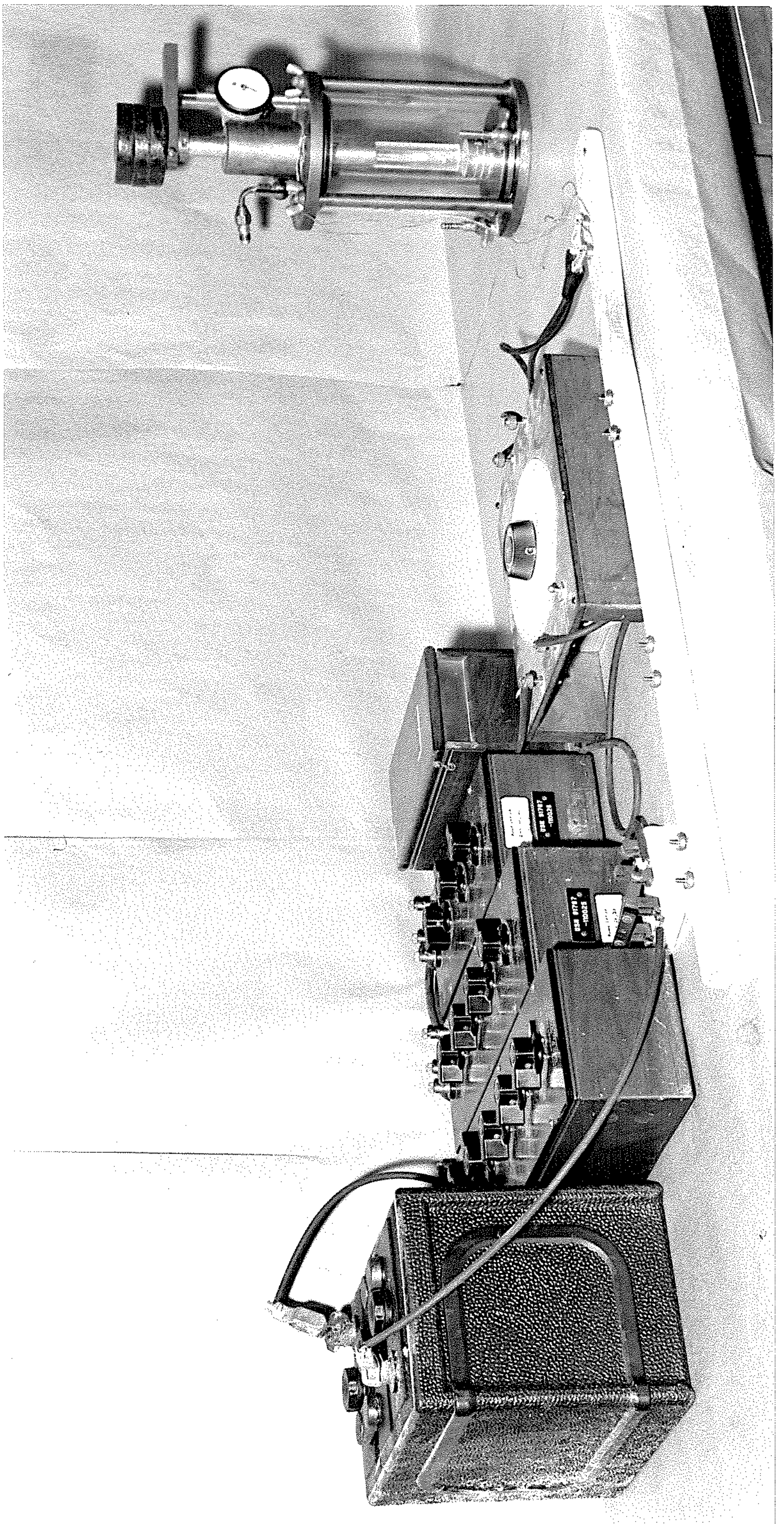


Figure 15 : Set-up comprising the triaxial testing machine used to test a cylinder of Lotol LX - 497 - 2.

Table IV : Triaxial compression test on a cylinder of latex.

P In pounds	σ_1 In p.s.i.	ΔL In $\frac{\text{inch}}{1000}$	$\frac{\Delta L}{L_0}$ In %
23	30.0	0.0	0.0
28	42.7	16.7	9.8
33	55.4	33.5	19.7
38	68.1	50.5	29.7
43	80.8	61.0	35.9
48	93.5	67.5	39.7
53	106.2	73.0	43.0

Material tested :

Lotol LX 497 - 2.

Lateral pressure : $\sigma_3 =$ 30 pounds per square inch.

Dimensions of the cylinder : Diameter : 0.485 inch.

Thickness: 0.17 inch

σ_1 : vertical pressure in pounds per square inch.

P : load applied in pounds.

ΔL : changes in thickness in thousands of an inch.

$\frac{\Delta L}{L_0}$: elongation in per cent of the initial thickness L_0.

Rate of loading : 5 pounds every 10 minutes.

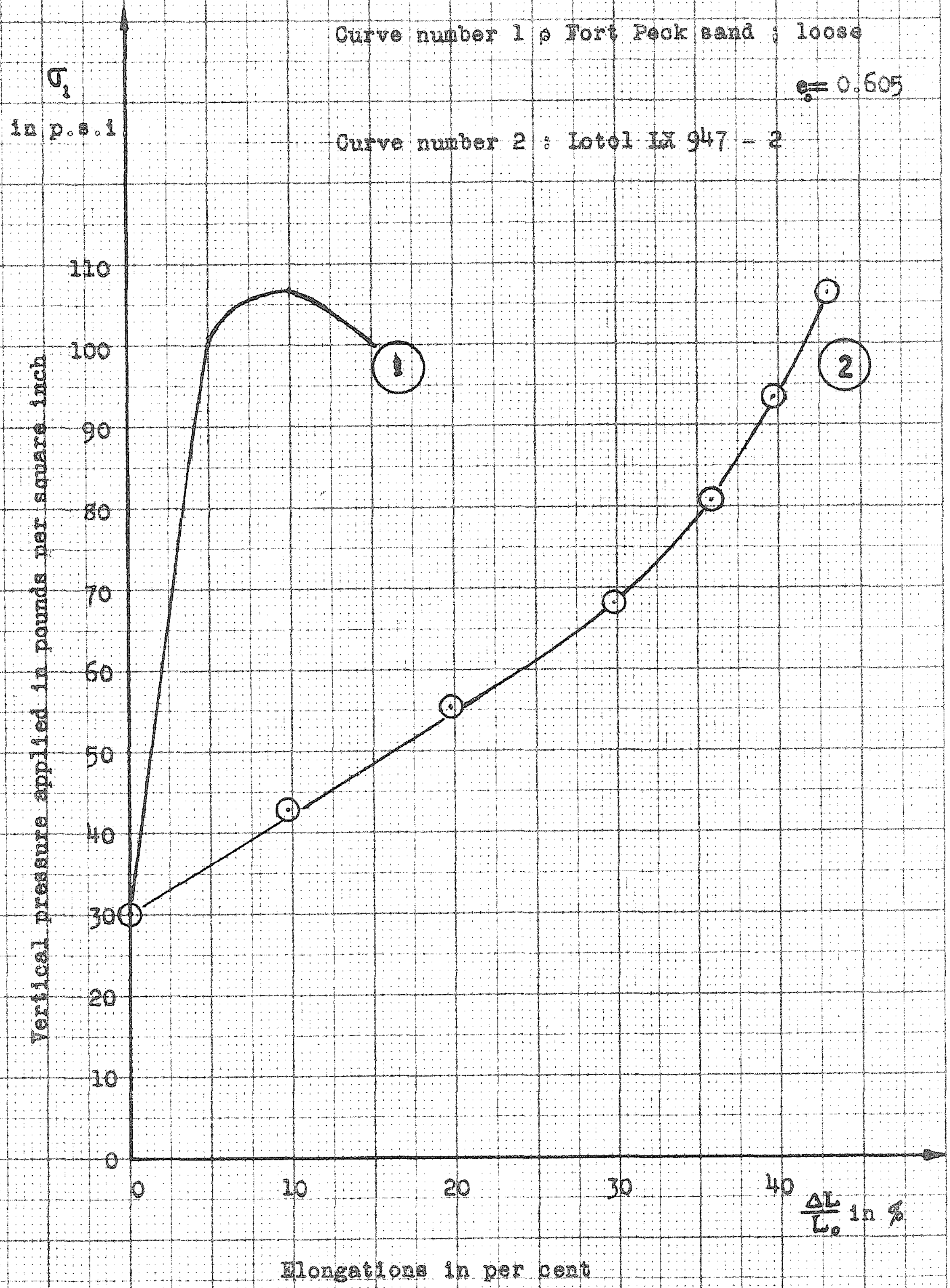


Figure 16 : Stress-strain curve for Lotol LX 947 - 2

For a vertical pressure of 60 pounds per square inch, we see on figure 16 that the sample of loose Fort Peck sand has undergone an elongation of about 1.75 per cent whereas Lotol LX 947 - 2 under the same load has undergone an elongation of about 23 per cent hence, much more than sand in a loose state. Undoubtedly, if the latex had been filling the pores of the sample of Fort Peck sand, the elongation under the vertical pressure aforementionned for the mixture would have been very close to the one undergone by the sand alone, the elongation for pure latex being much more important in magnitude than for sand. In conclusion, for a cylinder composed of a granular mass enrobed with latex, the straining behavior of the mixture in a loading test will be influenced predominently by the straining behavior of the granular mass. However, this conclusion is not true anymore in an unloading test. The mixture of grains and latex will tend to resume its original shape under decreasing loads provided it is elastic. As a granular mass does not have much elasticity, the degree of elasticity of the mixture will depend mostly on the elastic properties of the latex.

Therefore, while loading a cylinder of carbon grains mixed with latex, the behavior of the mixture will be conditioned by the straining behavior of the granular mass whereas while unloading, the recovery will be conditioned by the elastic behavior of the matrix material. This is precisely what we want for our granular pressure cells.

3.14. Preparation of a granular pressure cell.

A mold was made out of sheet metal as shown in figure 17. The triaxial testing machines used in the Soil Mechanics Laboratory have been designed to test cylindrical soil samples 1.25 inch in diameter. This is why the inner diameter of the mold has been chosen accordingly (1.25 inch). The granular pressure cell produced by means of that mold was fitting the triaxial testing machines without having to modify them.

The set-up used in order to make the pressure cell is sketched and described in figure 18. The stoppers which close the end sections of the mold are provided with 0.125 inch in diameter glass tubing so that vacuum can be connected at one end of the mold and the liquid latex jar at the other (figures 17 & 18). The stoppers are also provided with number 140 wire mesh (nominal opening : 0.0041 inch or 0.098 millimeter) to prevent the carbon grains enclosed in the mold from escaping through the glass tubing. Vacuum is put at one end of the mold to help the latex flowing through the mass of carbon grains in the mold and to try to prevent air pockets from being entrapped in the granular pressure cell prepared.

The grains of carbon we retained for our experiment were poured in the mold in successive layers about 1 inch thick, each pouring operation being followed by a compaction operation. The compaction operations were not conducted in a standard manner as is done in general in Soil Mechanics because we expected

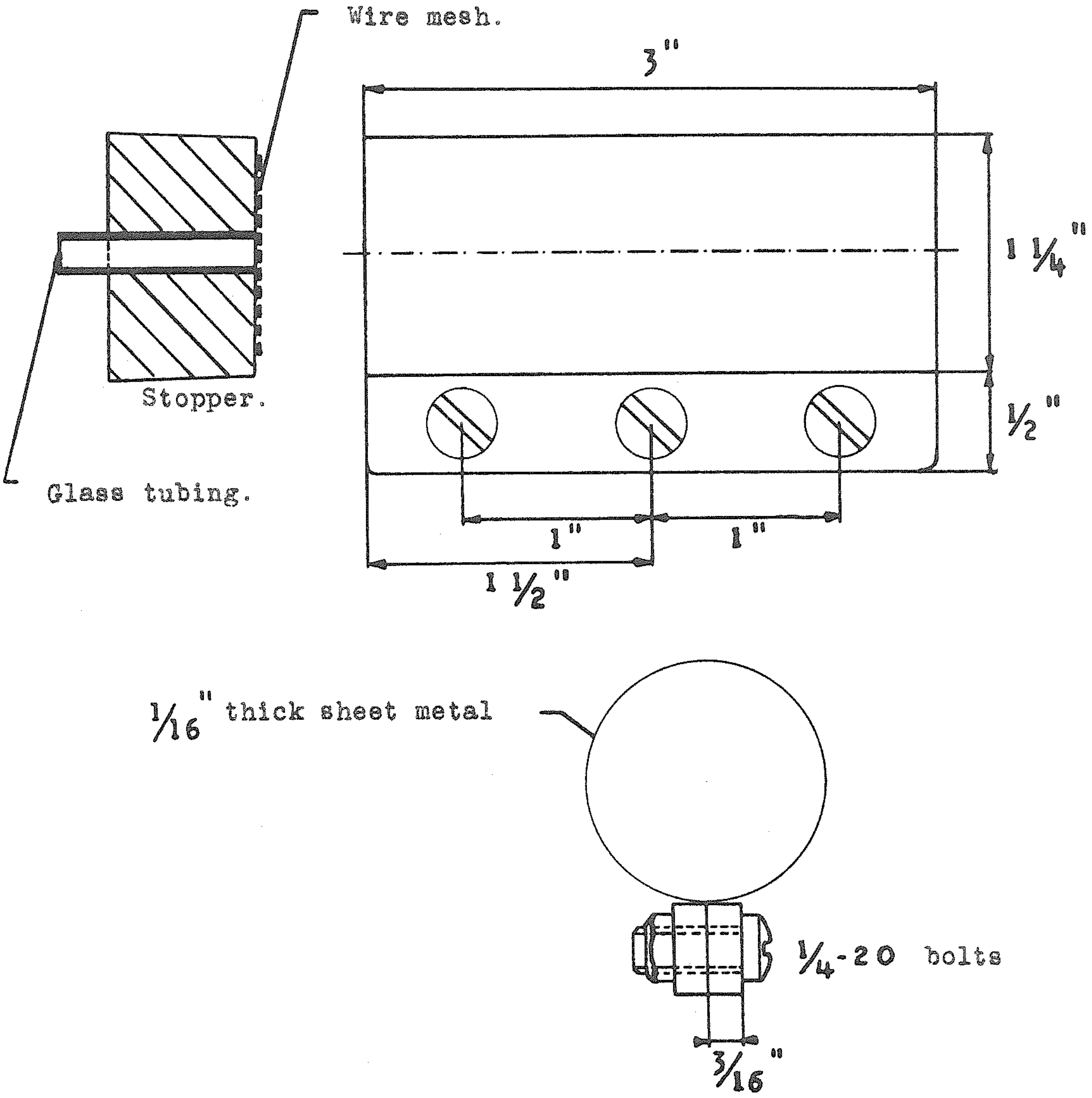


Figure 17 : Mold used for making pressure cell number 1.

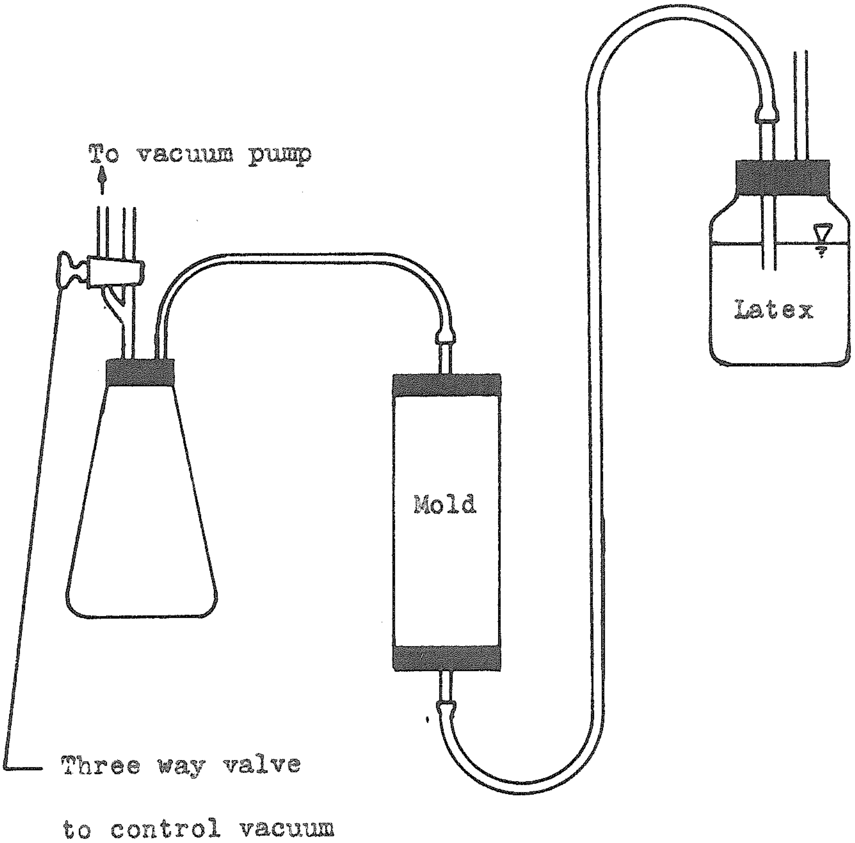


Figure 18 : Set-up used to fill the mold containing carbon grains with liquid latex.

the granular mass to be rearranged and compacted by the mere fact of connecting vacuum at one end of the mold,which means that if the vacuum is total, the granular mass would be subjected to a pressure of about 15 pounds per square inch on its end sections. As a matter of fact, once the mold was disconnected after the latex filling operation,we noticed that the carbon grains had been compacted against the vacuum side section and that at the latex inlet side, a cylinder about 0.25 inch thick of pure latex had developed between the stopper and the carbon granular mass, although the stoppers were pressed in tight against the grains before the mold was put in place for the latex filling operation.

Four hours after the filling operation had begun, we noticed that the level of the latex in the jar was not moving any more. An indication that the latex had stopped flowing through the mass of carbon grains. The operation was then discontinued. The mold was left to dry for twenty four hours before putting electrodes on the end sections. According to the results obtained in the evaporation test, we thought it was safe to unmold the granular pressure cell after about 5 hours. Although our pressure cell does not have the same dimensions as the sample used in the evaporation test, a rapid calculation shows that the volume of our pressure cell is of about 2.35 cubic inches versus 0.49 cubic inches for the sample used in the evaporation test. The total surface of our pressure cell is about 11 square inches versus 1.17 square inches for the sample of the evaporation test. Hence, the ratio of the volumes is about 4.7 whereas the ratio of the surfaces is about 9.4. Therefore, even though we have more water to evaporate in our pressure cell, we have 9.4 times more surface for evaporation. Hence we can expect our pressure cell to dry at least as fast as the sample used in the evaporation test. It is thus conservative to consider the pressure cell to be dry at 90 per cent after 5 hours and completely dry after 24 hours (According to Table II.).

When the granular pressure cell was removed from its mold, we noticed that the latex had penetrated only to a depth of 0.5 inch in the mass of carbon grains. As no test on the viscosity of our latex has been made, and the compaction of the carbon grains in the mold was unknown, it was impossible to estimate what the loss of head in the granular mass was and determine how far into the granular mass the latex could have gone. It should not be forgotten that under vacuum the evaporation was accelerated and that because of this, the viscosity of the inflowing latex was changing. The discharge of the latex into the granular mass was not measured, making it difficult to estimate what the influence of the change in viscosity of the inflowing latex might have been on its depth of penetration in the mold. Unless we find another method for making pressure cells, measurements of the degree of compaction, the viscosity of the latex and the change of viscosity with time under vacuum and the discharge of latex in a mold containing a compacted mass of carbon grains will have to be made in order to be able to control the thickness of the granular pressure cells to be made.

We took Woods metal in order to provide the pressure cell with electrodes. The surfaces of the end sections of our pressure cell were rough to the order of the size of the carbon grains used. The roughness of the surfaces was due to the fact that they were not bearing against the flatter surfaces of the stoppers, at both ends of the mold . Hence, in order to have good contact between the end surfaces of our pressure cell and the electrodes, we needed to have an electrode metal which could be applied to the pressure cell in a liquid form. Woods metal has the advantage, in our case, of being liquid at a temperature of the order of 70 degrees centigrade, which is low enough to deteriorate neither the carbon grains nor the latex matrix material. One disadvantage of Woods metal is that, because of surface tension, it cannot be poured in small thicknesses. The thickness of our electrodes was of about 1/8 inch. Also, it is, as all metals, rigid at room temperature compared to the main body of our granular pressure cell. It was noticed that the electrodes would not stick too well to the granular mass. While turning over the pressure cell, after having poured one of the electrodes with its lead enrobed in the electrode while pouring, (Figure I9.), the pressure cell hit an object lying on the bench where the pouring operation was performed and the electrode fell off. This is probably due to the fact that the weight of the electrode was enough to overcome the adhesion between the end sections of the pressure cell and the surface of the electrode which was applied to it.

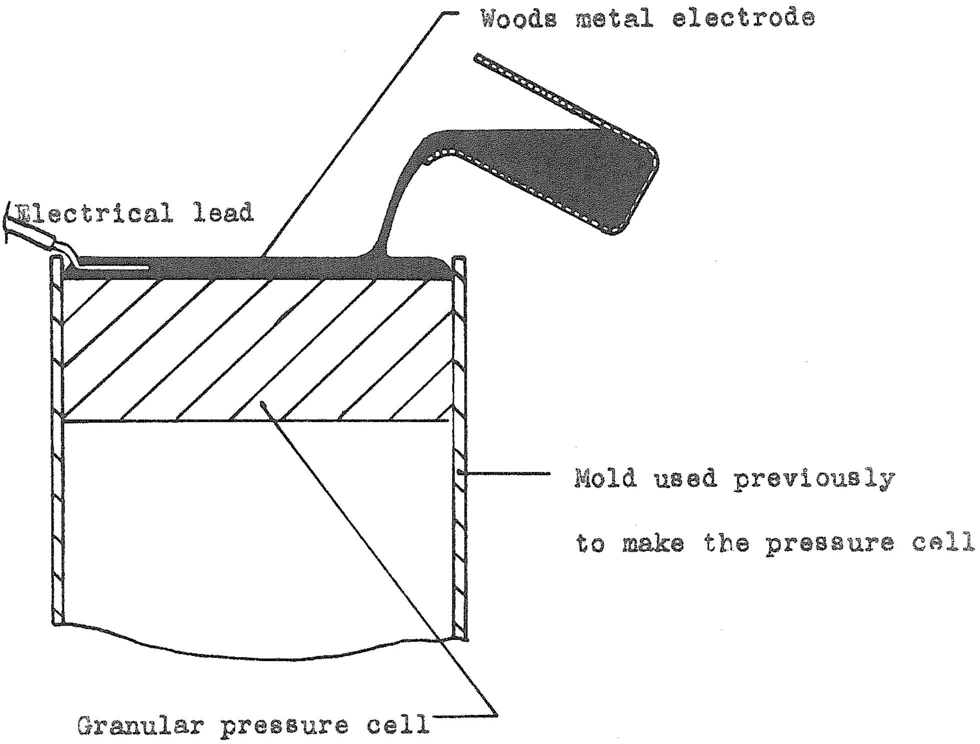


Figure 19 : Electrode pouring operation.

After the electrodes were poured, the pressure cell was dipped in latex to provide an all around coating of about $1/32$ inch to help the electrodes stick on the pressure cell when not submitted to compression. For this preliminary test, we were not concerned too much with the deficiencies of the electrodes pointed out earlier because our granular pressure cell number I was not made having in mind to use it for any other purpose than to check on the relationship existing between compressive pressure applied to the end sections of the pressure cell and the electrical resistance of the pressure cell.

However, what we learned in making pressure cell number I will be helpful in further developments.

3.15. Compressibility test.

A compressibility test was run to check if any air pockets were left in pressure cell number I. It was put in one of the triaxial testing machines of the Soil Mechanics Laboratory (Figure 20.). The leads were connected to the Simpson ohmeter model 260 number 6718 M. found in room 06 of the Thomas Engineering Laboratory building at C.I.T. The pressure was applied uniformly all around the pressure cell by means of compressed air. The range of pressures applied was from 0.0 to 40.0 pounds per square inch. The results of the compressibility test are given in Table V. No variations of electrical resistance was observed, meaning that the pressure cell was incompressible.

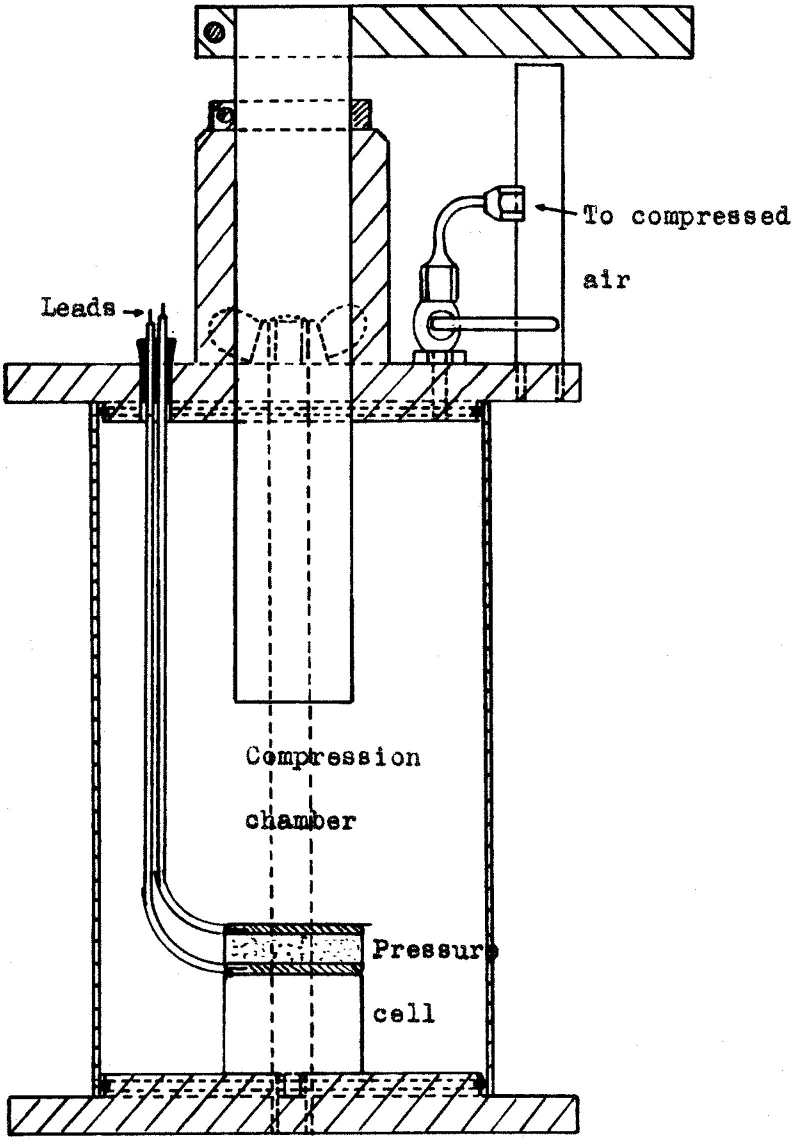


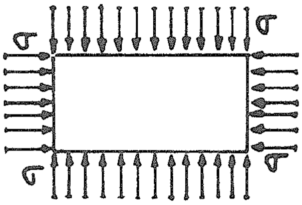
Figure 20: Compressibility test on pressure cell number 1.

Table V : Compressibility test on pressure cell numberI.

σ In p.s.i.	R In ohms
0	3.3
1	3.3
2	3.3
3	3.3
5	3.3
10	3.3
15	3.3
20	3.3
25	3.3

R : electrical resistance in ohms.

σ : pressure applied to the pressure cell in pounds per square inch.



3.16. Compression tests on granular pressure cell number 1.

3.161. Testing set-up.

The triaxial testing machine containing pressure cell number 1 was put in the loading system of figure 21 which is self-explanatory.

3.162. Compression tests.

No lateral pressure was applied to the pressure cell. Once the triaxial testing machine was in place, the zero of the dial of the weighing scale was adjusted so that in our readings the weight of the testing machine would not be included. The load was applied by turning screw A in contact with the loading shaft of the testing machine. The load was read off the dial of the weighing scale. To have the pressure applied per unit area, it sufficed to divide the load read by the area of the cross-section of the pressure cell.

Four tests were conducted. Test number 4 included also an unloading test. The results of these tests are given in Table VI and are presented on figure 22.

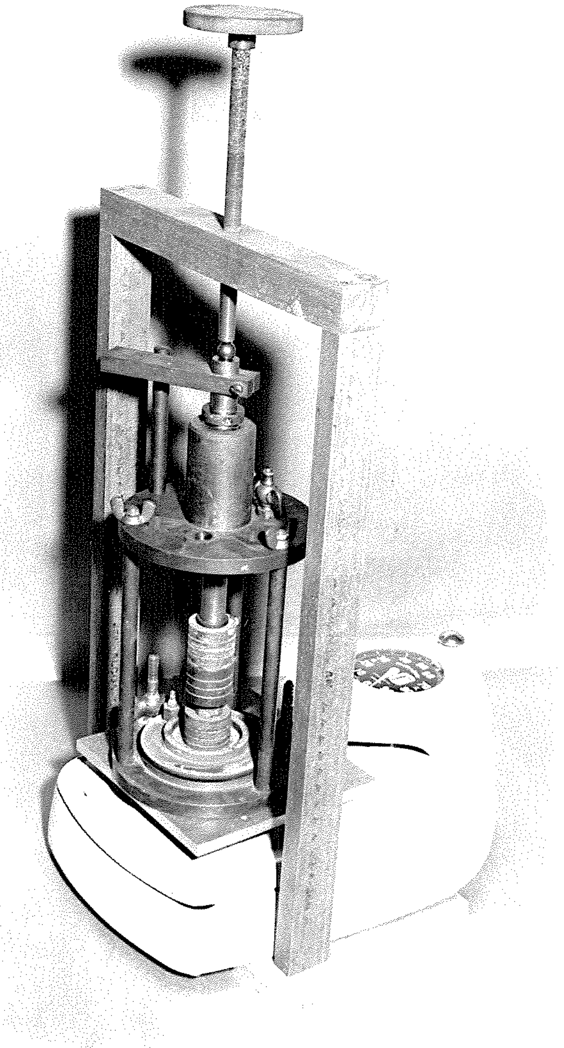


Figure 21 : Set-up used to test pressure cell number 1 in compression.

Table VI : Compression tests on granular pressure cell number 1.

Test number 1.

σ_1 In p.s.i.	R In ohms
0.0	1.3
0.65	1.0
1.3	0.75
2.6	0.6
6.17	0.5
10.7	0.4
45.0	0.3

Test number 2.

σ_1 In p.s.i.	R In ohms
0.0	1.3
0.65	1.0
1.3	0.75
2.3	0.6
3.25	0.5
13.0	0.3
45.0	0.25

Dimensions of pressure cell number 1 : Diameter : 1.25 inch.

Thickness: 0.5 inch.

R : electrical resistance of the pressure cell in ohms.

σ_1 : vertical pressure applied in pounds per square inch.

Electrical current passing through the pressure cell :

5.10^{-5} amperes.

Table VI : Compression tests on granular pressure cell number 1 (Continued).

Test number 3		Test number 4 (Loading)		Test number 4 (Unloading)	
σ_1 In p.s.i.	R In ohms	σ_1 In p.s.i.	R In ohms	σ_1 In p.s.i.	R In ohms
0.0	1.3	0.0	1.3	39	0.24
0.52	1.0	0.52	1.0	30.5	0.25
0.97	0.75	0.78	0.75	20.0	0.3
1.82	0.6	1.82	0.6	8.4	0.4
2.72	0.5	2.46	0.5	4.9	0.5
4.2	0.4	3.6	0.4	3.25	0.6
9.2	0.3	5.8	0.3	1.17	0.75
18.8	0.25	10.5	0.25	0.0	1.0
29.0	0.24	20.0	0.24		

The symbols are as defined on page 57.

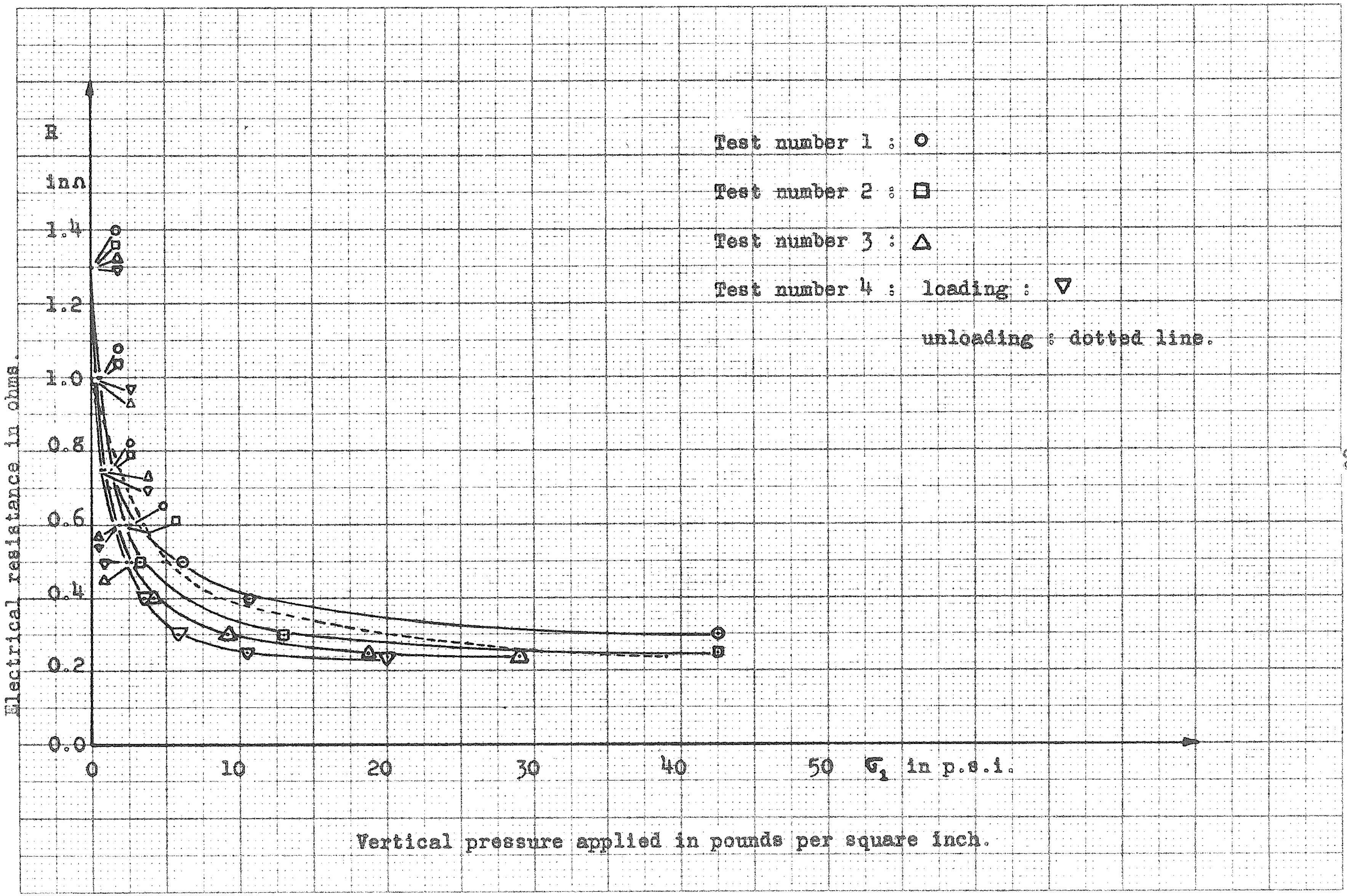


Figure 22 : Compression tests on granular pressure cell number 1.

3.17. Discussion of the compression tests on pressure cell number 1.

3.171. Electrical section.

3.1711. Testing set-up.

The ohmeter used in our tests, although in good operating condition, had the disadvantage that its zero drifted with time so that it had to be corrected constantly. At some times a drift of as much as 0.5 ohms read on the scale of the ohmeter occurred. This is quite appreciable unless we read an electrical resistance of about 50 ohms, in which case a drift of 0.5 ohms represents an error of 1 per cent in reading. However, if we consider the curves of figure 22 and we have to read the vertical pressure off one of these curves in the neighborhood of 10 pounds per square inch, an error of 0.5 ohms may correspond to an error in reading the pressure of 0.5 pounds per square inch or a non-negligible 5 per cent of the nominal value of pressure to be read. Therefore, the use of a Wheatstone bridge is recommended for future testing. It is a piece of apparatus generally used for the measurment of small and medium resistances (18).

3.1712. Electrical resistance.

The low electrical resistance of the pressure cell made it very difficult to make accurate readings on the ohmeter used. It will be necessary to investigate the possibilities of increasing the value of the electrical resistance of the granular pressure cells to be built in the future, under no vertical load applied, so as to enable us to establish calibration curves for such pressure cells in a range from about 100 to 10 ohms let us say, for vertical pressures applied from zero to about thirty pounds per square inch.

In the incompressibility test, we found an electrical resistance, for pressure cell number 1, of 3.30 ohms which is quite different from the value of 1.30 ohms found in our compression tests. This is due to the fact that in the compression tests made, the granular pressure cell was at all times subjected to the load of the loading shaft of the triaxial testing machine. So that actually, to the figures for pressure in Table VI, we ought to add the pressure due to the weight of the loading shaft of the testing machine. This correction was not made on the figures of Table VI because, as already mentioned, the purpose of this series of four tests was only qualitative and not quantitative.

3.172. Stress and strain section.

Unfortunately, no recording was made of the strains under load which occurred in the granular pressure cell. In the higher range of loads, from 10 to about 40 pounds per square inch, we had to adjust the loading screw continuously so as to keep the load applied to the pressure cell constant.

However, it was observed that the variations in load applied from the value decided upon were the largest in the very first minutes after the load was applied, that those variations were of the order of 0.7 per cent of the load applied, and that these variations were becoming smaller from one full loading test to another. Those variations indicate that the pressure cell was not behaving elastically under load but that after an as yet undetermined number of loading tests, one may expect a pressure cell to behave elastically. This will have to be checked in further testing.

The nonelastic behavior of pressure cell number 1 can be attributed to two reasons :

1. There is plastic flow of the latex.
2. When a mass of sand is subjected to a load, most of the deformation takes place almost instantaneously, but not all of it (3).

Figure 10.4 page 217 of reference 3 is a time curve for a typical load increment on sand. On that figure one can see that after 6 minutes, about 98 per cent of the compression has taken place. It is stated in reference 3, pages 216 and 217 :

> " After an increment of load has been applied, there is not a uniform and smooth rearrangement of grains from initial to final positions, but a successive irregular, localized building up and breaking down of stresses in grain groups. A continuous rearrangement of particles that are pressed tightly together and rolling on ,each other at one instant may in the next instant undergo a sudden jump in position relative to each other. The time lag in reaching the final state is called the frictional lag."

In view of the kind of carbon grains we used in our granular pressure cell number 1, we may expect frictional lag to occur while loading the pressure cell.

3.173. Stress - electrical resistance relationship.

As can be seen on figure 22, the tests conducted on pressure cell number 1 show a definite relationship between the vertical pressure applied and the electrical resistance R of the granular pressure cell. This was what we wanted to check. On figure 23, we plotted the law :

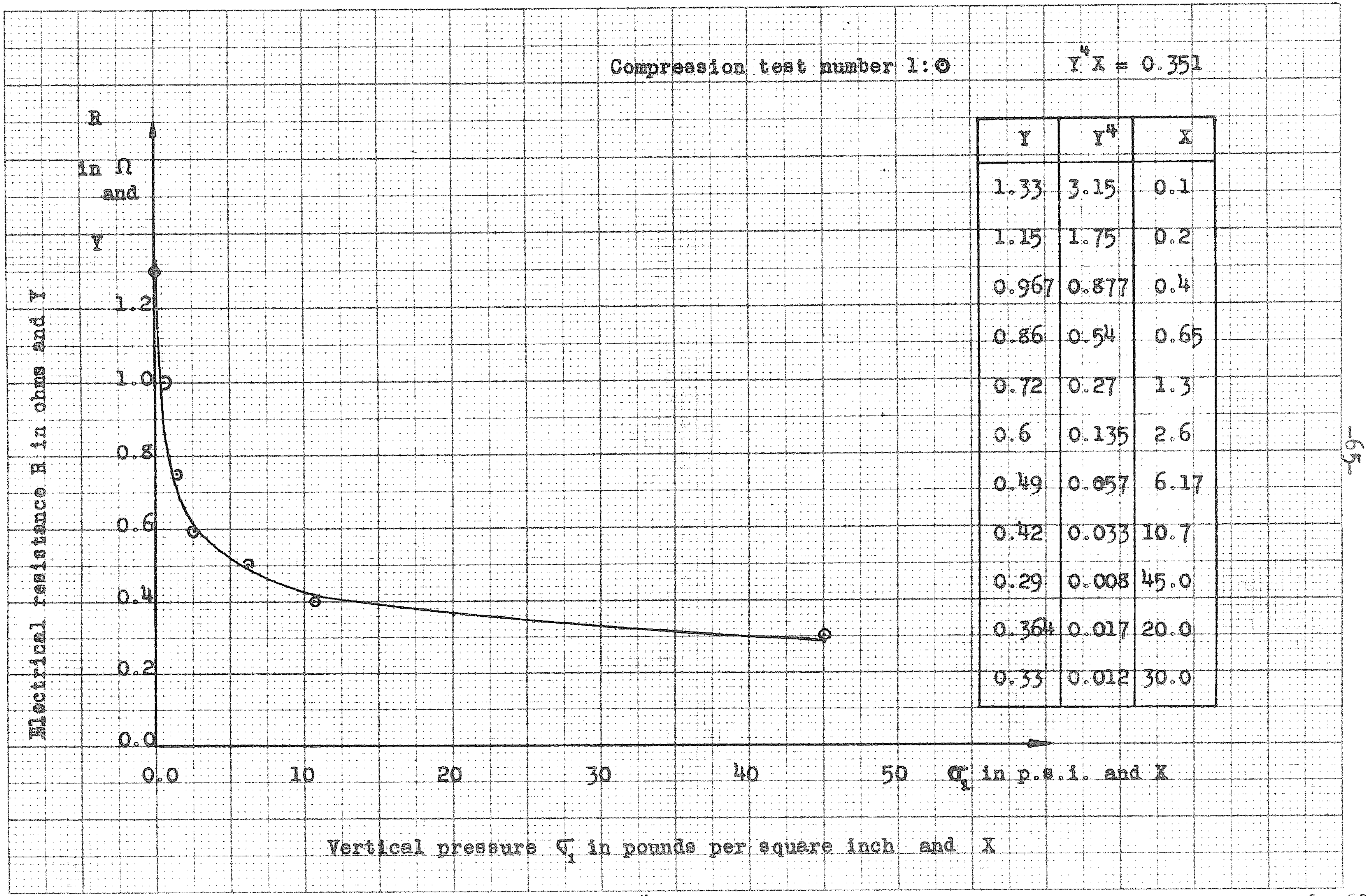
$$Y^4 X = C \qquad (2)$$

where Y is electrical resistance, X is vertical pressure and C is a constant. The plot was made for a value of C equal to 0.531. The experimental points obtained with test number I agree very well with the theoretical curve except, of course, when X tends towards zero. Y becomes infinite whereas the electrical resistance of granular pressure cell number I has a finite value of 1.3 ohms for a minimum pressure applied corresponding to the one due to the loading shaft of the testing machine.

In the case of a Blake transmitter, it was found that the relationship between pressure and electrical resistance was of the form :

$$Y^2 X = C \qquad \text{(See section 2.2.)}$$

As can be seen on figure 23, the function corresponding to equation 2 agrees closely with the experimental points in the range of vertical pressures from 0.1 to 40 pounds per square inch. It is not stated in reference 9 in what range of pressures applied to the end sections of a Blake transmitter, the relationship between electrical resistance and pressure applied is governed by equation I of section 2.2.



Y	Y^4	X
1.33	3.15	0.1
1.15	1.75	0.2
0.967	0.877	0.4
0.86	0.54	0.65
0.72	0.27	1.3
0.6	0.135	2.6
0.49	0.057	6.17
0.42	0.033	10.7
0.29	0.008	45.0
0.364	0.017	20.0
0.33	0.012	30.0

Figure 23 : Comparison between the function $Y^4X = 0.351$ and the results of the compression test number 1.

Neither is it stated what the characteristics of the carbon grains are; grain size, roughness, shape. Undoubtedly these factors will have influence on the variations of electrical resistance with pressure applied on the end sections of a cylindrical mass of carbon grains. It therefore cannot be explained with certainty why we did not find agreement between our own experiments and equation 1.

We have also to mention that because of the shortcomings of the set-up used in our tests as described in the previous sections, the errors in reading were important. It was not actually possible to read the ohmeter with more than 0.1 ohm accuracy. Accepting that fact, we drew on figure 24 the functions :

$$Y^4 X = 0.351 \qquad (3.)$$

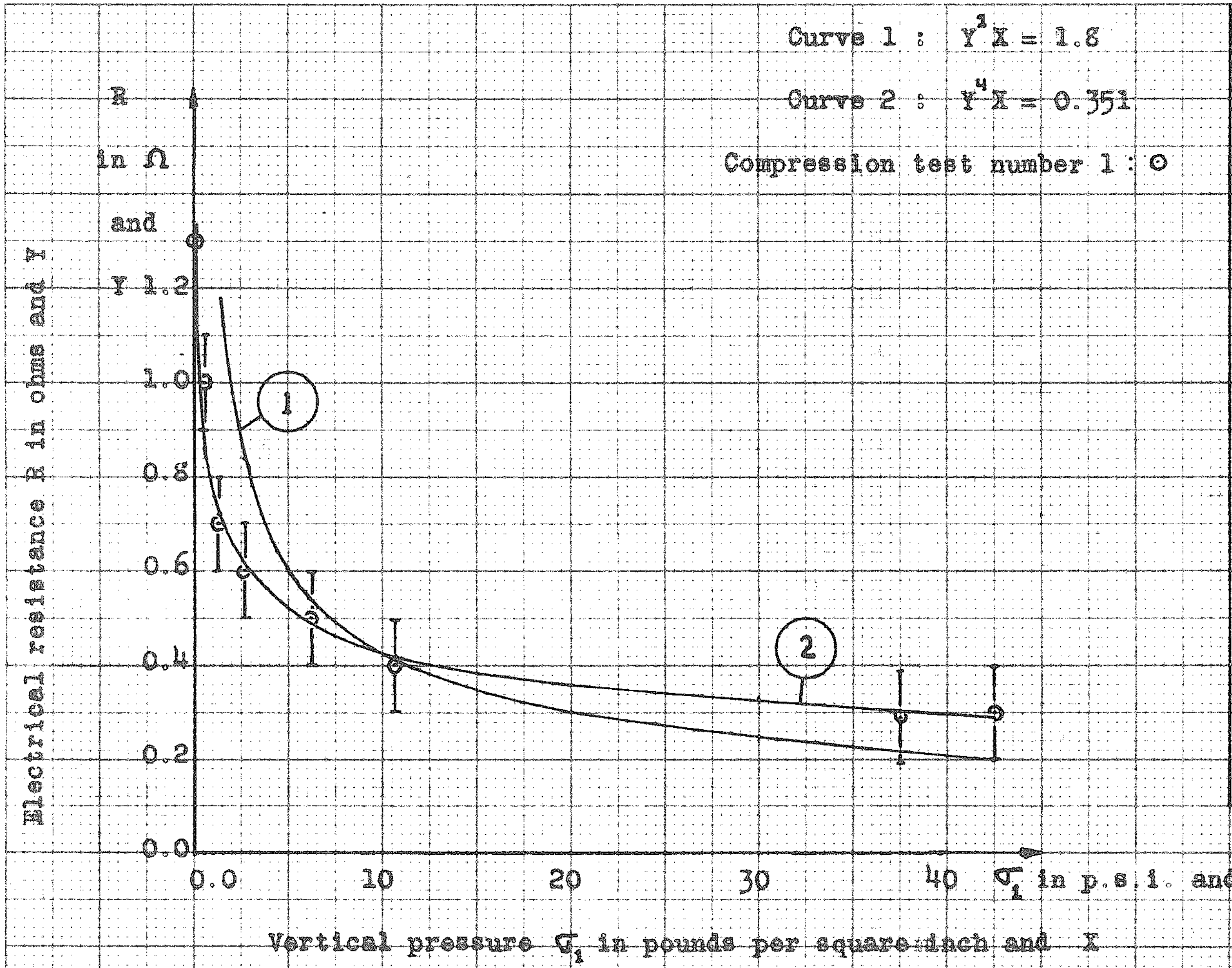
and

$$Y^2 X = 1.8 \qquad (4.)$$

For each experimental point, we indicated by a vertical line the width of a zone due to inaccuracies in reading the ohmeter. Figure 24 indicates that both functions 3 and 4 are in agreement with our experiments.

3.174. Temperature effects and variations of surface contacts.

Figure 22 shows that the four compression tests conducted on pressure cell number1 gave results which cannot be plotted on a unique curve. Once again because of the shortcomings in the testing set-up, it is impossible to say whether the five curves on figure 22 are due to errors in reading or to some other cause suggested in the following lines.



$Y^4X = 0.351$			$Y^2X = 1.8$	
Y	Y^4	X	Y^2	Y
1.33	3.15	0.1		
1.15	1.75	0.2		
0.967	0.877	0.4		
0.86	0.54	0.65		
0.72	0.27	1.3	1.39	1.18
0.6	0.135	2.6	0.7	0.84
0.49	0.057	6.17	0.29	0.54
0.42	0.033	10.7	0.17	0.41
0.364	0.017	20.0	0.09	0.3
0.33	0.012	30.0	0.06	0.24
0.29	0.008	45.0	0.04	0.2

Figure 24 : Comparison between the functions $Y^4X = 0.351$ and $Y^2X = 1.8$ and the results of the compression test number 1 on pressure cell number 1.

3.1741. Internal temperature effects.

The heating up of the pressure cell because of the value of the current passing through while testing could influence the value of the electrical resistance of the pressure cell. On the scale of the ohmeter we used, it is specified that the internal resistance of the meter is of 20.000 ohms per volt. If our pressure cell is connected to the ohmeter, from the formula:

$$I = \frac{V}{R} \qquad (5.)$$

where I is current in amperes, V is voltage in volts and R is electrical resistance in ohms, we find that the current I flowing through our pressure cell is about :

$$I = \frac{1}{20.000} = 5.10^{-5} \text{ amperes} \qquad (6.)$$

To arrive at this value of the electrical current, we neglected the value of the electrical resistance of the wiring, the connections in our circuit and our pressure cell. All these resistances are very small compared to the internal electrical resistance of the ohmeter.

The energy to dissipate due to the current passing through our pressure cell is given by the formula :

$$W = R\ I \qquad (7.)$$

where W is energy in watts per second.

In our case, we have :

$$W = 40{,}000.\ 25.\ 10^{-10} = 10^{-4} \text{ watts} \qquad (8.)$$

One calory per second equals 314 watts per second. Hence, 10^{-4} watts correspond to $3.1.\ 10^{-7}$ calories per second. This is an amount of heat that can easily be dissipated by our granular pressure cell without any increase of its internal temperature when one knows that the heat conductivity of carbon is of $1.\ 10^{-2}$ calories per second and square centimeter. For rubber, the heat conductivity is : $4.5.\ 10^{-4}$ calories per second and square centimeter. Also, the specific heats for carbon and rubber respectively are: 0.12 calories per gram at 20 degrees centigrade and 0.4539 calories per gram at 27 degrees centigrade. (17)

3.1742. Variations in surface contact between grains.

Variations in total surface contact for the entire pressure cell from one test to another can explain the differences in reading of electrical resistance for pressure cell number 1 from one test to another. Even if the current flowing through the pressure cell is low, where there is point contact the surface resistance is high. In the grains themselves, the lines of current will concentrate in the points, and we will have high densities of current in the points and perhaps more or less high temperatures which will help to burn the points so as to eliminate them by combustion. The surface of contact will be increased and the electrical resistance of the pressure cell, which depends only on surface contact resistance, will decrease.

In view of what has been observed and discussed in this section, we will have to determine in further testing whether or not it is possible to obtain a unique calibration curve, for the granular pressure cells we are about to make, after a certain number of loading tests.

3.18. Conclusions.

In future testing we will have to adopt a constant stress rather than a constant strain system.

We will use a Wheatstone bridge instead of an ohmeter to record the electrical resistance of pressure cells under test more accurately.

A dial gauge will be adapted to the testing set-up in order to record the strains occurring in the pressure cells tested.

We will have to determine how long it takes for a pressure cell to reach a state of equilibrium under a given load and give a constant reading of electrical resistance.

As soon as less angular carbon grains as the ones we used to make pressure cell number 1 can be obtained, we will make a granular pressure cell with such grains. It is obvious that in such a pressure cell, the effects described in the previous section would be eliminated to an appreciable degree depending on how rounded the carbon grains will be.

Ultimately, it is suggested that in further research projects related to this one, spherical carbon grains be used to make a granular pressure cell.

3.2. Control of the nominal value of the electrical resistance of a granular pressure cell.

3.2.1. Introduction.

Before making any other pressure cells it was decided to find out first how to control the nominal value of the electrical resistance of a granular pressure cell. That is, how to make a pressure cell whose electrical resistance would be high enough under no load so that the calibration curve for that pressure cell would lie in a range of electrical resistances such as to allow easy and reliable reading.

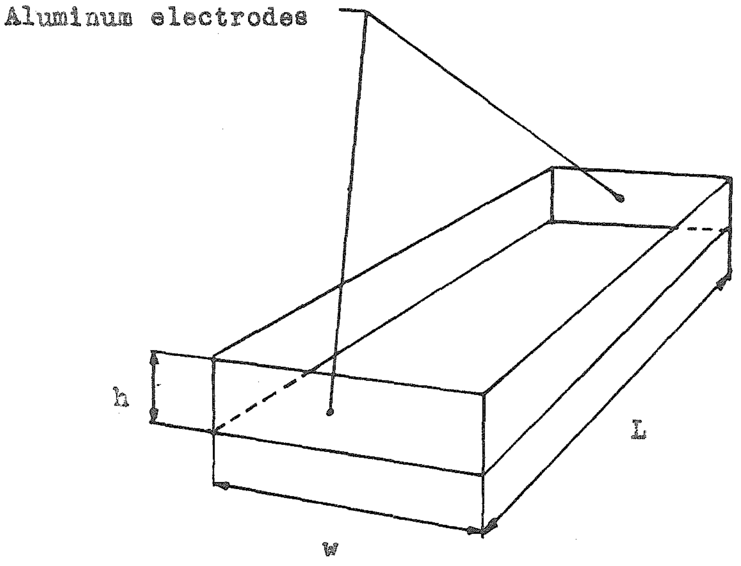
A good way of increasing the electrical resistance of a granular pressure cell is by mixing sand with the carbon grains. If one takes pure sand, that is to say a sand mainly composed of grains of quartz, one may expect for such grains an electrical resistivity of the order of 10^{-15} ohms-centimeter (17) at 20 degrees centigrade, whereas for carbon we can expect a resistivity of about $3.5 . 10^{-3}$ ohms-centimeter. It is obvious that those figures for a defined mass of grains will be higher because the influencing factor in such a case will be the surface contact between grains and not the internal resistance for each grain. It is also obvious that only after a non-negligible amount of carbon grains has been added to a definite mass of sand that the electrical resistance of that mass of sand grains will drop to a much lower value than for the pure sand mass. As long as the grains of carbon remain isolated from each other, the electrical resistance of the mixture of carbon and sand grains will remain the same as for an identical mass of sand grains only.

3.22. Experiments.

A rectangular cardboard box was used in our experiments. Its dimensions were as follows :

Length = 53 millimeters.
Width = 34 millimeters. (Figure : 25.)
Height = 7 millimeters.

An aluminum electrode was fitted on each end section of the box. The box was then filled with various mixtures of carbon and sand grains and the electrical resistance of the system was measured by means of the ohmeter mentioned in section 3.15.
The carbon grains used for these experiments were taken from the mass of grains prepared as described in section 3.11. (grains passing through sieve number 20 and retained on sieve number 40.)
The sand grains used were Ottawa sand C – 109 from the Soil Mechanics Laboratory. That sand was sieved in the same sieve series as were the carbon grains and the grains retained were again the ones passing through sieve number 20 and not passing through sieve number 40. Table VII is a presentation of the results obtained in this experiment. The results of Table VII have been represented on figure 26.



Dimensions of the box : length : L = 53 millimeters.

width : w = 34 millimeters

height : h = 7 millimeters

Figure 25 : Box used for a test on the influence of the concentration in sand in a sand-carbon grains mixture, on the electrical resistance of the mixture.

Table VII : Influence of variable quantities of sand, mixed with carbon grains, on the electrical resistance of a constant volume of the mixture.

Volume of sand In per cent of the total volume of the mixture.	Volume of carbon grains In per cent of the total volume of the mixture	Electrical resistance R In ohms.
0.0	100	160
10	90	180
20	80	220
30	70	380
40	60	550
50	50	3,000

Total volume of granular material used : 20 cubic centimeters.

Dimensions of that volume : the same as for the box described on figure 25.

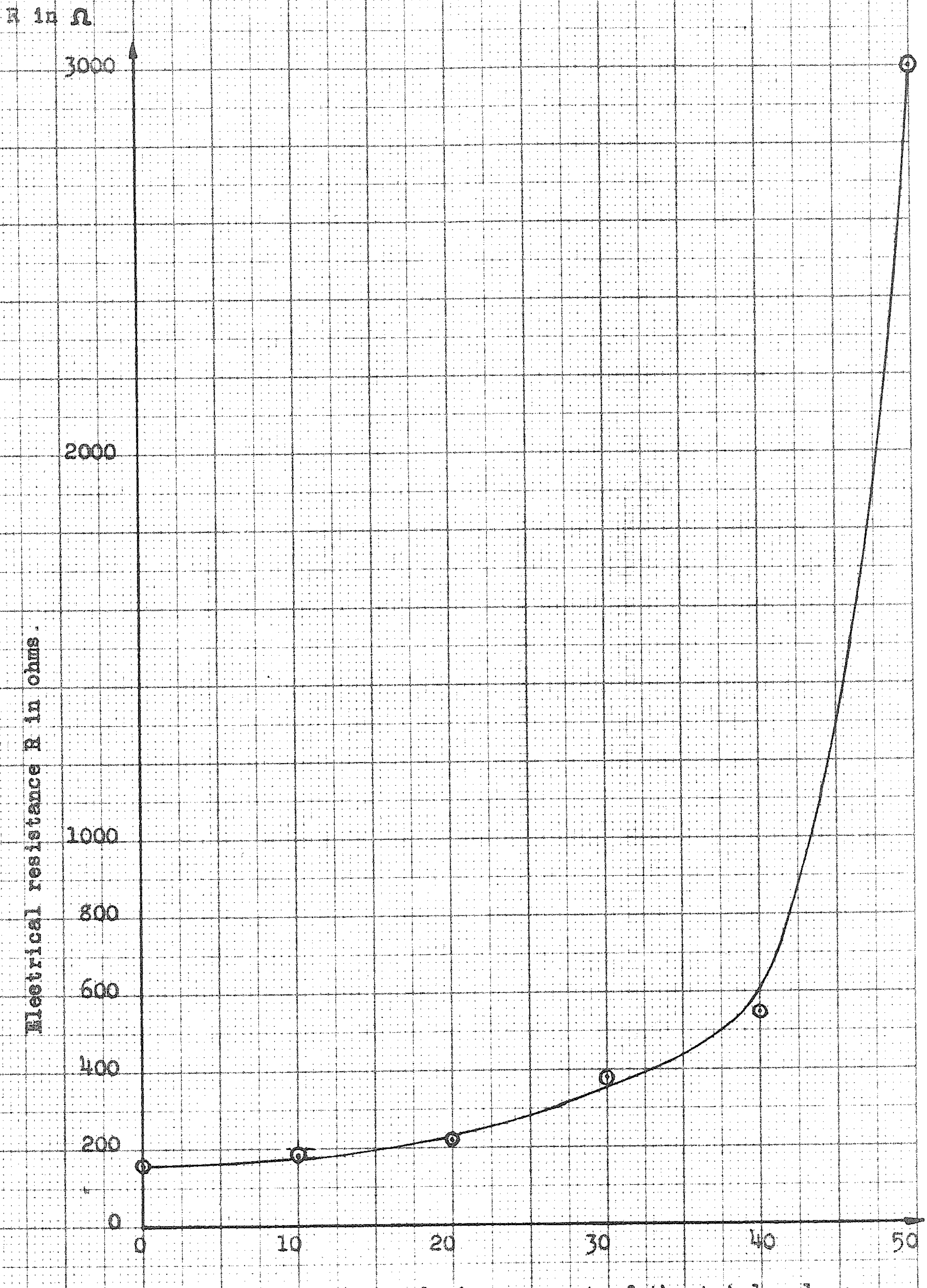


Figure 26 : Electrical resistance – concentration in sand relationship for a carbon grains – sand mixture.

3.23. Discussion of the results.

From figure 26 we see that a mixture of carbon and sand grains containing 30 per cent in volume of sand grains gives a reading of electrical resistance twice as high as for the same volume of carbon grains only. Also that it would be unpractical to use mixtures with more than 40 per cent in volume of sand unless one can measure very accurately the quantity of sand and carbon grains to be mixed. As will be seen later in this report, we will use quantities of about 0.2 to 0.5 grams of carbon grains as described in section 3.11 or of carbon grains mixed with sand grains of the same size to make granular pressure cells. If we make an error of 10 per cent in weighing the amount of sand to be used, we see from figure 26 that if the percentage of sand in our test box passes from 40 per cent to 45 per cent, we can expect the electrical resistance of the granular mass in the box to pass from 580 ohms to about 950 ohms. This is an increase in electrical resistance of 60 per cent. Assuming we use about 0.5 grams of granular material to make a pressure cell and assuming that carbon and sand have the same density (17), 40 per cent of sand in weight is about :

$$\frac{0.5 \cdot 40}{100} = 0.2 \text{ grams.} \qquad (9.)$$

And an increase in the proportion of sand to be used from 40 to 45 per cent in weight represents an error in weighing of only :

$$\frac{0.5 \cdot 5}{100} = 0.025 \text{ grams.} \qquad (10)$$

We see also that 20 c.c. of carbon grains put in our box give for the ensemble an electrical resistance of 160 ohms whereas for our pressure cell number 1 we obtained, under no load, an electrical resistance of 3.3 ohms.

This difference is due to two factors :

1) A difference in shape and dimensions between the two granular masses. Our pressure cell had the following dimensions :

Diameter = 1.25 inch or 3.17 centimeters.

Height = 0.5 inch or 1.27 centimeters.

Using the formula :

$$R = \rho \, \frac{L}{S} \qquad (\ 12\ )$$

Where R is electrical resistance in ohms, L is length between electrodes in centimeters, S is section in square centimeters and ρ is resistivity in ohms-centimeter.,We find for our pressure cell:

$$\rho = 3.3 \, . \, \frac{314\ (3.17)^2}{1.2\ .4} = 21.8 \text{ ohms-centimeter.} \qquad (\ 13\ )$$

If our granular pressure cell had been similar to our box, we would have found an electrical resistance under no load of :

$$R = \frac{21.8 \, . \, 5.3}{3.4 \, . \, 0.7} = 48.5 \text{ ohms.} \qquad (14\ )$$

or about 14 times more than for pressure cell number 1.

2) A difference in degree of compaction. The grains in our box were loosely placed and not compacted. We have seen in the introduction (Section 2.2) that a pressure of 0.04 pounds per square inch can give a reading of electrical resistance 10 times lower than no load at all.

It seems reasonnable for model testing to try to make a granular pressure cell whose dimensions would be of about

0.5 inch in diameter and 0.25 inch in thickness. Such a granular pressure cell, if one expects it to have the same resistivity as pressure cell number1 (21.8 ohms-centimeter.), would have under no load and if made without sand being mixed with the carbon grains an electrical resistance of :

$$R = \rho \frac{L}{S} = 21.8 \frac{0.63 \cdot 4}{(1.27)^2 3.14} = 10.9 \text{ ohms.} \qquad (15.)$$

This value for electrical resistance might well be much higher depending on the degree of compaction of the grains of carbon attained while making the pressure cell.

3.3. Preparation of granular pressure cell number 2.

3.31. Molding set-up.

As the method we used to make pressure cell number 1 is not the only one by which to make pressure cells, we thought of using another one requiring less equipment and which might prove to be more flexible and simpler for mass production : the one used to make the cylindrical sample of carbon grains mixed with latex used in the evaporation test (Figure 12 ; section 3.12) This set-up is more flexible in the sense that it is much easier and faster to make a large variety of molds as the one of figure 12, to make pressure cells of various dimensions, than molds of the type described by figure 17; especially for pressure cells of small diameter (About 0.5 inch or even less.). The mold of figure 17 is not as simple in its constitution as the one of figure 12. Also, the mold of figure 12 does not need to be adapted for the production of pressure cells of varying thicknesses. When using the mold of figure 12, the thickness of a granular pressure cell will depend only on the amount of granular material and matrix material used. Once these have been poured into the mold, it suffices to press down the piston more or less depending on the amount of granular material used. In the case of the mold described by figure 17, it might be more difficult to adjust the stoppers to press the granular material in the mold at a desired degree of compaction. Also, by using the previously described molding procedure (Section 3.12.), one does not need to carry out the preliminary studies mentioned in section 3.14 which have to be made if the procedure used in making pressure cell number 1 is employed. Moreover, the mold of figure 12 can be used with any kind of polymer resin whereas the mold of figure 17 cannot. Polymers are expensive and highly viscous, so that the set-up of figure 21 would be inadequate. There would be too much waste of polymer in the tubing connected to the aspiration end of the mold and besides, because of its high viscosity, the polymer might not penetrate the mold to an appreciable extent if at all.

Using the mold of figure 12 to make pressure cells, the procedure for making them will be exactly as explained in section 3.12. The timing for the various steps in the process of demolding and letting the pressure cells dry will be based on the results given by the evaporation test. In order to try to avoid having air pockets left in the pressure cells to be made, once the latex and the carbon grains have been poured in the mold, it will be placed in a triaxial testing machine and a vaccum applied (Figure 27.). The piston is then lowered into the mold slowly until it is stopped by the presence of the mass of carbon grains which will have been pressed down into the latex and compacted at the same time. Then the vacuum is cut off and the granular pressure cell is left to dry. Relying on the information given in table II, the mold is removed from the the triaxial testing machine and the bottom plate is removed after 4 hours. The pressure cell is extruded after six hours and after 29 hours the pressure cell is ready to receive its electrodes.

3.32. Choice of electrode material.

For the reasons given in section 3.14, Woods metal has been discarded. One criterion in the choice of an electrode material is that the resistivity of such a material must be low compared to that of the granular pressure cell to which it has to be applied. Also it has to have mechanical properties such that it is not brittle nor rigid. For economical reasons it is preferable that the electrode material be non-expensive. Chemically it had better be non-corrosive. So far, in the order of increasing resistivity, we have the choice between copper (1.7 10 ohms-centimeter), aluminum (2.8 10 ohms-centimeter), brass (7 10 ohms-centimeter) and iron (10 ohms-centimeter) (17). Copper and brass have to be eliminated from our choice. It is stated in reference 16 :

> " Copper either in the form of the metal, the oxides, or the soluble salts has a decidedly injurious action upon rubber. It has been proved that exceedingly small quantities of copper or its salts, much smaller than was originally supposed, have the power to cause the decay of rubber goods."

Aluminum foil 0.001 inch thick produced by Alcoa Aluminum Co., was tried but was found to deteriorate by heavy oxidation and perforation from the part of the carbon grains in contact with the electrodes after a few loading tests. We then tried iron wool. Iron wool has several advantages : it is very flexible, hence will adapt very easily to the end surfaces of the granular pressure cells. Because of its fibrous structure, it is very easy to make electrodes with their leads in one piece (Figure 28). Also, the fibrous structured electrodes can easily be soaked in with latex and then pressed down against the end sections of the pressure cell. The latex will be the bonding material between the electrode's fibres and the granular pressure cell. The contact between the electrodes and the pressure cell will thus not be altered with time and when the pressure cell will have been submitted to repeated loadings and unloadings.

A sample of an iron wool electrode was prepared in order to determine its electrical resistance (Figure 29). It was molded by hand to a disc shape with two leads diametrically opposed. It was soaked in latex except for the leads, and pressed in between two one inch square aluminum plates. Once the mixture iron wool-latex was dry, it was cut with a pair of scissors to the shape of a circular disc (Figure 30). The dimensions of the electrode were about : diameter = 0.5 inch.

thickness= $1/32$ inch.

The two leads were connected to a Wheatstone bridge which will be described later in this report. We found an electrical resistance for the electrode of 0.1 ohm. This is quite a low value of electrical

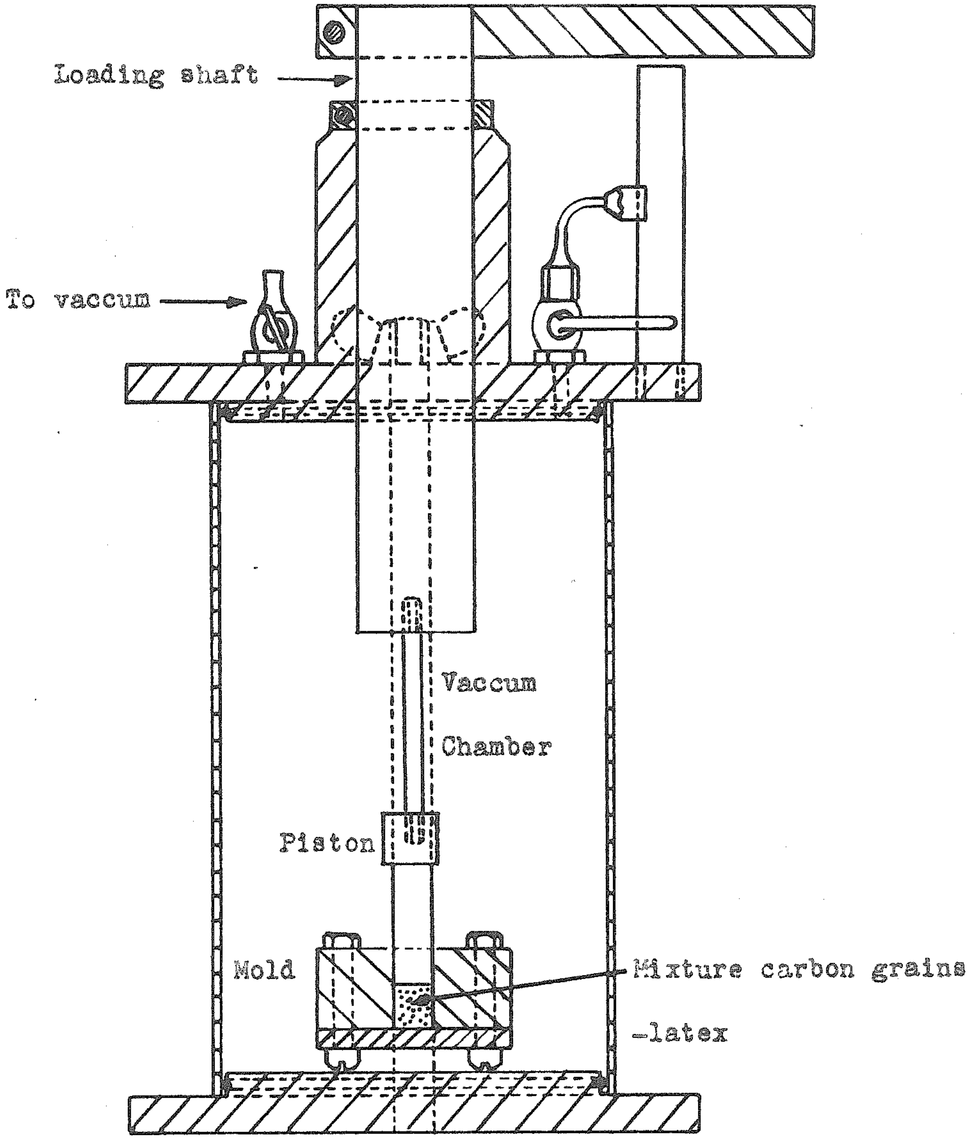


Figure 27 : Molding set-up used to make granular pressure cells.

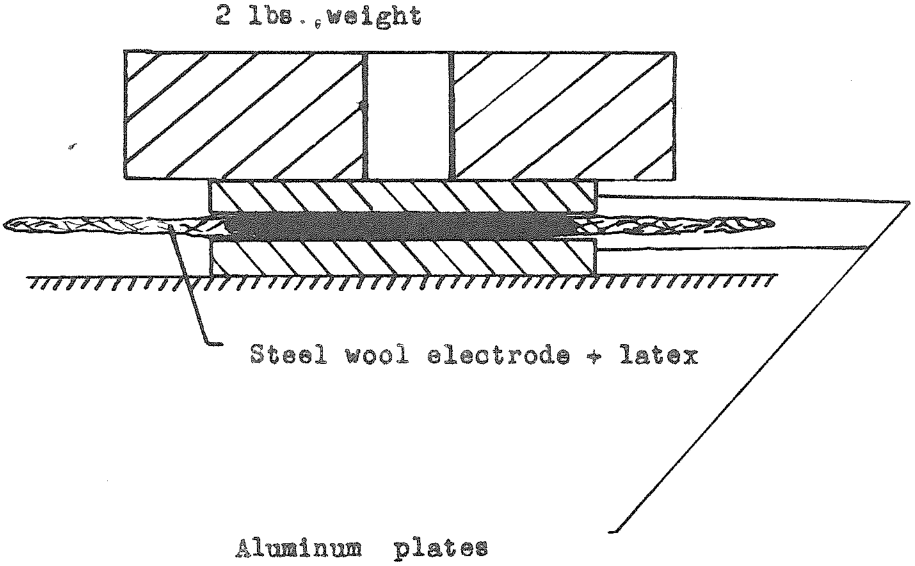


Figure 29 : Preparation of an electrode.

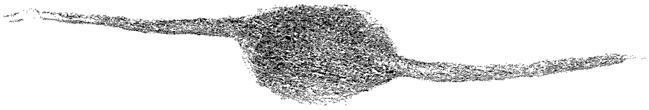


Figure 28 : Steel wool electrode.

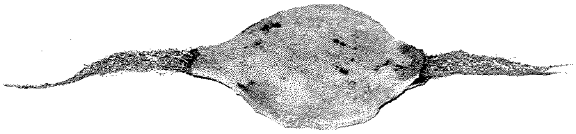


Figure 30 : Steel wool electrode mixed with latex.

resistance compared to the values we will have for the granular pressure cells to be prepared in the future by the method described in section 3.31.

3.33. Experimental set-up used to test granular pressure cell number 2.

The triaxial compression testing machine used to test pressure cell number 1 was transformed in order to be able to use it for pressure cell calibration purposes as shown in figure 31. The transformations made consisted in the plexiglass rods A and B used to extend the loading shaft of the triaxial testing machine (Rod A : diameter = 1 inch ; length = 3.25 inch. Rod B : diameter = 1 inch ; length = 2.25 inch.) and to bring the base of that same machine to a higher level. These extensions had to be made because the triaxial testing machines used in the Soil Mechanics laboratory were designed to test cylindrical soil samples which would be about 1 to 2 inch long whereas our pressure cell number 2 is only about 0.5 inch thick.

A Wheatstone bridge was used to measure the electrical resistance of pressure cell number 2 under load (Figure 32). The equipment used in the Wheatstone bridge is listed in Table VIII. The letters in between parentheses correspond to the ones used in figure 32 so as to show where each piece of equipment was used in the bridge. A dial gauge model C 815 of the Federal Product Co., was mounted on the triaxial testing machine in order to record the axial strains under load for the pressure cell. This will enable us to establish stress-strain diagrams for

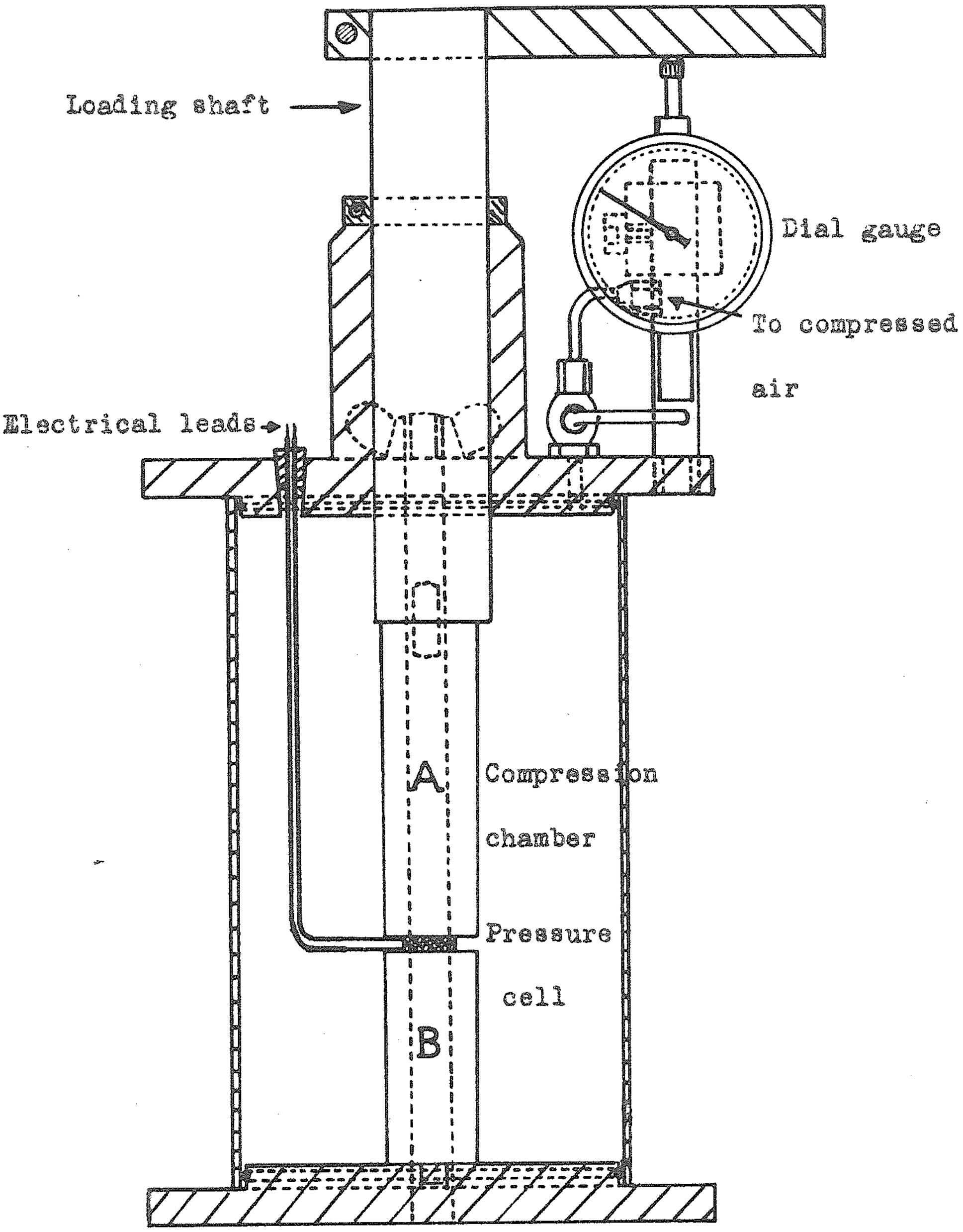
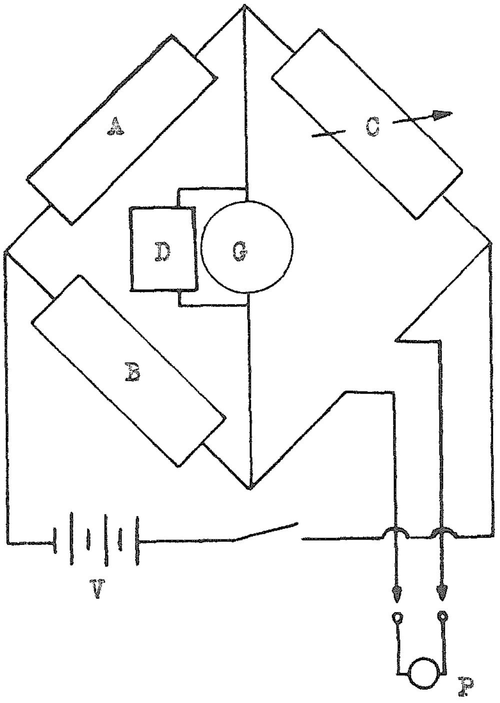


Figure 31 : Testing set-up used to establish calibration curves for granular pressure cells in the range of vertical pressures from 5 to 15.2 pounds per square inch.

A : Decade box number: 13259	General Radio Co. Cambridge, Mass.
B : Decade box number: 12158	General Radio Co. Cambridge, Mass.



C : Decade box number: 12359	General Radio Co. Cambridge, Mass.
D : Voltage divider	Home made.
G : Galvanometer number: 771460	Leeds & Northrup .
V : Power supply.	
P : Granular pressure cell.	

Figure 32 : Wheatstone bridge used to measure the electrical resistance of granular pressure cells.

Table VIII : List of the instruments used in the Wheatstone bridge of figure 32.

A : Decade box number 13259 ; General Radio Co.

Total resistance : 11,110 ohms

(10 1000, 10 100, 10 10, 10 1)

B : Decade box number 12158 ; General Radio Co.

Total resistance : 1,111 ohms.

(10 100, 10 10, 10 1, 10 0.1)

C : Decade box number 12359 ; General Radio Co.

Total resistance : 111 ohms.

(10 10, 10 1, 10 0.1)

D : Voltage divider : home made ; 20,000 ohms - 4 watts.

G : Galvanometer number 771460 ; Leeds & Northrup.

V : Battery ; Rebat type RM 21 - 6 ; Reading Batteries Inc.

Characteristics : 6 volts, 90 amperes.

A, B, C, D were borrowed from room 110 Thomas, C.I.T.

V was borrowed from room 010 Thomas, C.I.T.

G was borrowed from E.E. stock-room, Spalding, C.I.T.

granular pressure cells which will be compared to the stress-strain curves of figure 9.

Using the same lettering as on figure 32 for the resistances used in our Wheatstone bridge, we have that the electrical resistance to be measured X is equal to :

$$\frac{B}{A} \cdot C \qquad (16)$$

and that the best accuracy in measuring the electrical resistance X is obtained by making $\frac{B}{A} = 1$ (18).

It is also advisable to use a value of electrical current as low as possible so as to minimize heat generation by Joule Effect. The maximum value of electrical resistance we could use for A and B with the decade boxes we used was of 1,110 ohms. Assuming that the lowest value of electrical resistance for the pressure cell under load will be of 10 ohms, we will have an electrical current in our Wheatstone bridge given by the formula :

$$I = \frac{V}{R} \qquad (17)$$

where V is voltage in volts, R is electrical resistance in ohms and I is electrical current in amperes. In our case,

$$I = \frac{6}{1,110+10} = 0.00536 \text{ ampere} \qquad (18)$$

Let us assume : 1) That our pressure cell is a section of carbon taken out of a rod of infinite length.

2) Because of the electrical current flowing through our pressure cell, that it is composed of sources of heat uniformly distributed

throughout its volume.

3) That we know the temperature at the lateral surface of the pressure cell.

In that case, the temperature on the centerline of the pressure cell will be given by the formula (19) :

$$T_{max} - T_R = \frac{qr^2}{4k} \qquad (19)$$

where T_{max} is the temperature at the center-line in degrees centigrade, T_R is the temperature at the lateral surface in degrees centigrade, q is the heat generated in calories per cubic centimeters per second, r is radius in centimeters and k is heat conductivity in calories per centimeter per second and per degree centigrade.

In our case : $r = 1.27$ cm.

$$k = 0.01 \text{ cal.cm}^{-1}\text{.sec}^{-1}\text{.}^{\circ}\text{C}^{-1} \qquad (20)$$

and

$$q = 0.238 \frac{\rho I^2}{\pi r^2} \text{ cal.sec}^{-1} \qquad (21)$$

where ρ is resistivity in ohms-centimeter, I is electrical current in amperes.(17 and 19).

Putting the values 20 and equation 21 in equation 19, we find :

$$T_{max} - T_R = 0.238 \frac{\rho I^2}{0.04\pi} \qquad (22)$$

Assuming an electrical resistance under load of minimum 10 ohms for pressure cell number 2 and knowing that its diameter is the same as its thickness or 0.5 inch (1.27 cm.), we find,using equation 12:

$$\rho = 10 \text{ ohms-cemtimeter} \qquad (23)$$

Putting the values 18 and 23 in equation 22, we find :

$$T_{max} - T_R = 5.4\ 10^{-4}\ {}^{\circ}C. \qquad (24)$$

This result shows that the temperature distribution in the pressure cell can be expected to be uniform when it is subjected to the current of 0.00536 amperes flowing through it.

Knowing the temperature of the surrounding still air, we can now find the temperature T_R by means of the formula (19):

$$T_R - T_c = 348\ \frac{\rho I^2}{\alpha d^3} \qquad (25)$$

where T_c is temperature of the air surrounding the pressure cell in degrees centigrade, d is the diameter of the pressure cell in centimeters and α is Newton's coefficient or coefficient of external conductivity in calories per hour,per square centimeter and degree centigrade. Reference 19 gives some values for Newton's coefficient, as for instance :

$\alpha = 0.3$ for still air-metal contact. (26)

In our rough calculations we may use that value. We will find then from equation 25 :

$$T_R - T_c = 0.0632\ {}^{\circ}C. \qquad (27)$$

Hence from the relations 24 and 27 we can expect that, for the value of electrical current which will be flowing through the pressure cell, the heat produced by Joule Effect will be dissipated without having the pressure cell heating up.

Although the results 24 and 27 apply only to the case of an infinitely long conductor, they can be considered as a rough but safe approximation in the case of our pressure cell. Because, whereas dissipation of heat occurs only through the lateral surface in the case of an indefinitely long conductor, the end sections of the pressure cell will, in our case, participate in the dissipation of heat in a far from negligible manner.

3.34. Preparation of pressure cell number two.

Pressure cell number 2 was prepared by the method described in section 3.31. A quantity of 0.5 grams of carbon grains prepared as explained in section 3.31 and no sand was used. Once the granular mass and its matrix material were dry, we applied the steel wool electrodes one at a time (Figure 33a, b and c.). A small quantity of latex was spread on an aluminum plate (Figure 33a). The steel wool electrode was put over it and the pressure cell was pressed down on the electrode (Figure 33b). A load of 500 grams was then put on the pressure cell to keep it in good contact with the electrode while the bonding latex was allowed to dry.(figure 33c). Once the two electrodes had been applied, the excess of latex which had spread outwardly from underneath the pressure cell, while the latter was pressed down against the electrodes, was trimmed off. Then the whole pressure cell was covered with a thin coat of latex. The dimensions of the main body of the pressure cell, that is without its electrodes were:

Diameter : 0.5 inch.

Thickness: 0.5 inch.

3.35. Incompressibility test.

Pressure cell number 2 was put in the testing set-up described in paragraph 3.33 and shown on figure 31. Compressed air was connected to the triaxial testing machine. The pressure was applied at a rate of one pound per square inch

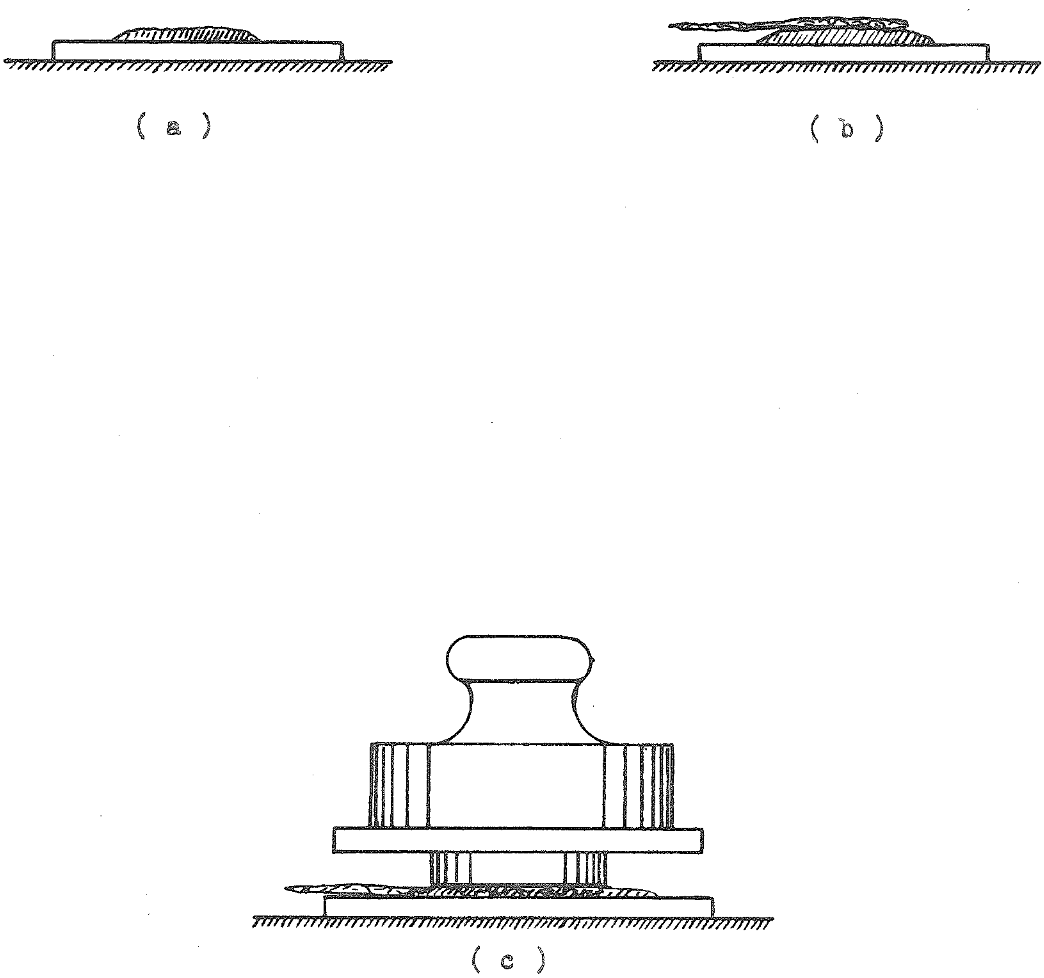


Figure 33 : Application of electrodes to the end sections of granular pressure cells.

per minute. The results of this test are given in Table IX and on figure 34. The range of pressures applied went from 0 to 30 pounds per square inch. The room temperature was of 80 degrees Farenheit. The average of the readings of electrical resistance for pressure cell number 2 is 34.7 ohms. The maximum difference between that average value for electrical resistance and the readings is of 0.4 ohms (Table IX) which is an error of about one per cent of the value of electrical resistance read. That error is acceptable.

3.4. Temperature effect on granular pressure cells.

3.41. Introduction.

We decided to use pressure cell number 2 to determine what the influence of the temperature of the surrounding medium is on the value of the electrical resistance of a granular pressure cell. It is known (17) that the resistivity of carbon decreases with temperature. We have for an increase of temperature from 0 to 500 degrees centigrade, a variation in resistivity for carbon of (17) :

$$(3,500 - 2,700)\ 10^{-6} = 800\ 10^{-6} \text{ ohms-cm.} \qquad (28)$$

or $1.6\ 10^{-6}$ ohms-cm. per degree centigrade.

Considering a cylinder of carbon having the dimensions of pressure cell number 2, such a carbon cylinder will have its electrical resistance varying by an amount given by formula 12 (Section 3.23). In our case we find :

$$R = 1.63\ 10^{-6} \text{ ohms per } {}^{\circ}\text{C.} \qquad (29)$$

Considering a range of variation in temperature of about 50 degrees

Table IX : Incompressibility test on pressure cell number 2.

Loading		Unloading	
Pressure σ In pounds per square inch.	Electrical resistance R In ohms.	Pressure σ In pounds per square inch.	Electrical resistance R In ohms.
0.0	34.5	35	34.7
5	34.7	30	34.8
10	34.7	25	34.7
15	34.3	20	34.9
20	34.3	15	35.0
25	34.6	10	34.9
30	34.6	5	34.9
35	34.7	0.0	34.8

Room temperature throughout the test : 80 F.

Rate of loading : 1 pound per square inch per minute.

Average value of the electrical resistance read : 34.7 ohms.

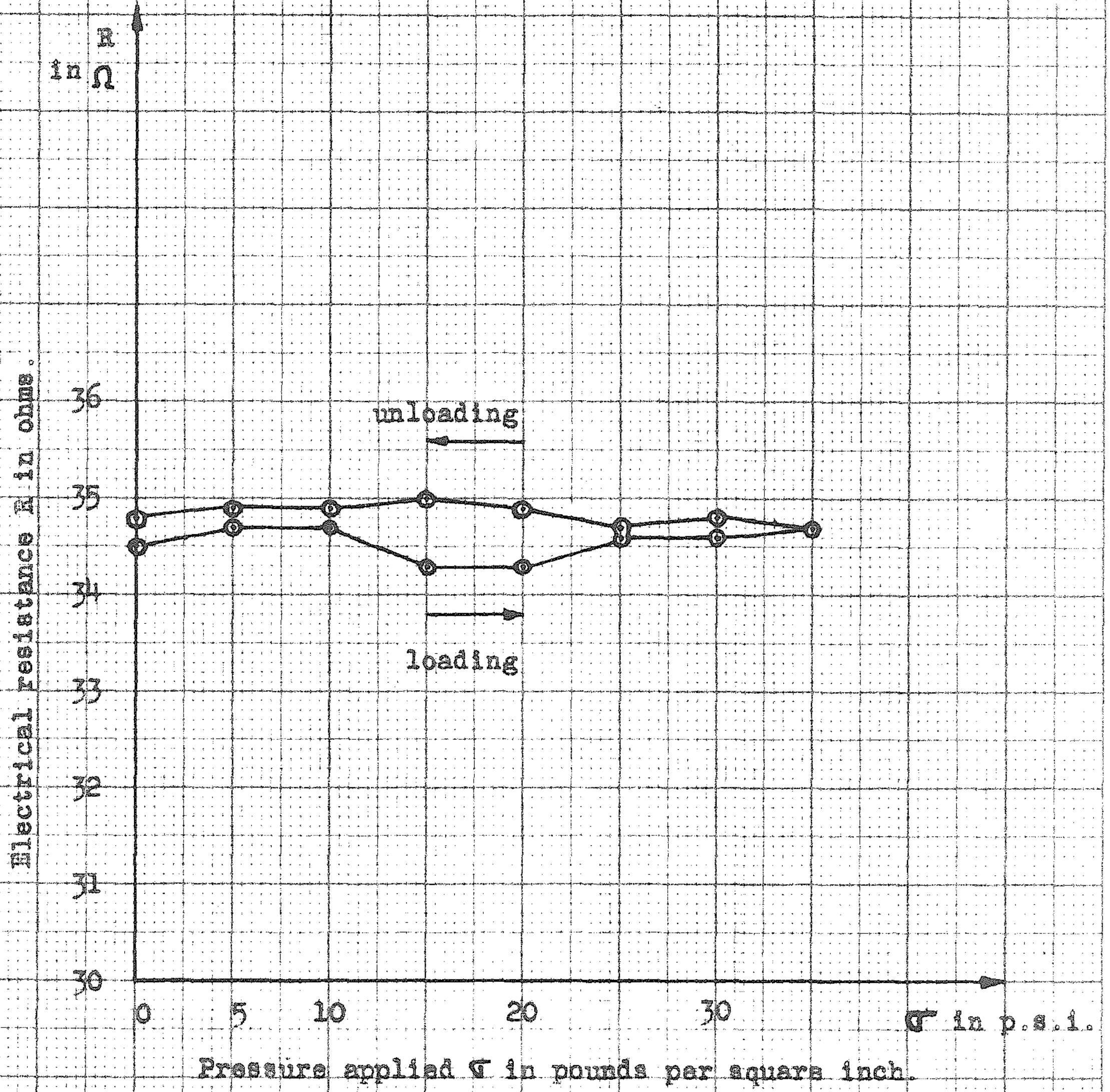


Figure 34 : Incompressibility test on pressure cell number 2.

centigrade, we may expect a variation in electrical resistance for a carbon cylinder having the dimensions of granular pressure cell number 2 of :

$$1.63\ 10^{-6} . 50 = 8.15\ 10^{-5} \text{ ohms} \qquad (30)$$

which is a change hardly noticeable in our case, where we are interested in variations in electrical resistance of the order of at least one ohm.

As has been mentioned previously, the variations in electrical resistance for a granular pressure cell are due to variations in surface contact between grains of carbon. Perhaps changes in temperature in the surrounding medium may influence the amount of surface contact in the pressure cell by causing dilatation or contraction of the pressure cell depending on whether there is an increase or a decrease in temperature in the surrounding medium, and hence in the pressure cell itself. Having the amount of surface contact varying because of temperature, the electrical resistance of the pressure cell will obviously vary also.

The linear coefficients of thermal expansion for carbon and for rubber are respectively of about (17):

$$7.8\ 10^{-6} \text{ per } ^\circ\text{C.}$$

and

$$7.7\ 10^{-5} \text{ per } ^\circ\text{C.} \qquad (31)$$

The volume of pressure cell number 2 is about 3.04 cubic centimeters. Assuming a void ratio e of 0.65 for the granular mass of carbon in the pressure cell, from the formula (3):

$$e = \frac{V}{V_s} - 1 \qquad (32)$$

where e is void ratio, V_s is volume occupied by the carbon grains and V is the volume of the pressure cell, we find :

$$V_s = \frac{V}{e+1} = 1.82 \text{ cm}^3 \qquad (33)$$

The volume of rubber in our pressure cell will then be of :

$$3.04 - 1.82 = 1.22 \text{ cm}^3 \qquad (34)$$

For an increase of 50 degrees centigrade in the temperature of our pressure cell we will have an increase in volume for the carbon mass given by the formula :

$$\Delta V = 3\alpha.\Delta T.V \qquad (35)$$

where ΔV is increase in volume, α is coefficient of linear expansion, ΔT is variation in temperature and V is the volume considered. For the carbon mass we find :

$$\Delta V = 2.15\ 10^{-3} \text{ cm}^3 \qquad (36)$$

For the volume of latex in our pressure cell we find :

$$\Delta V = 13.8\ 10^{-3} \text{ cm}^3 \qquad (37)$$

The total increase in volume for our pressure cell due to an increase in temperature of 50 degrees centigrade will be of :

$$(\ 2.15 + 13.8\ )\ 10^{-3} = 15.94\ 10^{-3} \text{ cm}^3 \qquad (38)$$

From expressions 36, 37, and 38 we see that about 87 per cent of the volume change in pressure cell number 2 will be due to the matrix material although it represents only about 40 per cent of the total volume of the pressure cell. In that case, it is obvious that an increase in temperature of the medium surrounding the pressure cell will cause the matrix material to separate more or less the carbon grains it enrobes and thus decrease the value of the total area of contact between the carbon grains composing the pressure cell.

Therefore, it is obvious that the electrical resistance of a granular pressure cell in which latex is the matrix material will increase with temperature.

It remains now to determine what the variations of electrical resistance with temperature for pressure cell number 2 are. That determination has been done experimentally and is described in the following sections.

3.42. Experimental set-up and testing procedure .

For the test of temperature effects on the value of the electrical resistance of a granular pressure cell, pressure cell number 2 was used. Its dimensions were :

Diameter : 0.5 inch.
Thickness: 0.5 inch.

Under no load and at a temperature of 26.6 degrees centigrade, the electrical resistance of pressure cell number 2 was found to be of 33 ohms. Pressure cell number 2 was put in a plastic material sack and submerged at a depth of 3 inches in water for reasons explained further down in the text. Two water containers were used as shown in figure 35. The pressure cell was put in the inner most container. The outer container was filled successively with hot and cold water so as to cover a range of temperatures in the inner container from 8 to 35 degrees centigrade. As it was found that the pressure cell was sensitive to small variations in load, it was decided not to stir the water in the inner container, but to fill the outer container to the same level as the inner container so that the heat would be transmitted equally through the entirety of

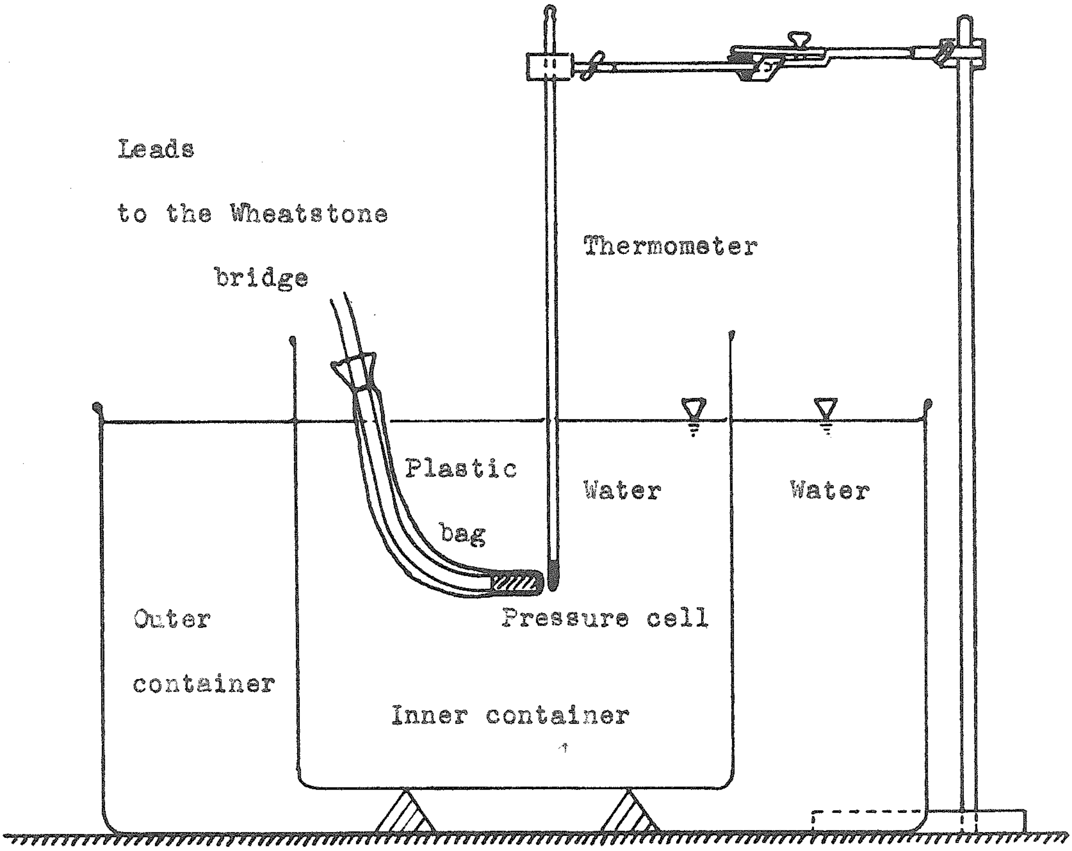


Figure 35 : Set-up used to determine the temperature - electrical resistance relationship for pressure cell number 2.

the lateral surface of the inner container. As we may then expect the surfaces of equal temperature to be cylinders having the same axis as the inner container, it was decided to put the pressure cell with its own axis lying on the axis of symmetry of the set-up. In that case we could be sure to have a constant temperature on the lateral surface of the pressure cell. A thermometer was used to record the temperature of the water surrounding pressure cell number 2. It was located as close as possible to the pressure cell (at about 0.5 inch from the axis of the pressure cell) to minimize the effect of possible non-uniform distribution of temperature in the inner container. On the thermometer, at a height of 3 inches from the bottom up, a mark has been engraved which represents the level at which the thermometer ought to be dipped in the water to have maximum accuracy in recording the temperature. It is the depth at which the pressure cell was put.

The results of the test are given in Table XI and on figure 36. Considering the main curve of figure 37 (Portions 2 and 3), the maximum variation in temperature with time is of about 0.1 degree centigrade in 3 minutes. It takes roughly 5 seconds to make a reading off the thermometer. During those 5 seconds the temperature will have changed to about 0.00278 degree centigrade so that we can reasonably assume a steady state of temperature while making a reading of temperature.

3.43. Influence of possible non-uniform distribution of temperature on the results of the tests.

Before discussing the results of the test, it was decided to examine several possible causes of error which might have implied a difference in temperature between the thermometer and the pressure cell. Also if a non-uniform temperature distribution might have existed at any time in the pressure cell during the test. The points which will be developed in this section are the following :

1) Possible difference in temperature between the thermometer and the water at the surface of the pressure cell.
2) Difference in temperature between the water at the surface of the pressure cell and the surface itself.
3) Temperature distribution in the pressure cell.

3.431. Possible difference in temperature between the thermometer and the water at the surface of the pressure cell.

The thermometer was put at a distance of approximately 0.25 inch from the lateral surface of the pressure cell. Hence it is not at all obvious that, throughout the test, the temperature recorded was the same as that at the surface of the pressure cell. It is why we decided to determine the temperature distribution in the inner container after having poured hot water in the outer container. In order to do so, three thermometers were used as shown on figure 36. The results of this test are given in

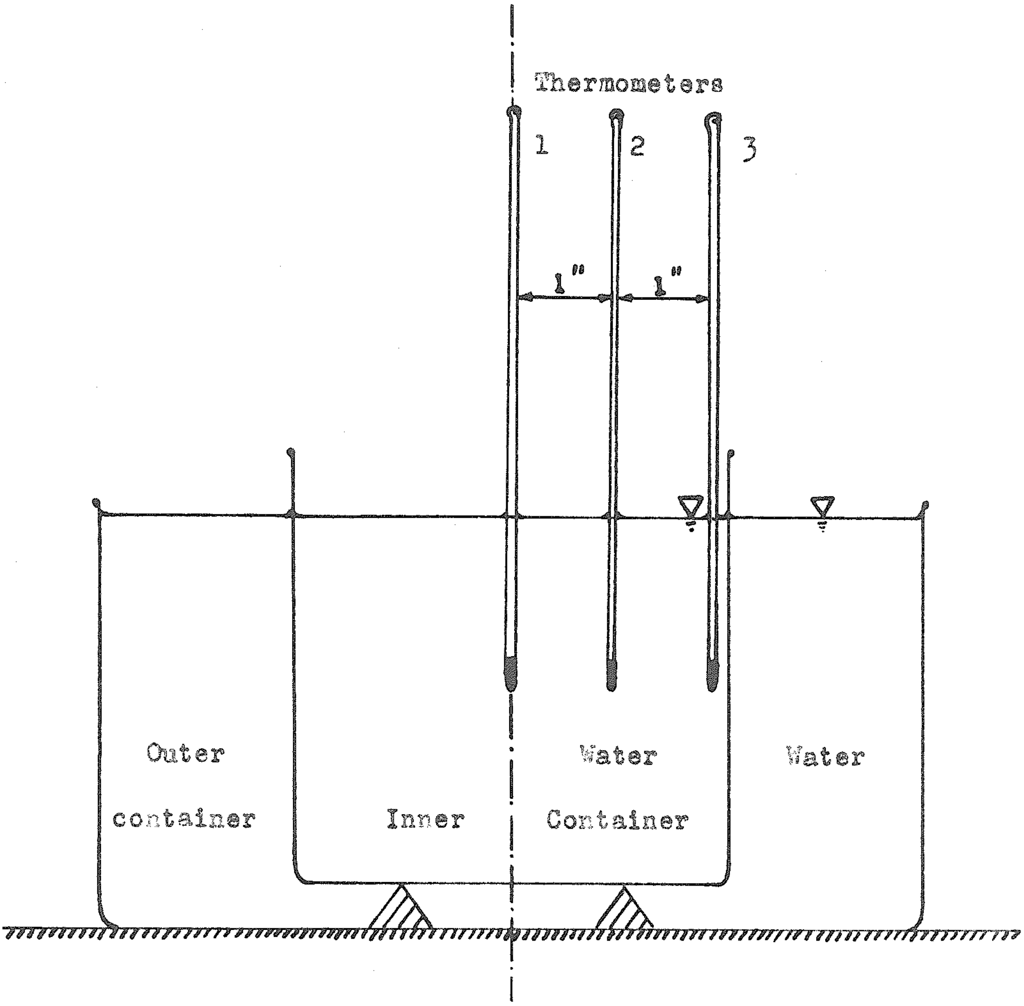


Figure 36 : Set-up used to determine the temperature distribution in the inner container when hot water is poured in the outer container.

Table X : Temperature distribution in the inner container due to the pouring of boiling water in the outer container, at time t = 0.

Time elapsed t in minutes	Temperature recorded by thermometers number 1, 2 and 3 in degrees C.		
	1	2	3
0	22.5	22	22.4
4	28.9	28.9	28.7
6	35.8	35.8	36
8	39.4	39.4	40
10	45	45	46
13	47.3	47.3	48
20	48.4	48.4	49
25	49	49	49.2
30	49	49	49.4
40	49	49	49.3
53	48	48	46.2
61	46	46	43.8
75	36.8	36.7	36.6
90	32	32	31.9
120	28.9	28.9	29

Table X. In view of those results, we can now conclude that in our test on temperature effects on pressure cell number 2, the temperature recorded was the same as that of the water at the surface of the pressure cell. Table X shows that the temperature distribution in the inner container was constant up to at least 1 inch from the axis of the container.

3.432. Difference in temperature between the water at the surface of the pressure cell and the surface itself.

We must now see if we can consider the temperature recorded to be the same as that of the surface of the pressure cell, and if not instantaneously, after how much time elapsed can both temperatures be considered as equal.

The only case of heat transfer from a surrounding medium to a solid body in the unsteady case which is mentioned in reference books is the following :

" Heat transfer from a wall at uniform temperature suddenly brought in contact with a medium at different temperature."

Although this problem is not quite the same as ours, it might give us a fair idea of what is happening in the case of our pressure cell. In our calculations we are going to use the equation (20) :

$$Ts = T_0 + (T_i - T_0) \phi_s \left(\frac{4\alpha\tau}{L^2} , \frac{hL}{2k} \right) \qquad (39)$$

where L is thickness of the wall.

k is thermal conductivity of the material of the wall.

α is thermal diffusivity of the material of the wall.

T_0 is constant outer temperature, that is, the temperature of the surrounding medium with which the two sides of

T_i is initial uniform temperature of the wall.

T_s is surface temperature of the wall at time τ in degrees Fahrenheit as all above defined temperatures.

τ is time elapsed after the wall comes in contact with the medium, in hours.

Φ_s is the function represented in figure IX – 21, page 149 of reference 20, with the dimensionless groups $\frac{hL}{2K}$ and $\frac{4\alpha\tau}{L^2}$ as abscissa and parameter respectively.

h is heat transfer coefficient .

We are going to assume:

1) A wall of thickness L = 0.5 inch = 0.0417 foot (Diameter of our pressure cell) at a temperature $T_i = 80^\circ F.$, (Initial temperature of the pressure cell in our test) is suddenly put in contact on its two faces with water at a temperature $T_o = 94^\circ F.$ (Maximum temperature read on the thermometer).

2) $h = 200$ kcal. $m.^{-2}$ $hr.^{-1}$ = 41 B.T.U. $hr.^{-1}$ $ft.^{-2}$ $^\circ F.^{-1}$ (Contact water-metal), (19).

3) $\alpha = 0.0438$ $ft.^{2}$ $hr.^{-1}$ This value of α is found using the formula $\alpha = \frac{k}{c_p}$ (20), where c_p is specific heat. From reference 17 we have: c_p for carbon = 0.58 cal. $cm.^{-3}$ $^\circ C.^{-1}$

c_p for rubber = 0.495 cal. $cm.^{-3}$ $^\circ C.^{-1}$

Assuming a weighed average value of specific heat for our pressure cell we will find : $c_{p_{av.}} = 0.546$ cal. $cm.^{-3}$ $^\circ C.^{-1}$ = 34.1 B.T.U. $ft.^{-3}$ $^\circ F.^{-1}$ Reference 17 gives also :

k for carbon = 0.01 cal. cm. $sec.^{-1}$

k for rubber = 0.00045 cal. cm. sec.^{-1}

These lead to a weighed average value for k

$$k_{av.} = 1.495 \text{ B.T.U. } \text{hr.}^{-1} \text{ ft.}^{-1} \text{ }^{\circ}\text{F.}^{-1}$$

Finally we find, for our pressure cell, the above mentioned value of α.

With the help of the aforementioned assumptions we will find : $\frac{4\alpha\tau}{L^2} = 101\,\tau.$

$$\frac{hL}{2k} = 0.571$$

For $\frac{hL}{2k} = 0.571$, $\Phi_s = 0$ for a value of $\frac{4\alpha\tau}{L^2}$ down to 10 (Figure IX – 21, reference 20.) or in our case a time elapsed of 0.099 hour Hence about 6 minutes. From these results we may conclude that, in the case of our wall, after 6 minutes $T_s = T_o$. In the case of our temperature test on pressure cell number 2 the above conclusion will most probably hold also, noting that the diameter of the pressure cell is equal to the thickness of our wall and that we did not actually have any sudden changes in temperature between the pressure cell and the surrounding water as will be seen in the section dealing with the discussion of the results of our tests.

3.433. Temperature distribution in the pressure cell due to variations in temperature of its outer surface.

This time we are going to use the equation (20):

$$T_c = T_s + (T_i - T_s).F\left(\frac{4\alpha\tau}{d^2}\right) \qquad (40)$$

Where: T_c is temperature on the axis of the pressure cell.

T_s is temperature at the surface of our pressure cell.

T_i is initial temperature.

All temperatures are in degrees Fahrenheit.

d is diameter of our pressure cell in feet.

In our case : $T_i = 80\,^\circ F.$

$T_s = 94\,^\circ F.$

$d = 0.5$ inch $= 0.0417$ foot.

For α we shall use the value computed in section 3.432 ($\alpha = 0.0438$ $ft.^2\ hr.^{-1}$). Taking $\tau = 0.03$ hour or about 2 minutes, we find :

$$\frac{4\alpha\tau}{d^2} = 0.68$$

And from figure IV - 7, page 69, reference 20, we find :

$$F\left(\frac{4\alpha\tau}{d^2}\right) = 0.01$$

Replacing in equation 40, we find :

$$T_c = T_s - 0.15$$

Hence we can see that at least for the part of our test corresponding to parts 2 and 3 of the results plotted on figure 37, we can expect our pressure cell to be subjected to a uniform distribution of temperature knowing that the fastest rate of change in temperature with time is of about 0.1 degree centigrade in 3 minutes.

3.44. Discussion of the results of the test.

3.441. Preliminary.

The results of the test are given in table XI and on figure 37. The curve on figure 37 has been divided in 4 sections. Section 1 corresponds to the heating up of the water surrounding pressure cell number 2 after boiling water was poured in the outer container. Section 2 corresponds to the cooling down of the water in the inner container after it reached a peak in temperature of 34.65°C. Portion 4 corresponds to the cooling of the water in

Table XI : Variations of the electrical resistance of pressure cell number 2 with temperature.

Room temperature : 26.5 °C.

t : time elapsed in hours and minutes.

R : electrical resistance in ohms.

T : temperature recorded in degrees centigrade.

t		T	R
Hours	Minutes	in °C.	in ohms
0	0	26.5	35.1
0	0.5	31.3	40
0	1	31.8	40.8
0	1.5	32.1	42
0	2	32.4	42.5
0	2.5	32.9	43.5
0	3	33.2	44.3
0	4	33.5	44.9
0	5	33.7	45.1
0	6	34	45.6
0	7	34.2	45.9
0	8	34.5	45.9
0	9	34.65	45.9
0	12	34.65	45.9
0	13	34.6	45.7
0	14	34.6	45.6
0	15	34.6	45.4

Table XI : Continued.

t		T	R
Hours	Minutes	in °C.	in ohms
0	16	34.55	45.3
0	17	34.55	45.2
0	18	34.5	45
0	19	34.3	44.8
0	20	34.3	44.7
0	21	34.3	44.6
0	23	34.2	44.2
0	24	34.1	44.1
0	25	34.1	44
0	26	34.1	43.9
0	27	34	43.7
0	28	33.9	43.5
0	30	33.8	43.4
0	33	33.6	42.9
0	36	33.4	42.5
0	38	33.3	42.3
0	41	33.1	42.1
0	45	32.7	41.6
0	48	32.5	41.3
0	51	32.3	41
0	54	32	40.7
0	57	31.9	40.4
1	00	31.5	39.9

Table XI : continued.

t		T	R
Hours	Minutes	in °C.	in ohms
1	42	30.2	37.9
1	52	29.6	37.3
2	12	28	36.1
2	27	27	34.7
2	42	26	33.8
3	24	24.8	32
4	02	24	30.6
4	42	23.3	30
5	22	22.7	29.5
6	02	20.9	27.9
11	52	20.3	27.6
12	17	19.9	27.4
13	17	16.2	26.3
13	27	15.8	26.2
13	54	14.3	25.5
14	18	12.4	25.1
15	19	8.6	24
16	22	8.4	23.7
17	52	12.3	24.2
18	50	13.9	24.6
19	08	14.4	24.8
20	47	16.3	25.6
21	50	17.1	26

Table XI : continued.

t		T	R
Hours	Minutes	in °C.	in ohms
23	02	17.8	26.2
23	49	17.9	26.3
24	18	18.2	26.4
24	47	18.5	26.6
25	27	19	26.8
26	14	19.4	27
28	15	19.8	27.2
32	30	20.9	28
32	37	21.4	28.3
33	01	22.8	29.1
33	45	25.5	31.7
34	21	25.1	31.4
34	48	24.6	30.9
35	46	23.7	30.1
36	38	23.2	29.7
37	18	22.9	29.5

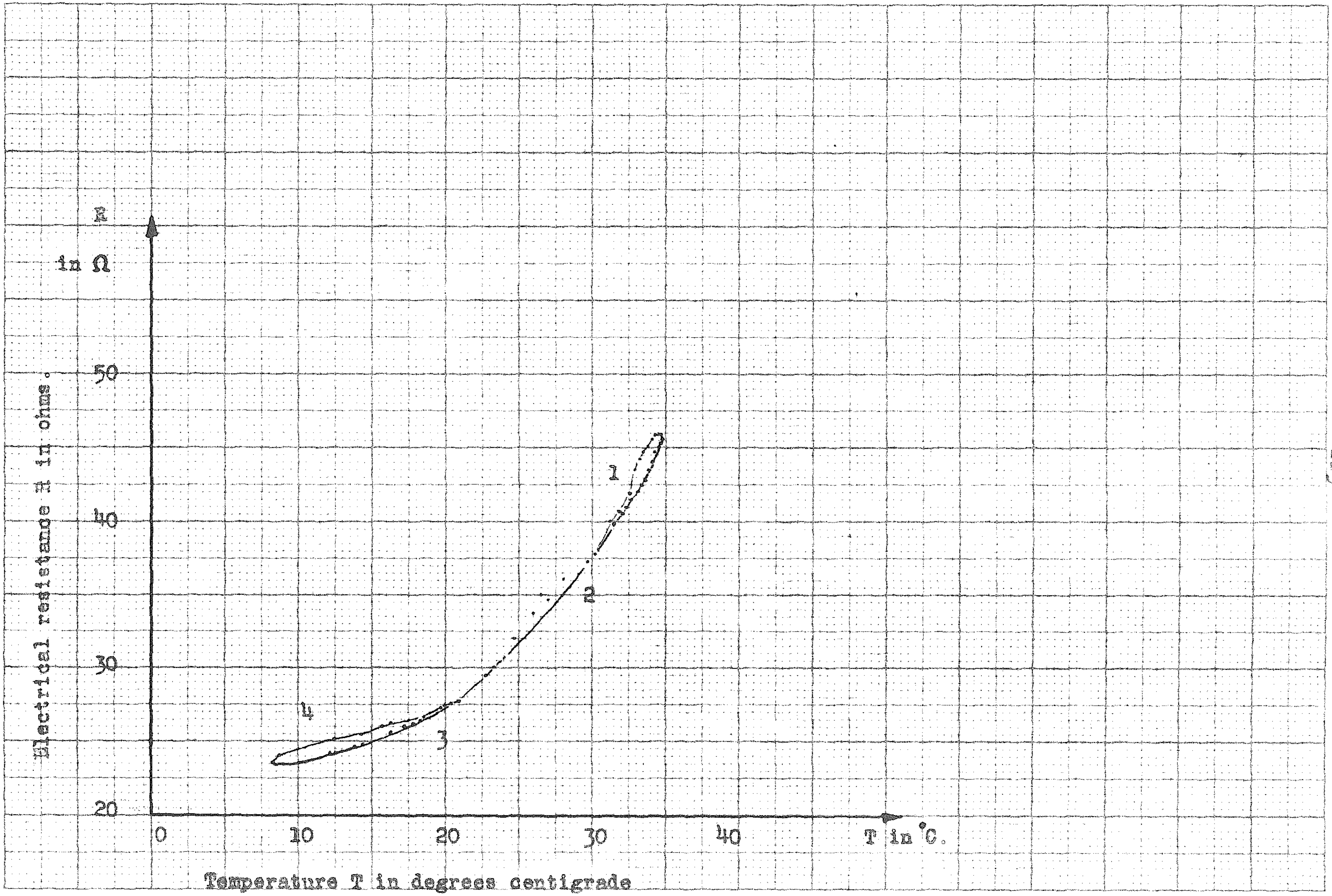


Figure 37 : Variations of the electrical resistance of pressure cell number 2 with temperature.

the inner container after ice cubes had been poured in the outer container. And portion 3 corresponds to the heating of the water after it reached a minimum temperature of 8.4°C.

The electrical resistance of the pressure cell was of 35.1 ohms for a water temperature of 26.5°C., which was the temperature recorded before the test began.

3.442. Discussion of the results.

From Table XI we see that the rate of decrease in temperature with time for section 2 and 3 of the diagram on figure 37, is at the most of about 0.1°C. in three minutes, or 0.18°F. in three minutes. In view of the results obtained in section 3.432, we can reasonably conclude that for sections 2 and 3 of our diagram the temperature read on the thermometer is also the temperature of our pressure cell.

In the case of portion 1, the rate of increase in temperature with time is much higher at first (4.8°C in 0.5 minute initially), it progressively decreases and becomes zero when the temperature recorded reaches its maximum of 34.65°C. A study of the difference in temperature between water and a wall plunged in that water was made for the first 12 minutes covering portion 1 of the curve in figure 37. For that study, the same assumptions as in section 3.432 were made. It was also assumed that the temperature recorded increased not continuously from 26.5°C. to 34.65°C. (Table XI) but by jumps. Each jump in temperature corresponds to the difference in temperature between each successive recording as tabulated in Table XI. The results of the study are given in

Table XII and have been plotted on figure 38. In Table XII, columns 5 to 16 give the value of the expression $(T_i - T_o)\varphi_s$ of equation 39, for each individual jump in temperature in the surrounding water. The figures are positioned, in the columns, in order to have the first figure in each successive column on the line corresponding to the time (Indicated in column 1) at which each jump is supposed to have occurred. Column 17 has been obtained by summing up all the figures of columns 5 to 16 line by line. Hence the figures in column 18 represent the differences in temperature between the surface of the wall and the surrounding medium due to all the jumps in temperature which occurred in the latter.

From those results we may conclude that in the case of our experiment on temperature effects on the value of the electrical resistance of pressure cell number 2, we may expect a difference in temperature between the pressure cell and the surrounding water for the first part of the experiment , which results have been plotted on figure 37 and constitute portion 1 of the plot. This would explain why portions 1 and 2 are not superimposable. By similarity, the same conclusion could be drawn regarding the difference between portions 3 and 4 of the plot.

From figure 37 we can conclude that the electrical resistance of a granular pressure cell increases with temperature; a result which confirms the predictions stated in section 3.41. The relationship between temperature and electrical resistence is not linear. $\frac{\Delta R}{\Delta T}$, where ΔR is increment of electrical resistance and ΔT is corresponding increment of temperature, increases with temperature.

Table XII : Temperature effects on a wall due to sudden jumps in temperature in the surrounding medium.

Time elapsed τ in hours	Jump in temperature in °F.	$\frac{4\alpha\tau}{L^2}$	Φ_S	$(T_0 - T_i)\Phi_S$ for each jump in temperature												$T_S - T_0$ in °F.
				τ_0	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}	
$\tau_0 = 0$	8.76	0	1	8.76												8.76
$\tau_1 = 0.0083$	0.9	0.84	0.6	5.26	0.9											6.16
$\tau_2 = 0.016$	0.54	1.68	0.35	3.07	0.54	0.54										4.15
$\tau_3 = 0.025$	0.54	2.52	0.3	2.63	0.32	0.32	0.54									3.81
$\tau_4 = 0.032$	0.9	3.37	0.2	1.76	0.27	0.19	0.32	0.9								3.44
$\tau_5 = 0.041$	0.54	4.2	0.2	1.31	0.18	0.16	0.19	0.54	0.54							2.92
$\tau_6 = 0.05$	0.54	5.05	0.1	0.87	0.14	0.11	0.16	0.32	0.32	0.54						2.54
$\tau_7 = 0.066$	0.36	6.74	0.05	0.44	0.07	0.05	0.08	0.18	0.16	0.19	0.36					1.58
$\tau_8 = 0.083$	0.54	8.4	0.0	0.0	0.02	0.03	0.03	0.09	0.08	0.11	0.13	0.54				1.03
$\tau_9 = 0.1$	0.36	10.1			0.0	0.0	0.0	0.04	0.03	0.05	0.07	0.19	0.36			0.93
$\tau_{10} = 0.116$	0.54							0.0	0.0	0.0	0.04	0.11	0.13	0.54		0.82
$\tau_{11} = 0.133$	0.27										0.0	0.05	0.07	0.19	0.27	0.58
$\tau_{12} = 0.15$	0.0											0.0	0.04	0.11	0.09	0.24
$\tau_{13} = 0.2$	0.0												0.0	0.0	0.0	0.0
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Column numbers

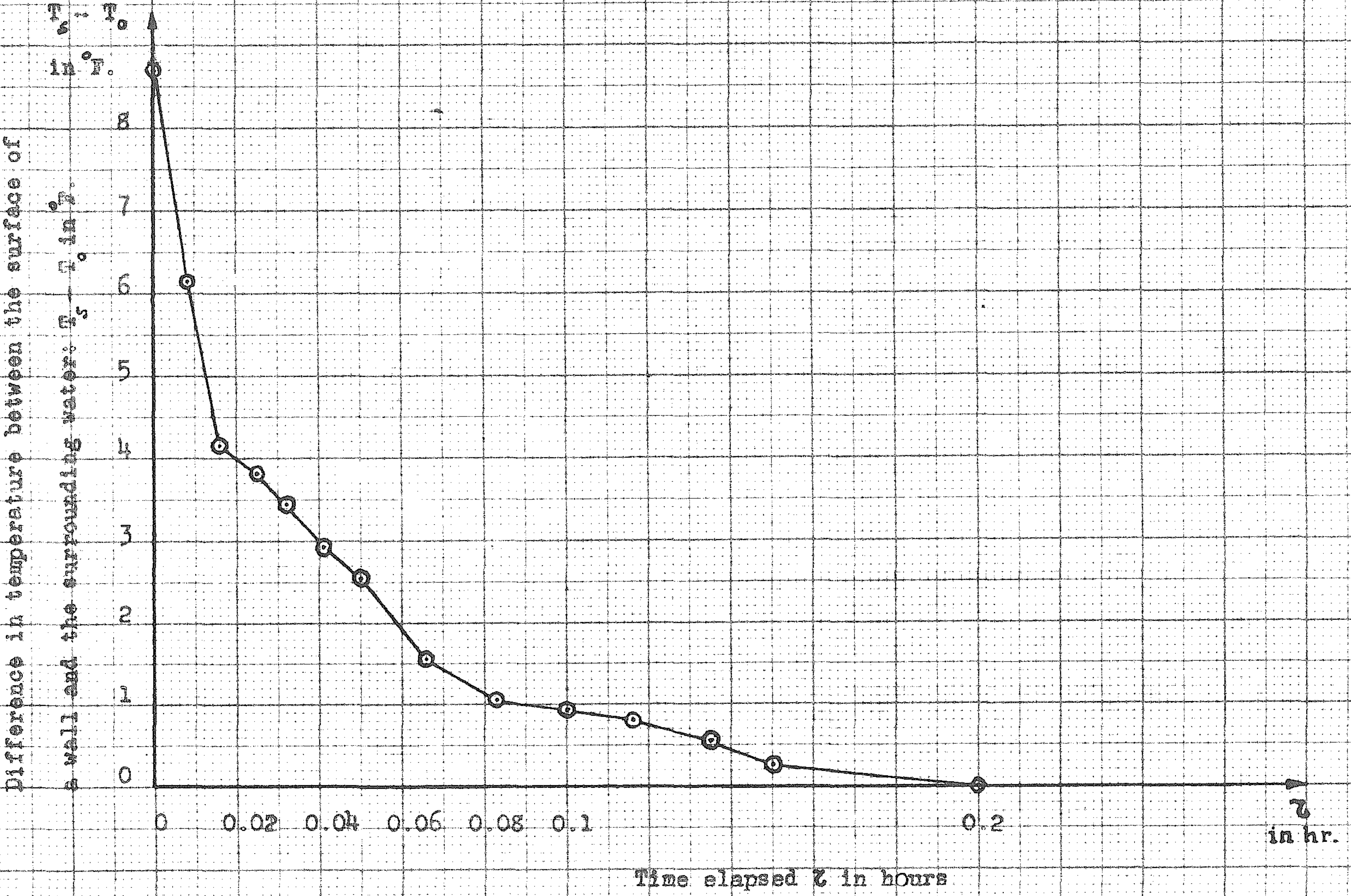


Figure 38 : Effect of sudden jumps in temperature in the surrounding water on the surface temperature of a wall.

In the range 10°C. to 20°C.,

$$\frac{\Delta R}{\Delta T} = 0.36 \text{ ohms} \,.\, ^{\circ}C.^{-1} \qquad (41)$$

In the range 25°C. to 35°C.,

$$\frac{\Delta R}{\Delta T} = 1.36 \text{ ohms} \, ^{\circ}C.^{-1} \qquad (42)$$

Result 41 represents an error in reading the electrical resistance of pressure cell number 2 of 1 per cent per degree centigrade whereas 42 represents an error in reading of about 4 per cent per degree centigrade.

In view of the foregoing lines, one may conclude that it will be important to know the temperature at which the calibration curve of a granular pressure cell similar to pressure cell number 2 will have been established and , also, to know the temperature of the surrounding medium when such a pressure cell is used. If not, one will possibly make errors which will make the use of a granular pressure cell completely senseless.

In further research, it will be of great interest to investigate the possibility of making pressure cells less temperature sensitive. For instance by using a matrix material having a coefficient of linear expansion smaller than the one of latex, so that the surface of contact between the grains embedded in the matrix material will vary much less with temperature than in the case of pressure cell number 2.

4. Determination of a calibration curve for a granular pressure cell to be used in model testing.

4.1. Preparation of granular pressure cell number 3.

A third granular pressure cell was prepared in the same way as was pressure cell number 2, but this time we used 0.27 grams of carbon grains prepared as described in section 3.11. The dimensions of the pressure cell without its electrodes were:

Diameter : 0.5 inch or 1.27 centimeters.

Thickness: 0.2 inch or 0.51 centimeters.

4.2. Set-ups used for calibration purposes.

Two set-ups were used in order to establish a calibration curve for pressure cell number 3, covering a range of vertical pressures from zero to about 15 pounds per square inch.

The first one is the triaxial testing machine described in section 3.33 and figure 35. It was found that a pressure of 5 pounds per square inch was necessary in the test chamber of the triaxial testing machine to counteract the weight of the loading shaft. For that reason, not wanting to have to take in account the weight of the loading shaft, we used a lateral pressure applied to the pressure cell of 5 pounds per square inch. In that case, the range of vertical pressures covered by loading pressure cell number 3 in the set-up of figure 35 was from five pounds per square inch on.

For vertical pressures from zero to 4 pounds per square inch, the set-up of figure 39 was used. It is composed of a bakelite rectangular base plate of dimensions as given in figure 39. Two rods, 0.25 inch in diameter (brass), are screwed into the base

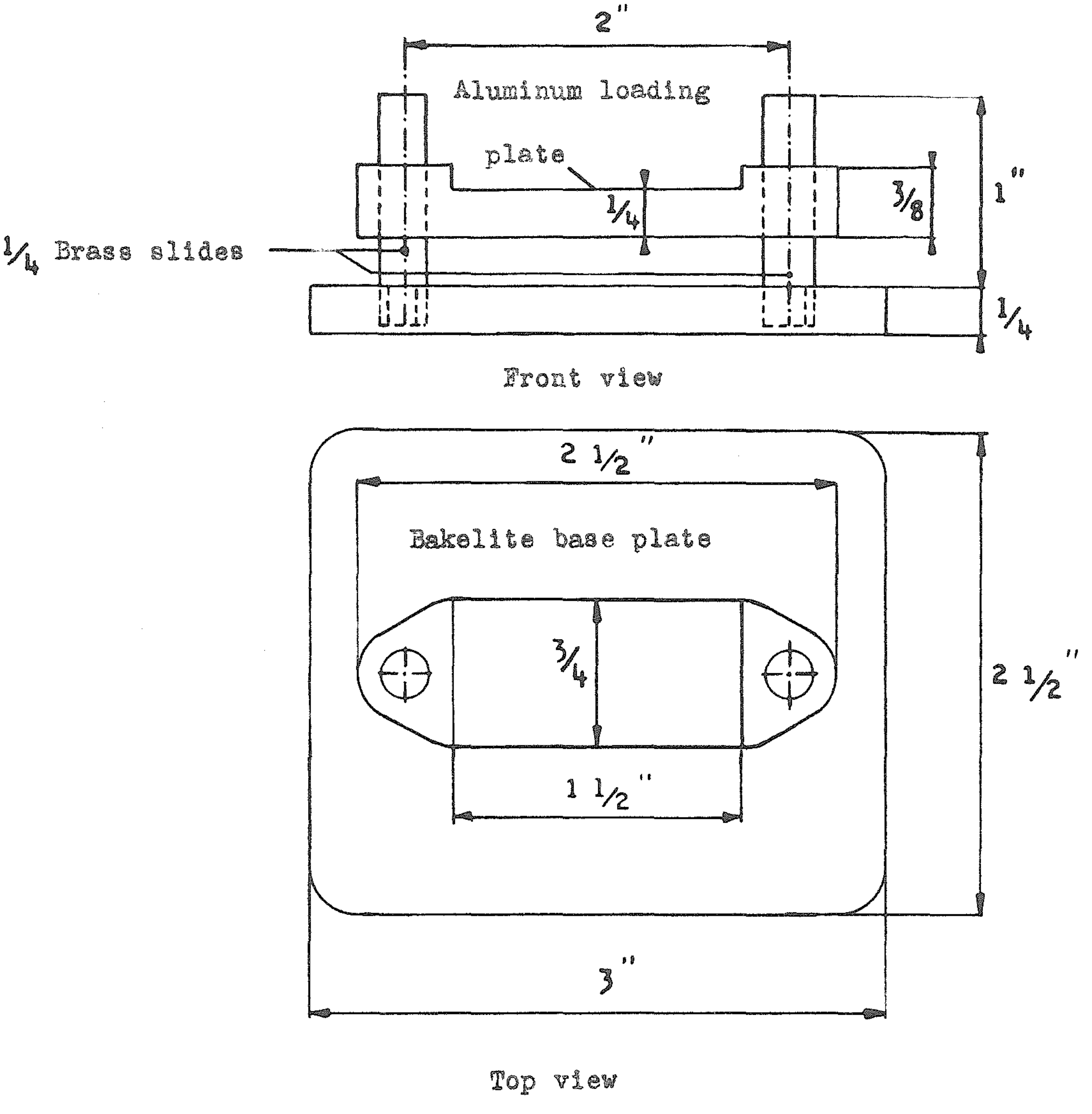


Figure 39 : Testing equipment used to establish the calibration curve for granular pressure cells in the range of pressures from zero to 4 pounds per square inch applied vertically.

plate 2 inches apart. These rods will serve as guides for the aluminum loading plate (Figure 39). The Wheatstone bridge described in section 3.3 was used to measure the electrical resistance of the pressure cell.

4.3. Testing procedure.

With both set-ups, the loading was performed by putting weights on either the loading shaft in the case of the triaxial testing machine, or the loading plate in the case of the set-up described in figure 39. A set of two pound weights was found in the Soil Mechanics laboratory and used in our tests.

The area of the end sections of the pressure cell number 3 was of :

$$\frac{\pi d^2}{4} = 0.785 \text{ inch} . \qquad (43)$$

Hence a load of two pounds on the loading shaft of the testing machine will correspond to a vertical pressure applied on the end sections of the pressure cell of about 2.55 pounds per square inch. So that the vertical pressures applied in the case of the tests conducted in the triaxial testing machine were, in pounds per square inch :

5; 7.55; 10.10; 12.65; 15.20.

During the first loading test, it was noticed that a three hour interval between each loading was needed for the pressure cell to arrive at a state of equilibrium under constant load applied and give a constant reading of electrical resistance.

This behavior could be explained by considering it to be due to frictional lag as mentioned in section 3.172. Also to possible plastic flow from the part of the rubber. It was also noticed that after about 6 loadings, readings of constant electrical resistance under a certain load could be made faster and that after the first 10 to 15 minutes since a load was applied, most of the change in electrical resistance had taken place, especially in the range of the higher vertical pressures applied.

4.4 Discussion of the results of the tests.

4.41. Electrical resistance-vertical pressure relationship.

The results of the tests are given in Table XIII and on figures 40 and 41. The results of each test have been drawn in a succession so as to show clearly what the evolution of the relationship between vertical pressure applied and the electrical resistance of pressure cell number 3 was through the different loading tests. From figures 40 and 41, after about 7 tests, the results of subsequent tests appear to be reasonably superimposable. Looking at the results of tests number 8 to 10 in Table XIII, it appears that the readings of electrical resistance under the same load conditions in each test vary from about 0.1 to 0.2 ohm, which represents errors of about 1 to 2 per cent of the value of electrical resistance read. It ought to be mentioned that our Wheatstone bridge cannot give an accuracy in reading of more than 0.1 ohm.

4.42. Stress-strain relationship for pressure cell number 3.

Table XIII gives also the values of the strains to which the pressure cell was submitted while under load. In the three last tests, number 8 to 10, the stress-strain relationship

Table XIII : Triaxial compression tests on pressure cell number 3.

Test number 1				
Loading			Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch$\times 10^{-3}$	Electrical resistance in ohms	Vertical strains in inch$\times 10^{-3}$
5	25.1	0.0	17	3.8
7.55	16.1	2.6	7.2	5.1
10.1	10.6	4	6.1	5.9
12.65	8.5	4.5	5.9	6.3
15.2	5.9	6.3		
Test number 2				
5	11	3.8	11.3	3.8
7.55	9.3	4	8.7	4.7
10.1	8.9	4.2	7.4	5.5
12.65	8.1	4.8	7.2	5.8
15.2	7.2	5.8		
Test number 3				
5	11.3	3	13.8	3.4
7.55	11.5	3.1	10.2	4.4
10.1	10.6	3.7	8.7	5.1
12.65	9.7	4.4	8.6	5.3
15.2	8.6	5.3		

Lateral pressure applied : σ_3 = 5 pounds per square inch.

Other specifications as mentioned on page 124.

Table XIII continued.

Test number 4				
Loading			Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch×10^{-3}	Electrical resistance in ohms	Vertical strains in inch×10^{-3}
5	13.3	3	13.9	3.3
7.55	12.1	3.3	11.2	4.4
10.1	11	4	9.8	5.2
12.65	10.3	4.5	9.6	5.4
15.2	9.6	5.4		
Test number 5				
5	13.9	3.8	14	4.3
7.55	12.7	4.1	10.9	5.5
10.1	11.1	4.8	9.8	6.2
12.65	10.9	5.5	9.7	6.3
15.2	9.7	6.3		

Dimensions of the pressure cell : Diameter : 0.5 inch
Thickness: 0.2 inch

Average temperature throughout the tests : 72°F. ± 1°F.

Table XIII continued.

Test number 6				
Loading			Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch×10^{-3}	Electrical resistance in ohms	Vertical strains in inch×10^{-3}
5	13.8	4	14	4.4
7.55	13.1	4.3	11.2	5.7
10.1	11.5	5	10	6.2
12.65	10.9	5.6	9.9	6.5
15.2	9.9	6.5		
Test number 7				
5	13.3	4.3	13.1	4.5
7.55	12.9	4.5	10.8	6
10.1	10.9	5.4	9.8	6.7
12.65	10.1	6.1	9.7	6.9
15.2	9.7	6.9		

Table XIII continued.

Test number 8				
	Loading		Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch×10^{-3}	Electrical resistance in ohms	Vertical strains in inch×10^{-3}
5	13.1	4.5	13.2	4.5
7.55	12.7	4.6	10.9	6
10.1	10.7	5.5	9.7	6.7
12.65	10	6.2	9.6	6.9
15.2	9.6	6.9		
Test number 9				
5	13.2	4.4	13.3	4.7
7.55	12.8	4.6	11.2	5.9
10.1	11	5.5	10	6.5
12.65	10.1	6.2	9.8	6.9
15.2	9.8	6.9		
Test number 10				
5	13.2	4.5	13	4.6
7.55	12.7	4.8	11.7	4.5
10.1	11	5.6	10	6
12.65	10.3	6.1	9.6	6.9
15.2	9.6	6.9		

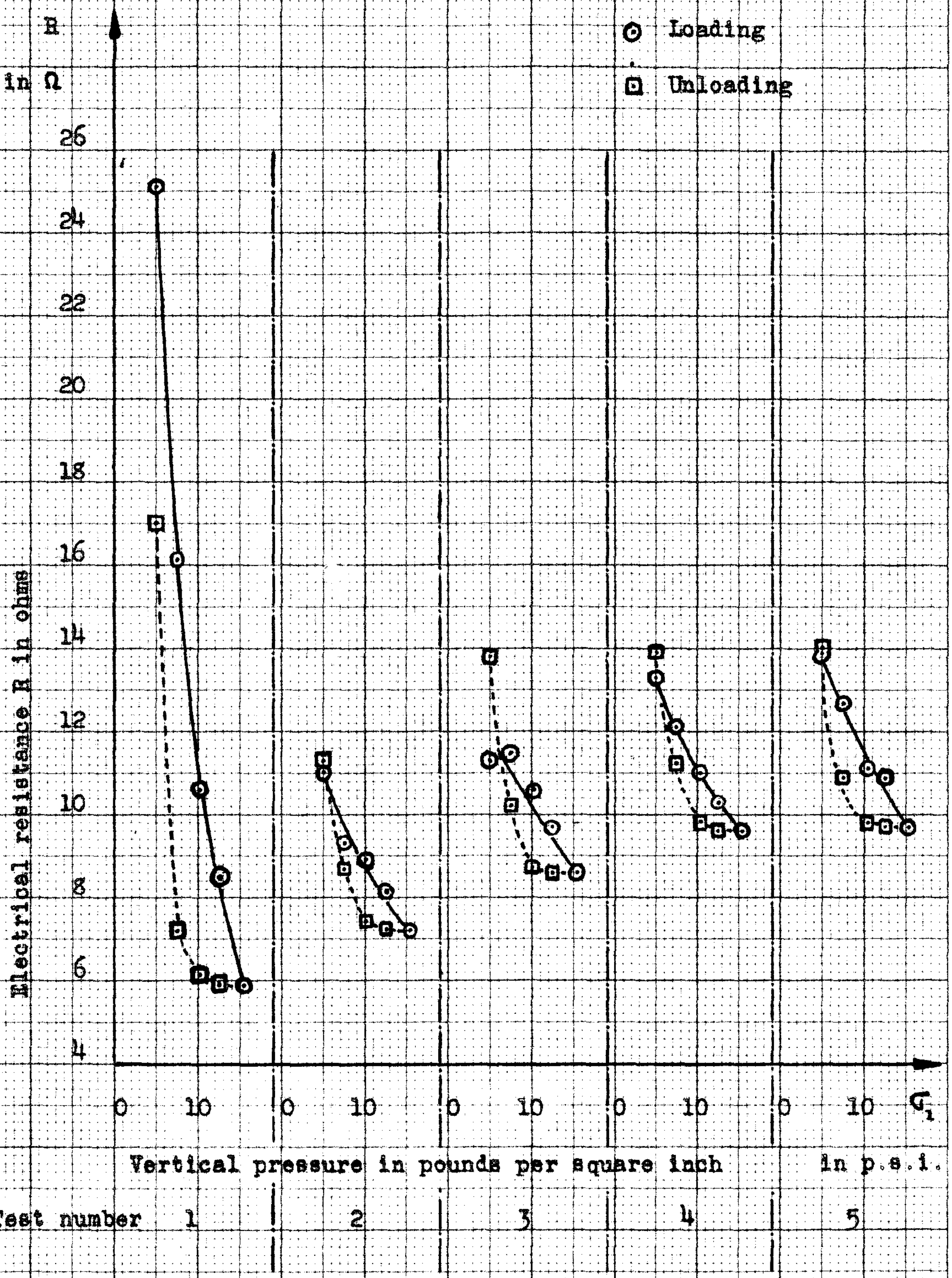


Figure 40 : Vertical compression tests on pressure cell number 3.

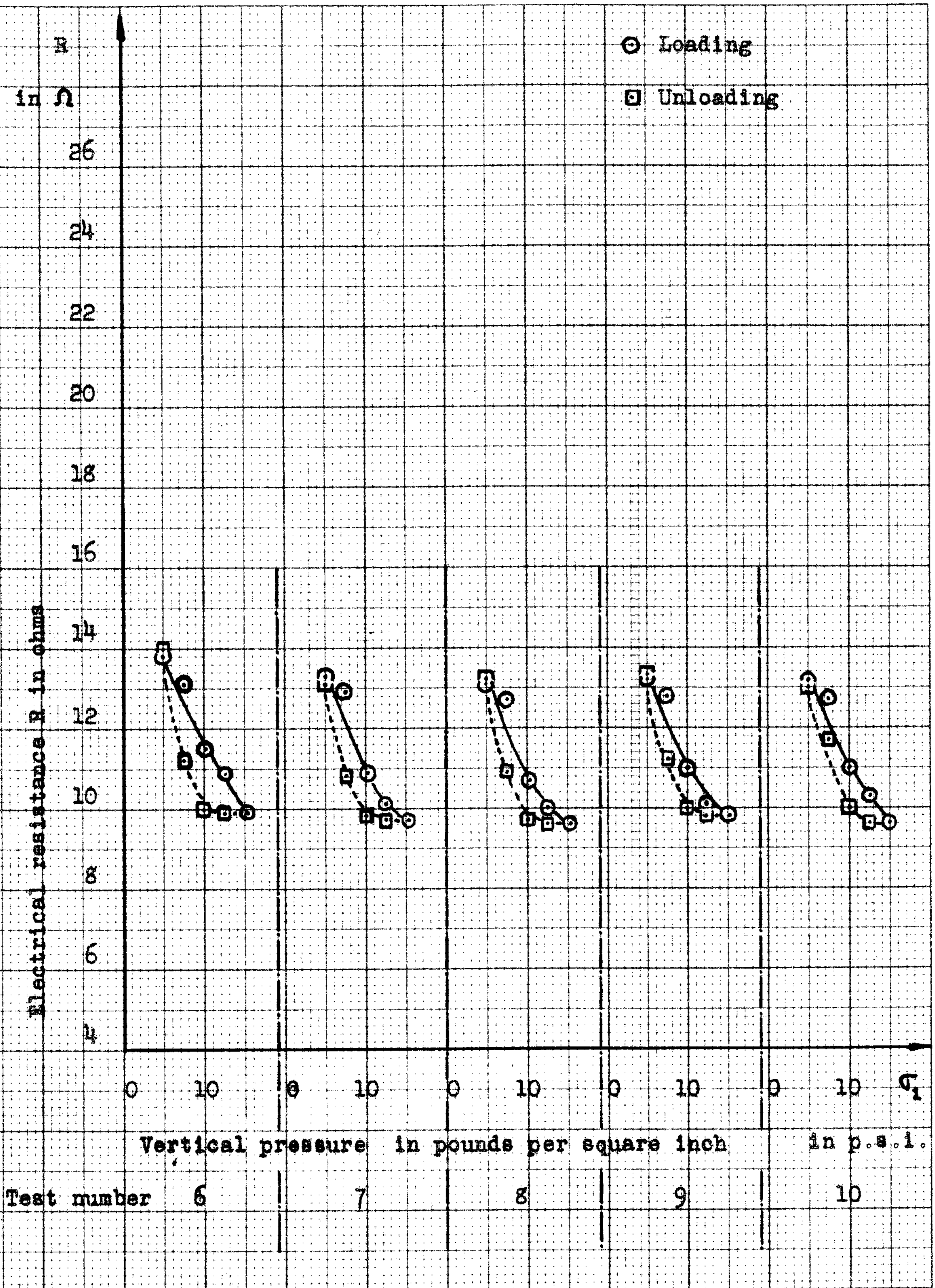


Figure 41 : Vertical compression tests on pressure cell number 3

for pressure cell number 3 are similar as are the stress-electrical resistance relationships.

Figure 42 is a stress-strain diagram which comprises the stress-strain curves for Fort Peck sand given in reference 3, page 336, and the stress-strain curve obtained by taking an average of each corresponding value given in Table XIII. for tests number 8 to 10. In order to be able to use the results given in Table XIII we substracted, from the values of strains, an amount corresponding to the strain read for $\frac{\sigma_1}{\sigma_3}=1$. Where σ_1 is vertical pressure applied and σ_3 is lateral pressure. The transposed values of strain for tests number 8 to 10 are given in Table XIV. A correction was also brought to the value of the thickness L of the pressure cell taking in account the permanent strain having taken place during the tests number 1 to 7. Figure 42, shows that the stress-strain relationship for pressure cell number 3 falls in between the stress-strain curves for loose and dense sand, as we hoped it would. As the carbon grains in our pressure cell were compacted during the molding process, it is quite understandable that the stress-strain curve for pressure cell number 3 falls closer in shape to the stress-strain curve for dense sand than for loose sand.

4.5. A calibration curve for pressure cell number 3.

After the series of tests conducted on pressure cell number 3 in the triaxial testing machine had been completed, the pressure cell was tested in the range of pressures zero to 5 pounds per square inch in the testing set-up of figure 39.

Table XIV : Experimental results on the stress–strain relationship for pressure cell number 3.

Vertical pressure in p.s.i.	$\frac{\sigma_1}{\sigma_3}$	Vertical strains $\Delta L'$ in inch x 10^{-3}				$\Delta L = \Delta L' - 4.47$ in inch x 10^{-3}	$\frac{\Delta L}{L_1}$ in %
		Test number 8	Test number 9	Test number 10	Average		
5	1	4.5	4.4	4.5	4.47	0	0
7.55	1.51	4.6	4.6	4.8	4.7	0.23	0.118
10.1	2.2	5.5	5.5	5.6	5.53	1.06	0.542
12.65	2.53	6.2	6.2	6.1	6.17	1.7	0.87
15.2	3.04	6.9	6.9	6.9	6.9	2.43	1.24

Lateral pressure $\sigma_3 = 5$ pounds per square inch.

Thickness of the pressure cell : Initially ; $L = 0.2$ inch.

Corrected ; $L_1 = 0.2 - 0.00447 = 0.19553$ inch.

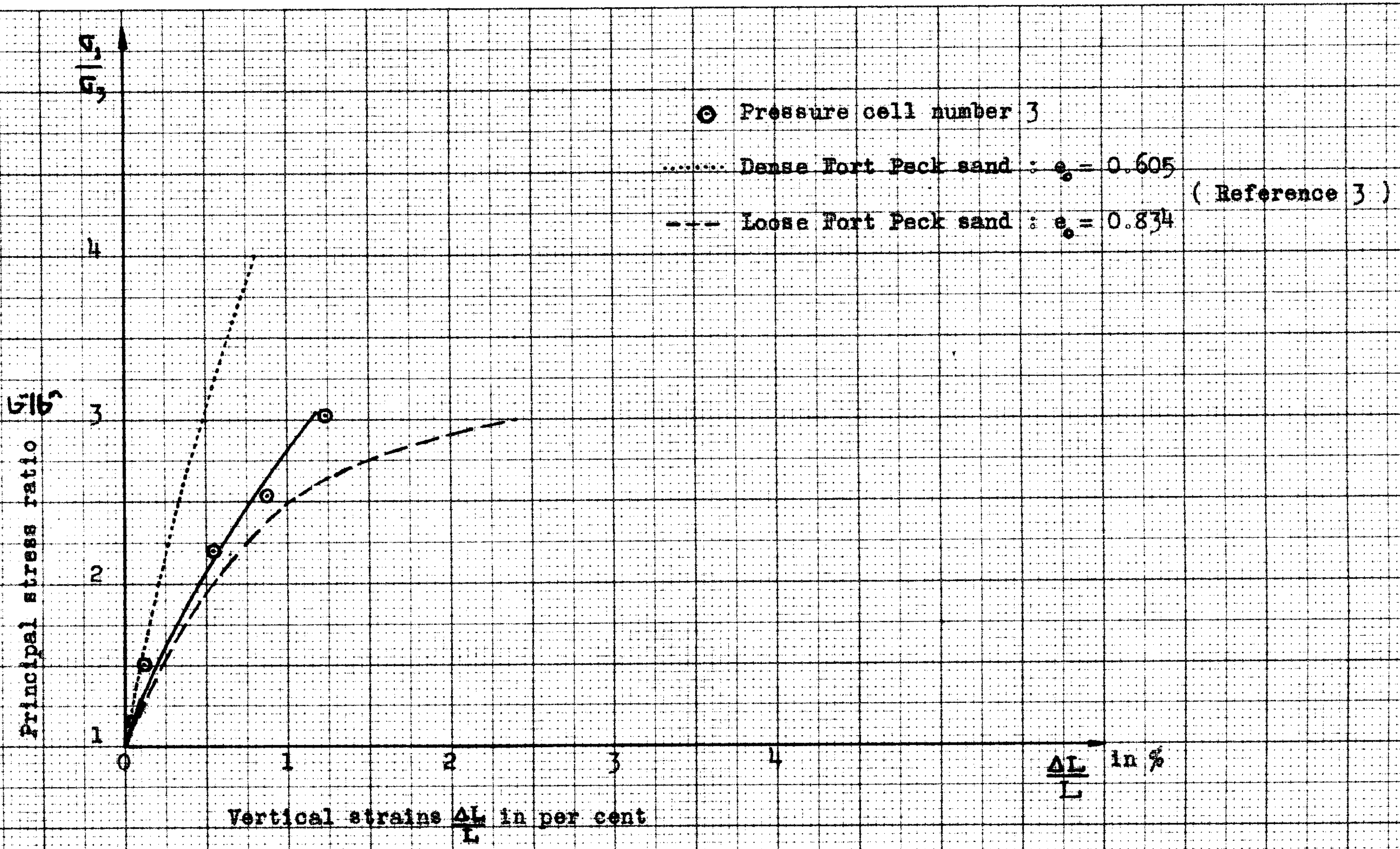


Figure 42 : Stress-strain relationship for pressure cell number 3 compared to stress-strain relationships for a typical sand.

Three loading tests were performed and the results of these being consistent with each other and reproducible, the testing was ended. The results of these tests are given in Table XV . Table XVI gives the combined results of the loading tests performed on pressure cell number 3 in the range of pressures applied from 0.0 to 15.2 pounds per square inch. As already mentioned, the values of electrical resistance given in Table XVI are average values of the results given by tests number 8 to 10, in the range of pressures from 5 to 15.2 pounds per square inch. The results of Table XVI were used to establish a calibration curve for pressure cell number 3 at a room temperature of 72°F., which is given on figure 43.

5. Use of pressure cell number 3 in laboratory experiments.

5.1. Introduction.

It was decided at this stage, having a calibration curve for pressure cell number 3, to use it in actual laboratory testing conditions in order to compare the results obtained to theoretical estimations and see how the pressure cell would behave. To determine to what extent it may be improved in its basic conception and examine the applicability of the theory of elasticity to a granular soil.

5.2. Vertical pressure under a circular rigid footing on sand.

5.21. Experimental set-up.

The set-up used here consisted mainly of a cylindrical galvanized bucket 11.7 inches in inside diameter and 4.5 inches in height. The bucket was filled up to a height of 3.6 inches with Ottawa sand found in the Soil Mechanics laboratory.

Table XV : Vertical compression tests on pressure cell number 3 in the range of vertical pressures from 0 to 4 pounds per square inch. No lateral pressure was applied.

Vertical pressure in p.s.i.	Electrical resistance in ohms		
	Test number 1	Test number 2	Test number 3
0	33.1	32.8	33.1
0.5	30.5	30.8	30.7
1	30.3	30.7	30.5
2	28.7	28.4	28.4
3	25.9	25.9	26.1
4	18.2	17.8	18

No vertical strains were recorded.

Table XVI : Vertical pressure - electrical resistance R relationship for pressure cell number 3.

Vertical pressure σ_1 in p.s.i.	Electrical resistance R in ohms
0	33
0.5	30.7
1	30.5
2	28.5
3	26
4	18
5	13.2
7.55	12.8
10.1	10.9
12.65	10.1
15.2	9.7

The values of electrical resistance in this table are computed from the results given in Table XV (Average of tests number 1,2 and 3.) and Table XIII (Average of tests number 8, 9 and 10.).

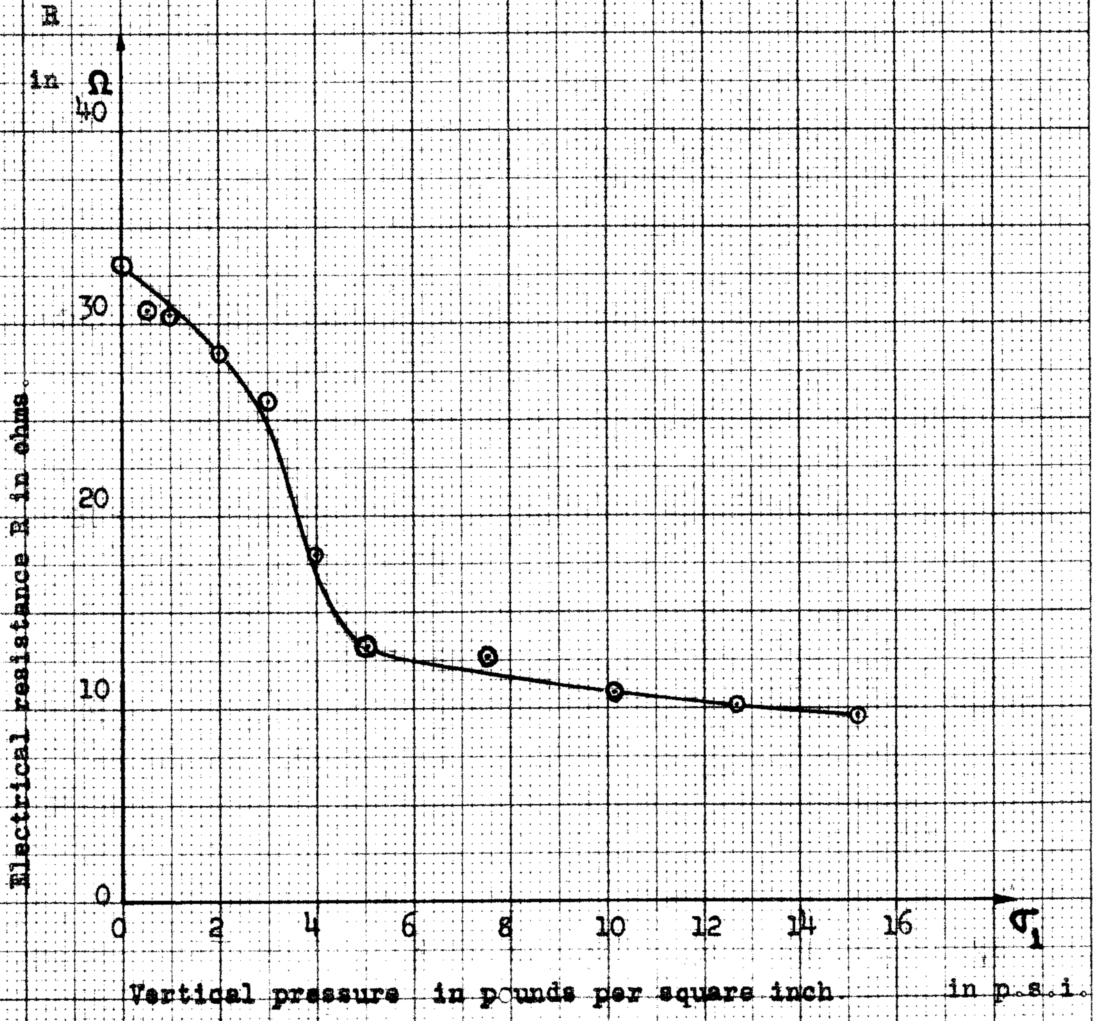


Figure 43 : Calibration curve for pressure cell number 3.

A grain-size analysis was made and the results reported in Table XVII and on figure 44. 85.8 per cent of the grains of the sand used here were retained in sieve number 40 of the sieves serie described in section 3.11. The sand in the bucket was compacted lightly. An aluminum disc 3 inches in diameter and 0.9 inch thick was used as a footing. As a loading system we used the cover of a triaxial testing machine supported as shown clearly in figure 45. The load was applied through dead weights consisting of a set of cast iron discs weighing 5 pounds each. Pressure cell number 3 was put horizontally at an initial depth of 1.3 inches under the surface of the sand and coaxial with the center of our circular footing in the first loading test. It was placed at 1.35 inches in the second test.

5.22. Testing procedure and results.

Two loading tests were performed. The load was applied as shown in figure 45. The results of the tests are given in Table XVIII (Test number 1) and Table XIX (Test number 2). column 2 in both tables give the vertical displacements of our footing as recorded by the dial gauge (see section 3.33 for description) installed as shown in figure 45. Knowing the vertical displacements endured by the footing throughout the tests, we were able to determine the importance of the displacements occurring after each additional load was applied compared to the total displacment . As the initial and final distances between the center of the footing and the pressure cell were measured, we were able to estimate the

Table XVII : Grain size analysis for the Ottawa sand used in our laboratory testing.

Sieve number	Nominal opening in mm.	Weight of sand retained in grams	Amount of sand retained in % of total weight	Per cent finer by weight
4	4.76	0	0	100
10	2	0	0	100
20	0.84	0.515	1.03	98.97
40	0.42	42.82	85.8	13.17
60	0.25	5.2	10.4	2.77
140	0.105	1.33	2.7	0.07
200	0.074	0.03	0.06	0.01

Total weight of Ottawa sand sieved : 50 grams.

Sieve series used : U.S. Standard Sieve Series ;
Newark Wire Cloth Co., Newark, N.J.
Comprises sieves number 4, 10, 20, 40, 60, 140, 200.

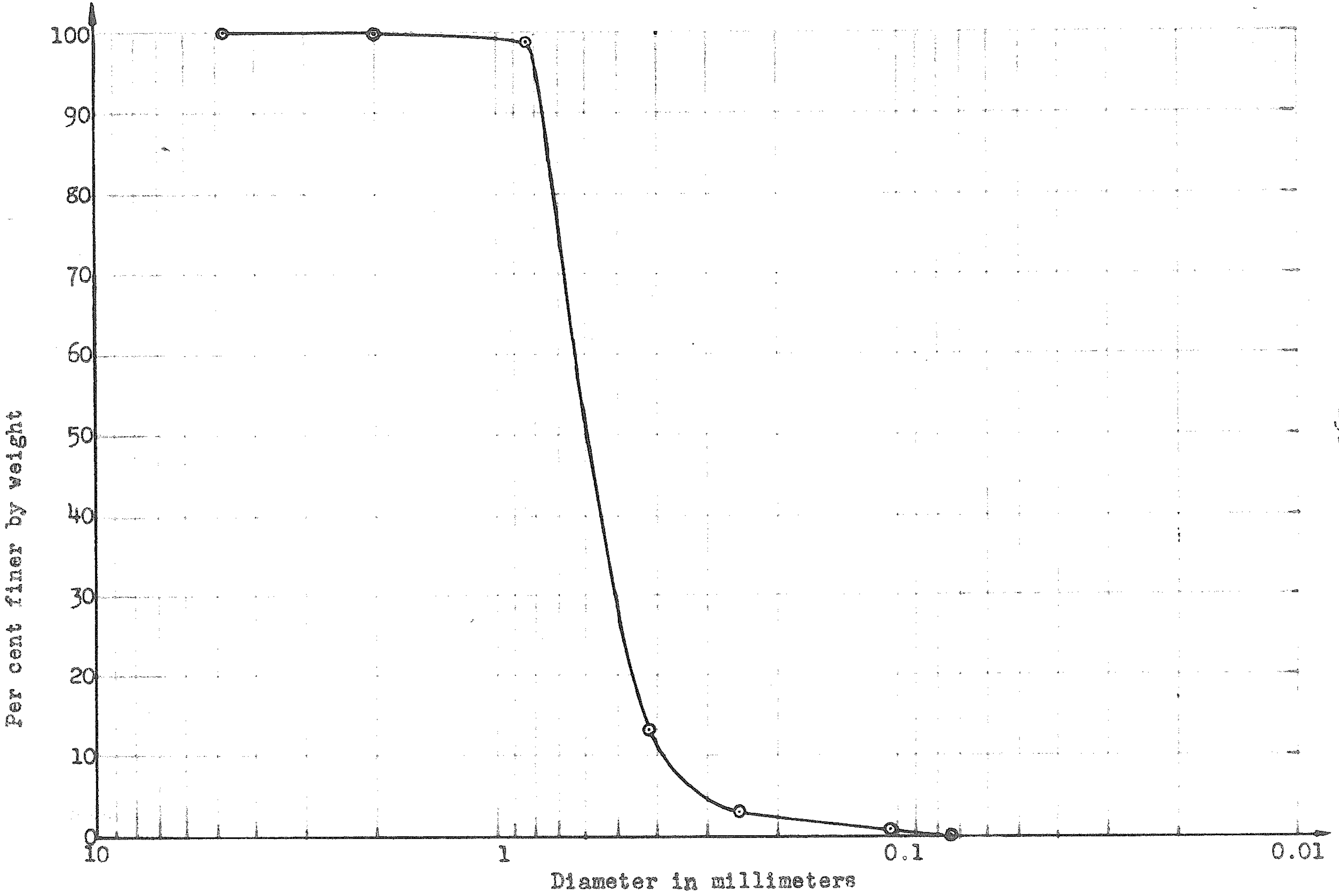


Figure 44 : Grain-size distribution Curve for Ottawa sand used in our tests.

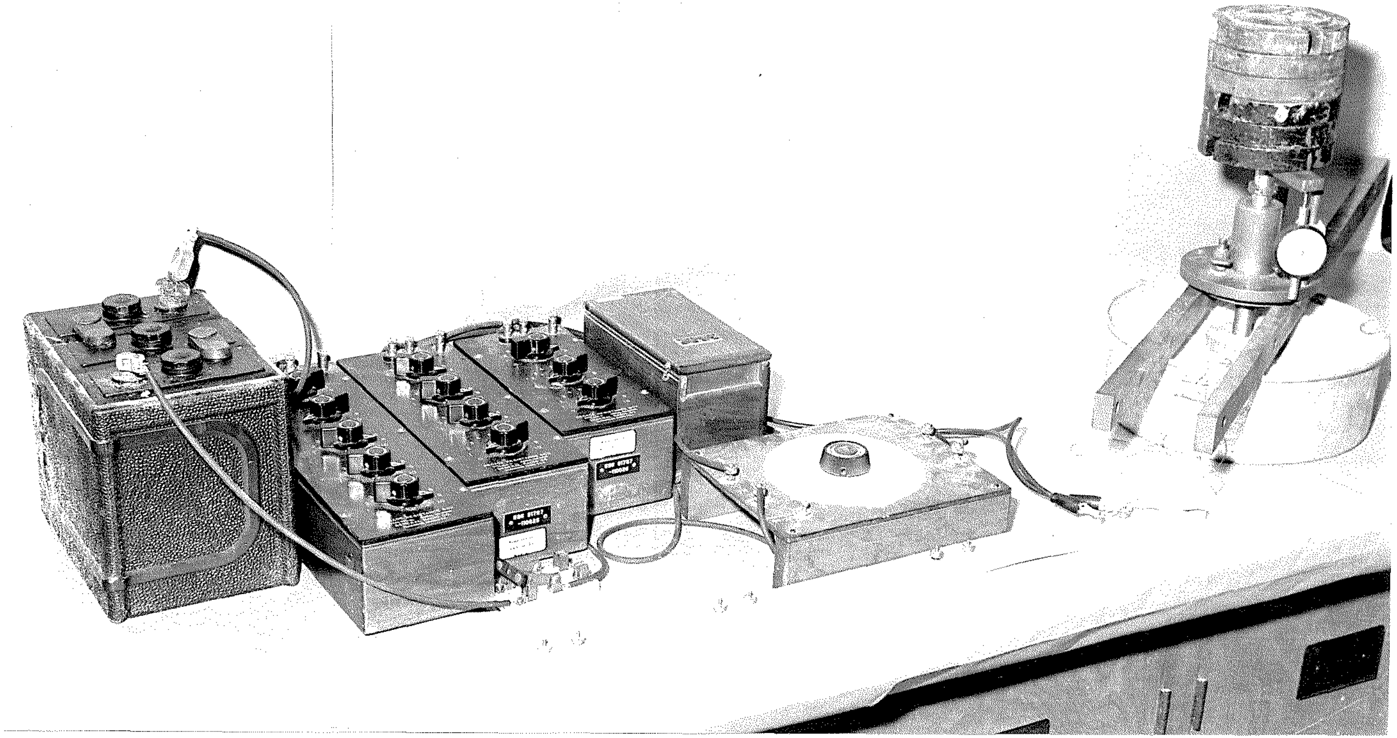


Figure 45 : Set-up used, in laboratory experiments, to determine the vertical pressure under a rigid circular footing on sand.

Table XVIII : Determination of the vertical pressure under the center of a circular footing on sand. Test number 1.

Load applied + weight of footing in p.s.i.	Settlement of the footing in inches	Distance z footing to pressure cell in inches	Electrical resistance in ohms	R/z	I_z	Vertical pressure at the pressure cell σ_z	
						Calculated in p.s.i.	Measured in p.s.i.
0.0	0.0	1.35	33	1.11	0.7	0.0	0.0
1.08	0.009	1.34	32.1	1.12	0.7	0.76	0.6
1.8	0.041	1.31	31.3	1.12	0.7	1.27	1
3.22	0.083	1.28	27	1.17	0.72	2.32	2.3
4.64	0.179	1.17	16.6	1.27	0.76	3.54	4
5.3	0.278	1.1	13.3	1.35	0.79	4.2	4.8
1	2	3	4	5	6	7	8

Column nr.

Dimensions of the footing : Radius R = 1.5 inch.
(Aluminum) Thickness = 0.9 inch.
Area = 7.07 inch.

Initial distance between the footing and the pressure cell : z_i = 1.35 inch.
Final distance : z_f = 1.1 inch

Weight of the footing : 0.6 pounds.
Weight of the loading shaft : 2 pounds.
Load due to the sand on top of the pressure cell : 0.09 p.s.i.

Table XIX: Determination of the vertical pressure under the center of a circular footing. Test number 2.

Load applied + weight of footing in p.s.i.	Settlement of the footing in inches	Distance z footing to pressure cell in inches	Electrical resistance in ohms	R/z	I_σ	Vertical pressure at the pressure cell σ_z	
						Calculated in p.s.i.	Measured in p.s.i.
0.0	0.0	1.3	33.1	1.15	0.72	0.0	0.0
0.37	0.0	1.3	32.7	1.15	0.72	0.26	0.2
1.78	0.011	1.29	31.3	1.16	0.72	1.28	0.8
3.22	0.036	1.27	28.7	1.18	0.73	2.35	2
4.62	0.09	1.22	26.5	1.23	0.75	3.45	2.6
5.32	0.119	1.2	20.9	1.25	0.76	4.08	3.5
5.6	0.157	1.17	18.6	1.28	0.77	4.3	3.8
5.94	0.43	1.0	13.6	1.6	0.85	5.05	5
6.18	0.582	0.82	12.2	1.83	0.89	5.5	6.1
1	2	3	4	5	6	7	8

Column number.

Distance between the footing and the pressure cell : Initial z_i = 1.3 inch.

Final z_f = 0.82 inch.

All other complementary information is as given in table XIX.

vertical displacements of the pressure cell throughout the tests. In our estimations, we assumed there was similitude between the successive settlements of the footing and the vertical displacements of the pressure cell. The distances between the footing and the pressure cell throughout the tests are given in column 3. We applied the theory of elasticity (21, 22) to our case in order to determine the vertical pressure, at the level of our pressure cell, theoretically (Column 7) and were then able to compare these results to the vertical pressure recorded by the pressure cell (Column 8). In order to compute the vertical pressures under our footing, we assumed that we had a uniformly loaded circular area on a semi-infinite elastic, isotropic, homogeneous and weightless solid of Poisson Ratio $\mu = 0.45$. This problem has been solved by Love, on the basis of the Boussinesq equations (22), and tabulated by R. E. Fadum. The vertical normal stress at depth z beneath the center of a circular area with radius R carrying a load q per unit area is (22) :

$$\sigma_z = qI_\sigma \qquad (44)$$

wherein

$$I_\sigma = 1 - \left\{\frac{1}{1 + (R/z)^2}\right\}^{3/2} \qquad (45)$$

From R. E. Fadum's table (22; Appendix, Table III), we were able to find I_σ knowing R/z (Columns 6, Tables XVIII and XIX) and hence determine σ_z. In our experiments, we did not have a semi-infinite mass of sand but a layer 3.6 inches thick, on a rather rigid base. But in reference 22 we read :

" ... according to St. Venant's principle the influence of

> the rigidity of the base on the state of stress in an elastic layer decreases rather rapidly with increasing elevation above the base. In the upper half of the layer the state of stress is practically identical with that in an elastic, semi-infinite deposit which is acted upon by the same load."

As in both our tests our pressure cell was located rather in the upper half of our sand layer, we assumed it correct to base our theoretical computations on the case of a semi-infinite deposit.

5.23. Discussion of the results.

Figures 46 and 47 are diagrams of the theoretical vertical pressure σ_z, at the level of the pressure cell, versus the load per unit area q applied to our footing. On the same diagrams we have plotted the values of vertical pressure recorded by our pressure cell. Also plotted on figures 46 and 47, are diagrams of vertical displacements of the footing versus the load applied q. These latter plots were included to help in the interpretation of the vertical pressure-load applied diagrams. As figures 46 and 47 are quite similar, the interpretation of one of them will be applicable, qualitatively at least, to both.

Examining figure 46, we see that up to a load applied on the footing of about 3.2 pounds per square inch, the pressure recorded is smaller than the theoretical vertical pressure at the same location. The maximum difference between the theoretical and recorded pressures is of about 0.26 pounds per square inch, or about 15 per cent of the calculated pressure at about 2 pounds per square inch of load applied. However, the theoretical vertical pressure was calculated assuming that the sand mass in our experiment could be assimilated to a semi-infinite elastic medium with an

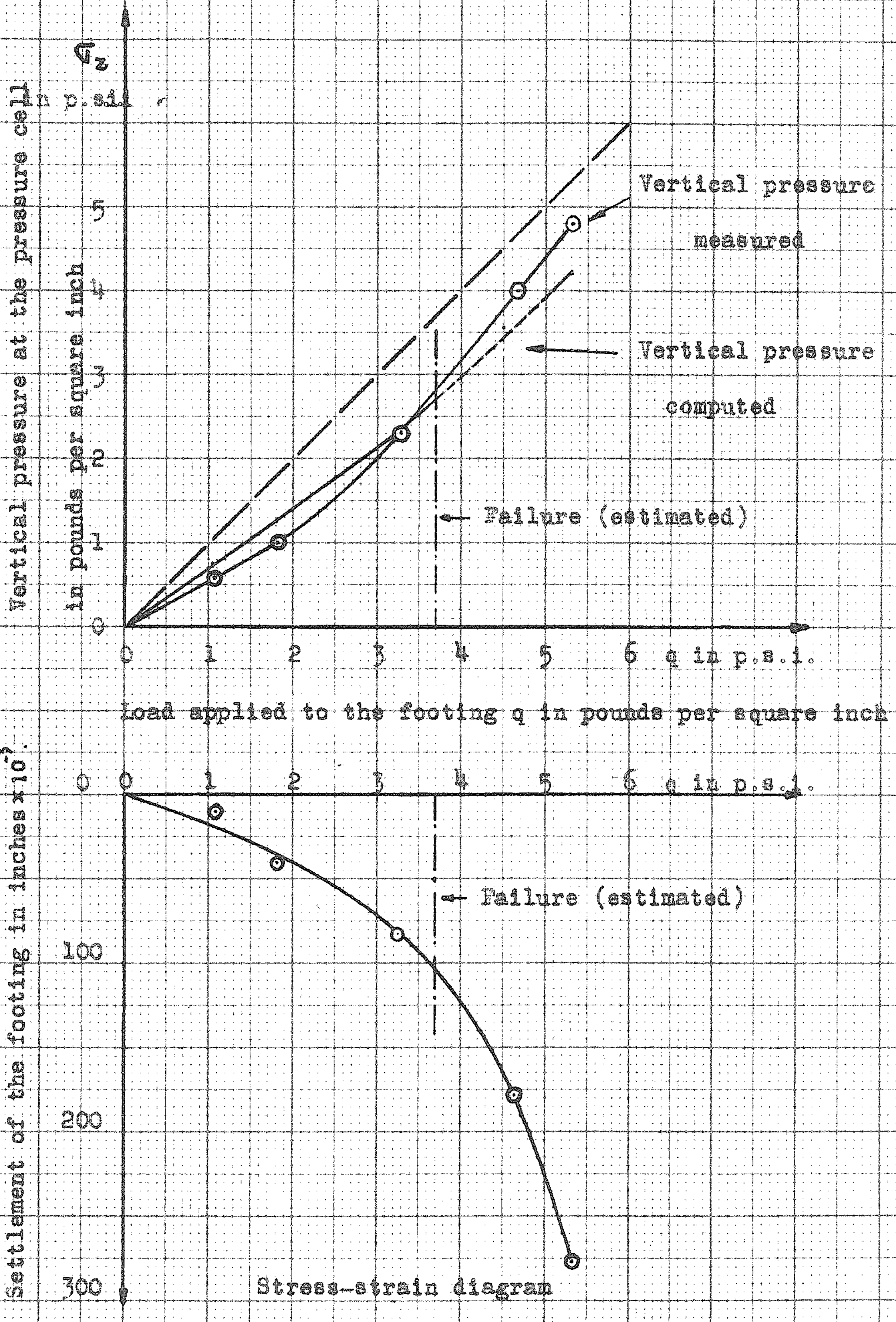


Figure 46 : Vertical pressure under the center of a circular footing.

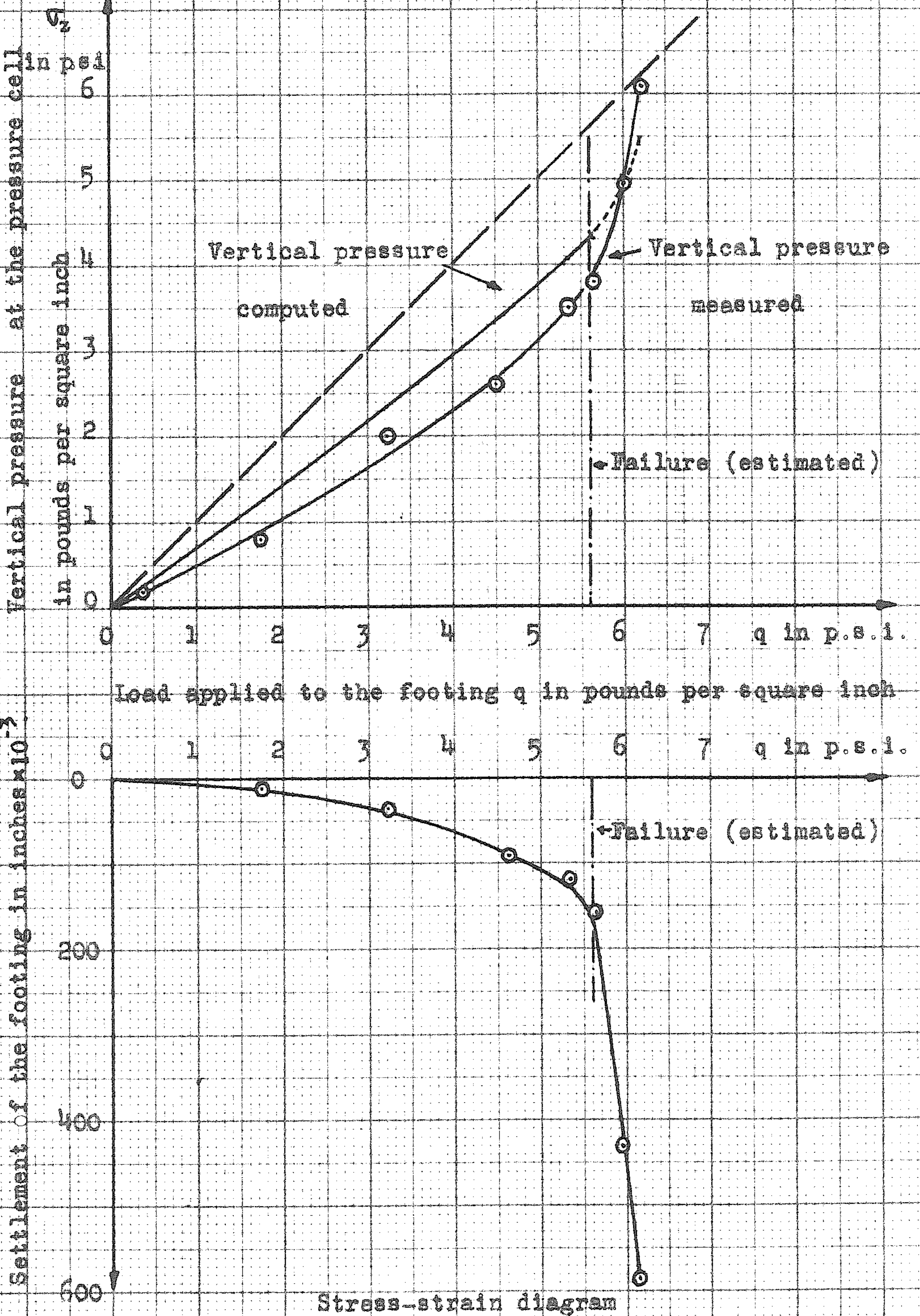


Figure 47 : Vertical pressure under the center of a circular footing.

assumed Poisson's ratio of 0.45. For comparison, let us mention that steel has a Poisson's ratio of 0.3 and that a perfectly incompressible material would have a Poisson's ratio of 0.5. Also to be considered is the fact that the Boussinesq equations apply only in the case of a uniformly distributed load on the surface of the elastic medium considered (22). Such an assumption is hardly verified in the case of a rigid footing on soil. In the case of a rigid footing on cohesionless sand, at the surface, at the rim of the base of the footing, even a very small stress exceeds the stress condition for failure. Hence at the rim, the contact pressure can never become greater than zero (See reference 22 and figure 48a). In the case of a rigid footing on an elastic medium, the distribution of pressure at the surface of contact looks as shown on figure 48b.

In view of the foregoing lines, it is then difficult to say whether a difference of 20 per cent between the pressures recorded and calculated is of any significance. Nevertheless, figure 46 shows that the maximum error between the calculated and recorded vertical pressures occurs for a vertical pressure roughly half the stress at failure. From then on, the error decreases to the point of being negligible close to failure. Once failure has occurred, the soil surrounding the pressure cell is in a plastic state except for a small cone located right underneath the footing itself (Figure 49). The Boussinesq equations have no meaning anymore in the plastic zones, and their use in the aforementioned cone can be questioned, such a cone being far from being semi-infinite in extent. It is also hard to tell if that cone

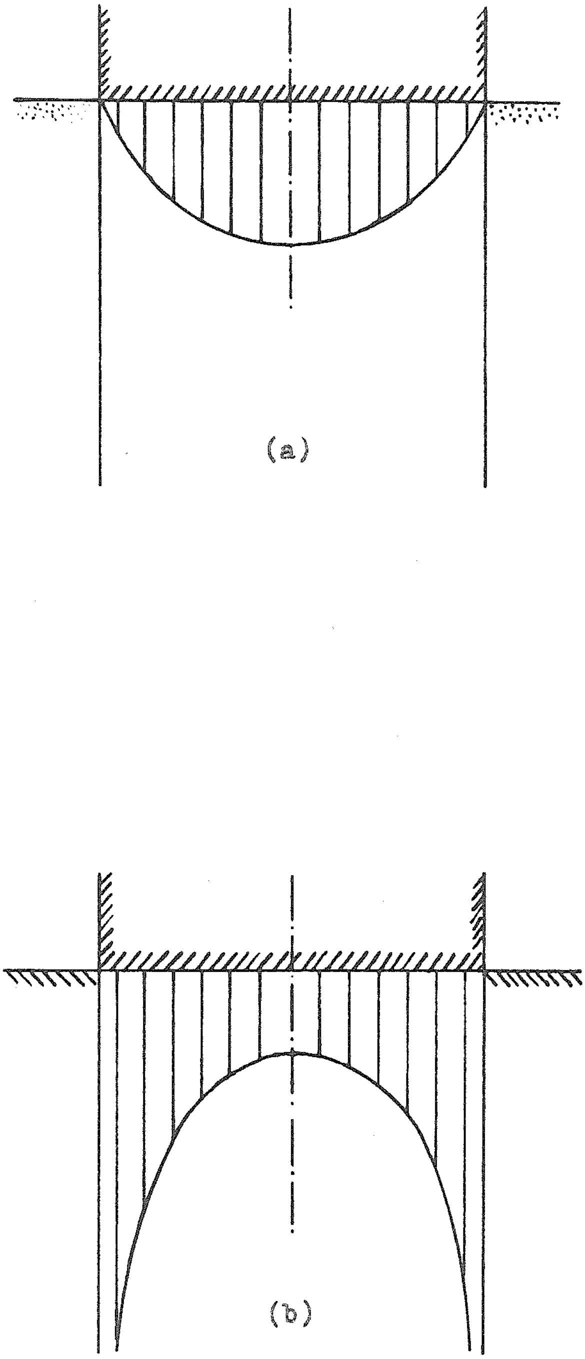
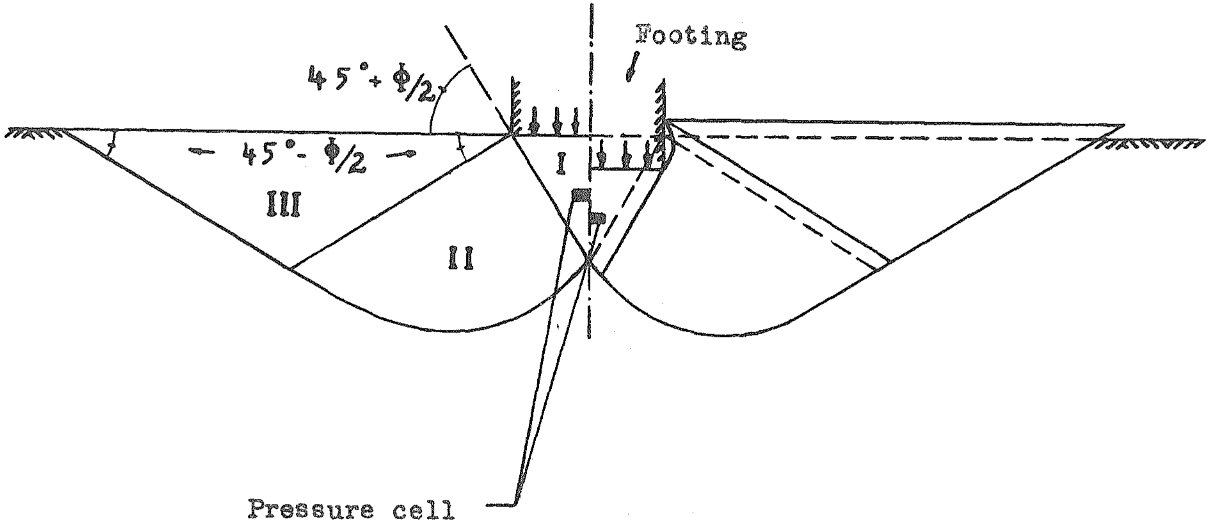


Figure 48 : Pressure distribution on the surface of contact of a rigid footing and : (a) a semi-infinite cohesionless medium, (b) a semi-infinite elastic medium.

(Reference 22, page 391.)



I : zone of vertical major principal stresses.

II : zone of radial shear.

III : passive Rankine zone.

Figure 49 : Boundaries of zone of plastic flow after failure of earth support of footings.

(Reference 22, page 121.)

could be considered as part of the footing and in constant elastic equilibrium because the surface of contact for our footing had been machined on a lathe and was then rather smooth. In that case, it is difficult to say if the footing was able to oppose, by friction, the tendency of the cone to spread out radially from underneath the footing (22). Lack of constant elastic equilibrium in the cone might explain the difference between the pressure recorded and the vertical pressure applied to the footing, the pressure cell being located in that cone after failure (Figure 49). The error between the vertical pressure read and applied on the footing was of the order of 10 per cent of the pressure applied, and seemed to decrease with increasing load.

5.24. Conclusion.

Although it was difficult to say how close the readings of the pressure cell were to the actual vertical pressure existing at its location, under our circular footing, it can be seen on figures 46 and 47 that those readings are quite reasonable and might be close to the actual vertical pressure our pressure cell was supposed to record. The results we arrived at, in the experiments described in section 5, lead us to conclude that they definitely strengthen the justification of further developments leading to perfecting our granular pressure cells.

6. Improved granular material to be used in granular pressure cells.

6.1. Introduction.

The granular pressure cells we built up to now are still subject to improvement. In the case of pressure cell number 3, it had been found that seven loading tests had to be performed before one could think of establishing a calibration curve for that pressure cell. Mechanical hysteresis occurs in these loading and unloading tests (Table 17). Permanent deformations were observed up to the eighth loading test.

The three above-mentioned occurrences are the result of the physical and mechanical characteristics of the granular and matrix materials used in our experiments.

The fact that it is only after a certain number of loading tests that our pressure cell started to give a reproducible stress-electrical resistance relationship can be attributed partly to the irregularities in the shape and size of the carbon grains we used. When a mass of angular grains of carbon like those we used is subjected to load, that mass will compact. But the surfaces of contact for each grain do not match necessarily the surfaces of contact of the surrounding grains because the grains are not all of the same size and shape. In some instances we may even have point contact between the grains in the mass. Hence the adjustment of all the grains to each other under load will not necessarily be instantaneous. The only way to avoid such a situation is by using grains of more uniform geometrical characteristics, the ultimate being the use of spherical grains all identical in size, in regular arrangements, the ultimate being the use of spherical grains all identical.

Permanent strain can be attributed to compaction of the grains under load and also to plastic flow in the rubber.

Mechanical hysteresis can be explained by the fact that rubber is not a pure elastic material.

No attempt was made in the present work to eliminate all the imperfections of the granular pressure cells allready made. But the experiments described in the following sections have been completed to corroborate the statments made in this introduction.

6.2. Improvement of the granular material.

The market was investigated in order to find spherical carbon granules, unfortunately such granules could not be found. However, we were able to find carbon grains less angular than the ones described in section 3.11.

The carbon grains we found are produced by the National Carbon Company under the label : Graphite Powder; grade B - B - 6. Figure 50 is a photograph of these grains taken with the equipment and under the conditions already described in section 3.11. Comparing figure 50 to figure 12 (Section 3.11), we can see that the roughness of the surfaces of the carbon grains in both figures is of the same order ($r^* = 0.064$ millimeters). It is why we decided not to use the grains grade B - B - 6 in their original shape, but to round them off first as explained in the following lines. It must be mentioned here that we attempted to round off

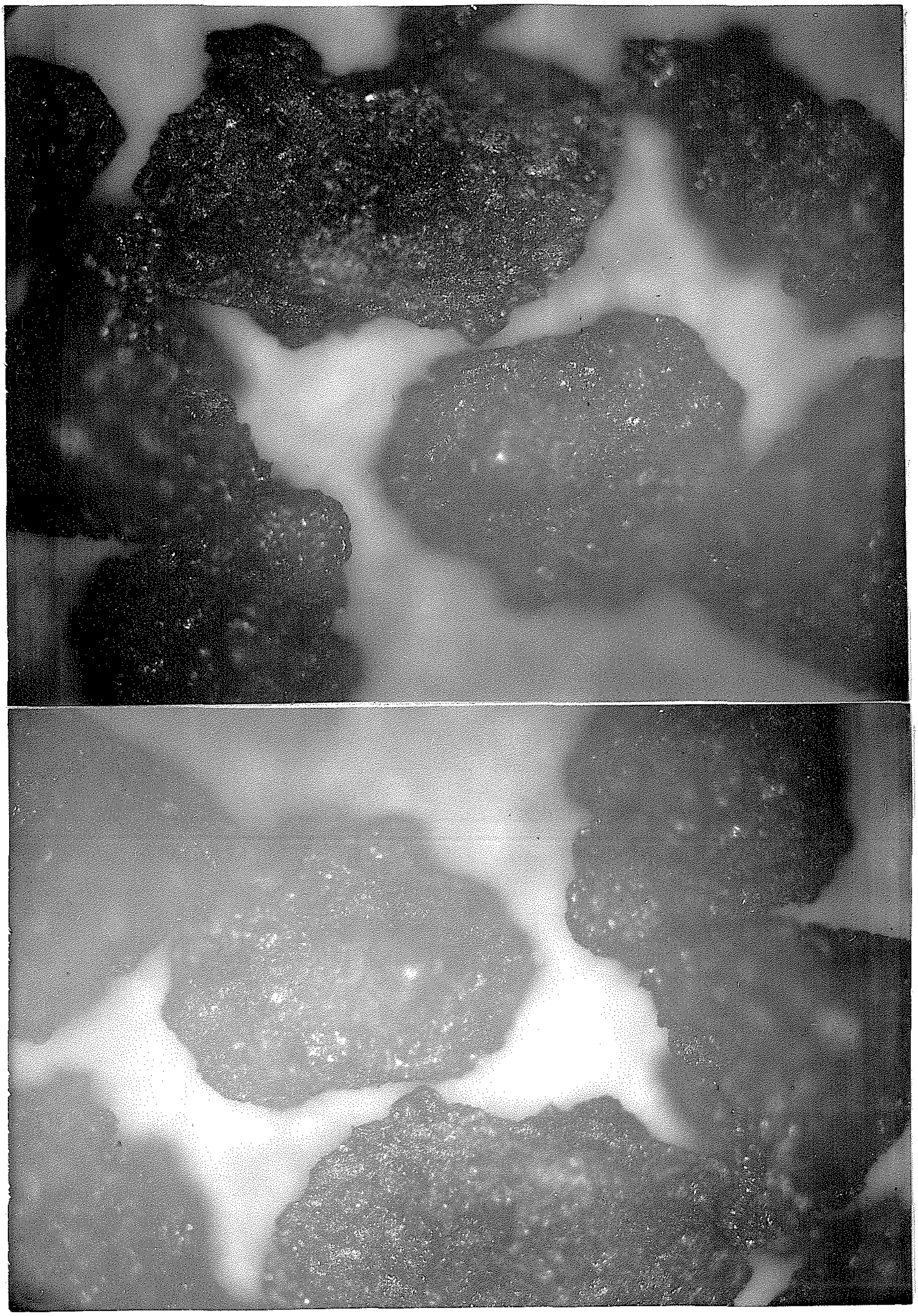


Figure 50 : Carbon grains grade B - B - 6

(magnification : 20)

the carbon grains of section 3.11, but were not successful, the grains being too hard.

A certain quantity of carbon grains grade B - B - 6 was put on a porous stone 4.5 inches in diameter, 1 inch thick produced by the Norton Company under the number P - 2120. The carbon grains on the porous stone were isolated by a cover 3 inches in diameter and 0.5 inch deep (figure 51). The porous stone with its enclosed carbon grains was tightened down on the sieve shaker of the Soil Mechanics laboratory as shown on figure 51. It was hoped that the horizontal motion of the shaker's plate would make the grains rub on the surface of the porous stone so as to smooth out angularities and in so doing provide the grains with more spherical surfaces of contact. The grains were looked at occasionally to check on the effects of the shaking action, and after 48 hours the shaker was brought to a halt because we noticed that the carbon grains were not becoming rounder any more but were merely being worn down to smaller dimensions. Figure 52 is a photograph taken of a sample of our rounded grains. Comparing figures 50 and 52, we can see readily what was the effect of the shaking action. The general shape of the grains is retained, the grains remained angular although sharp edges and corners have been rounded off. For the surfaces, with the magnification used in taking the photographs, we can say that they are now smooth. Although our grains remained angular after the shaking operation, we considered it worthwhile to see what the effect of the smoothness of the surfaces would be if such grains were used in a granular pressure cell. Therefore it was decided to make another

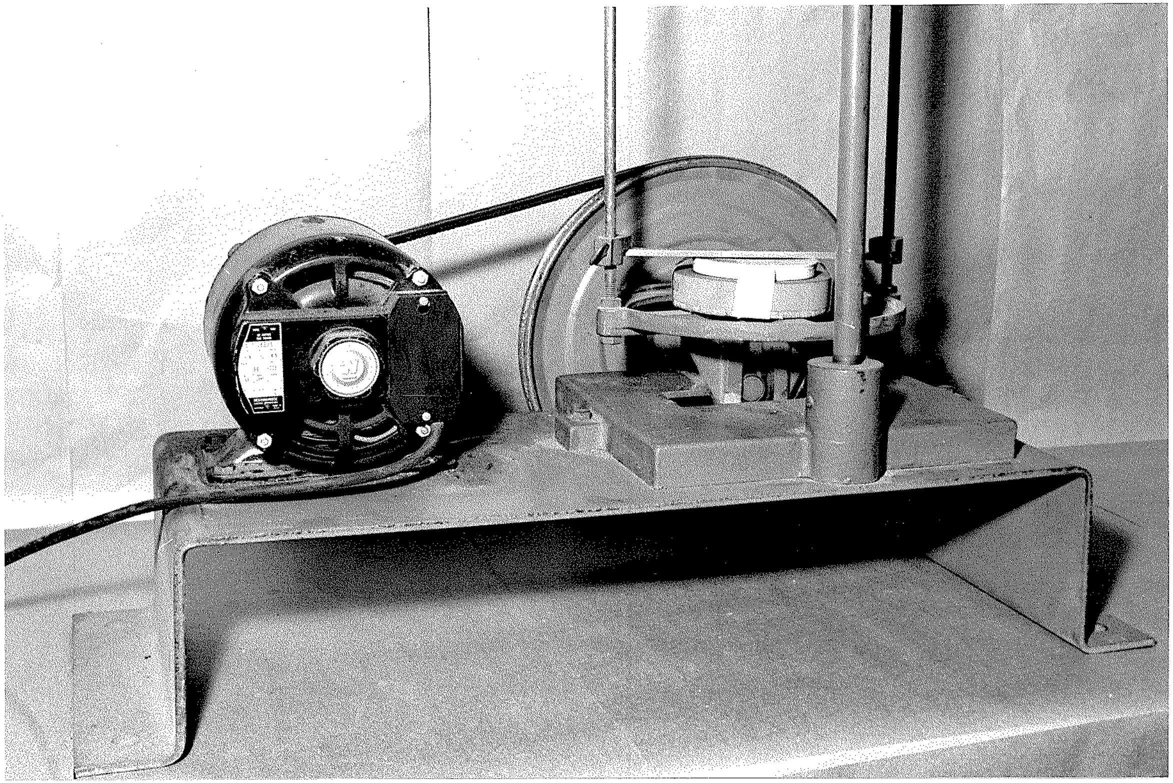


Figure 51 : Set-up used to smooth out the angularities of the carbon grains grade B - B - 6.

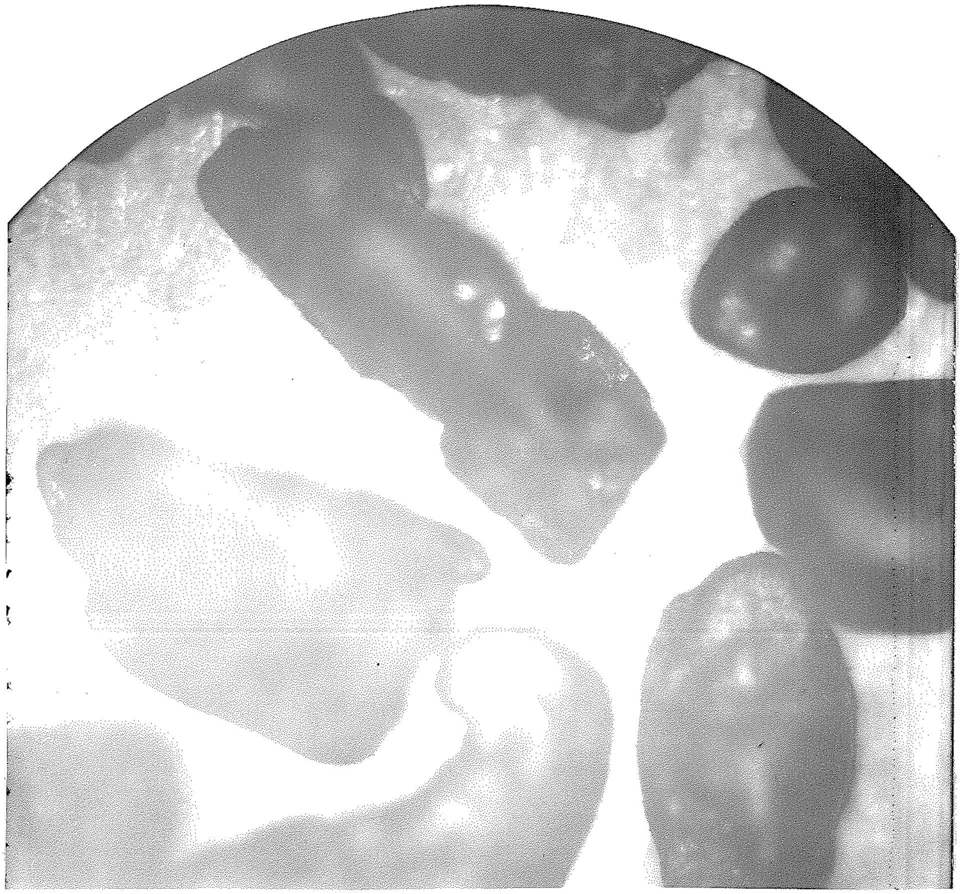


Figure 52 : Carbon grains grade B - B - 6 after the shaking operation.

granular pressure cell. The mass of carbon grains that had been undergoing shaking was sieved in the sieve series described in section 3.11, and only the grains not passing through sieve number 40 and passing through sieve number 20 were retained.

7. Preparation and testing of pressure cell number 4.

7.1. Preparation and tests.

Pressure cell number 4 was prepared and tested in an identical way as was pressure cell number 3. The full description of the preparation and testing procedures used in the case of pressure cell number 4 were as described in sections 4.1, 4.2 and 4.3. The dimensions of pressure cell number 4 were as follows:

Diameter : 0.5 inch.
Thickness: 0.3 inch.

The results of the tests are given in Table XX and on figure 53.

7.2. Discussion of the results.

From Table XX we can conclude that pressure cell number 4 does reach a state, at which a reproducible calibration curve can be expected, much faster than pressure cell number 3. Four loading tests sufficed to make the pressure cell reach a state where reproducibility could be expected. Such a result proves to be quite encouraging and justifies eventual attempts at using rounded or even spherical carbon grains in further experiments on granular pressure cells.

Table XX : Compression tests on pressure cell number 4.

Test number 1				
Loading			Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch$\times 10^{-3}$	Electrical resistance in ohms	Vertical strains in inch$\times 10^{-3}$
5	32	0	34	6.2
7.55	30.9	5.3	28.1	7.4
10.10	28.6	6.1	26	8
12.65	27	7	25	8.3
15.2	25	8.3		
Test number 2				
5	31	6	30.9	6.5
7.55	29.4	6.3	28.7	7.5
10.10	28	7	27.8	8
12.65	27.4	7.3	27.4	8.1
15.2	27.3	8.2		
Test number 3				
5	29.7	6.3	30.2	6.8
7.55	27.4	6.5	27.8	7.7
10.10	26.4	7	26.6	8.2
12.65	26	7.5	25.4	8.4
15.2	25.4	8.4		

Lateral pressure σ_3 applied : 5 pounds per square inch.

Dimensions of the pressure cell : Diameter = 0.5 inch.

Thickness = 0.3 inch.

Table XX continued.

Test number 4				
Loading			Unloading	
Vertical pressure in pounds per square inch	Electrical resistance in ohms	Vertical strains in inch×10^{-3}	Electrical resistance in ohms	Vertical strains in inch×10^{-3}
5.	28.9	6.7	28.6	7
7.55	27.8	6.9	26.4	7.9
10.10	26.3	7.4	25.3	8.5
12.65	25.9	8	25	8.8
15.2	25.2	8.6		
Test number 5				
5	28.7	6.8	28.9	6.9
7.55	27.5	7	27.2	7.4
10.10	26.6	7.8	26.2	8
12.65	25.5	8.1	25.6	8.7
15.2	25	8.7		
Test number 6				
5	28.8	6.7	28.5	7
7.55	27.9	6.8	27.6	7.8
10.10	27	7.5	26.6	8.3
12.65	26.1	8.2	25.1	8.5
15.2	25.1			

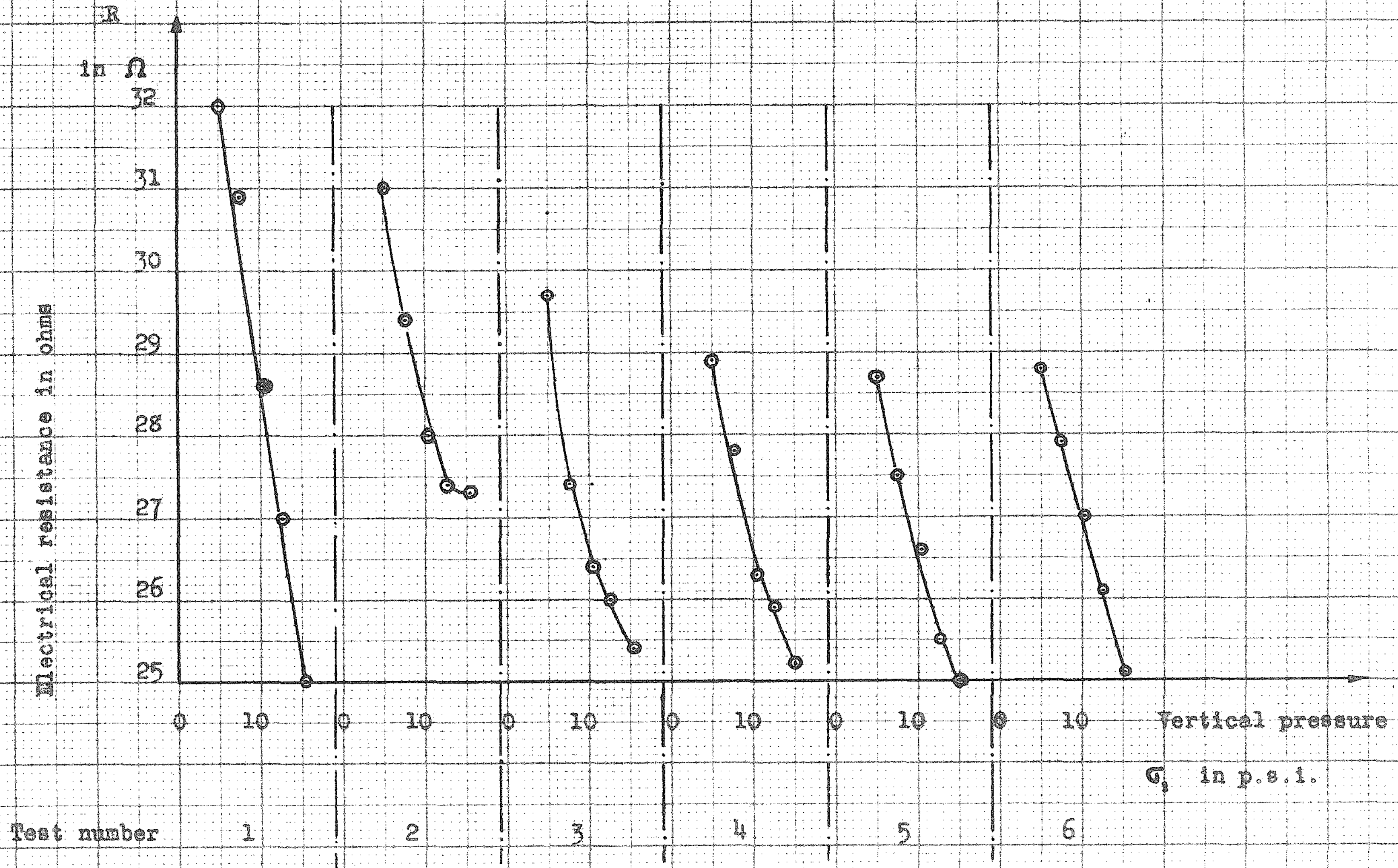


Figure 53 : Vertical compression tests on pressure cell number 4.

8. Conclusions and suggestions.

The main purpose of the present work was to design a granular pressure cell, determine its behavior under load, some of its physical properties and its suitability for use in soils.

A satisfactory molding set-up was designed in order to produce granular pressure cells. Such a set-up presents the advantages of simplicity, flexibility and adaptability to large scale production of pressure cells (Section 3.31 ; figure 12).

The pressure cells made up to date proved to be shock resistant. Because of the characteristics of the matrix material, they proved to be quite sensitive to temperature variations in the surrounding medium (Section 3.4). Pressure cell number 3 was used in laboratory tests in sand and proved to behave satisfactorily and give very reasonable results in measuring the vertical pressure under a footing on sand (Section 5.23).

Undoubtedly, granular pressure cells as built up to now can still be subjected to improvements. There are two domains of such improvements to be considered : those dealing with the matrix material and those dealing with the granular material.

1) Matrix material : Throughout our tests, we used rubber as matrix material. The low Young's modulus of the rubber proved not to be an influencing factor to any appreciable amount on the straining behavior of our pressure cells. On the other hand, its thermal characteristics made the pressure cells temperature sensitive. Therefore experiments with other resins might be envisaged. However the resins known to date have elastic properties such that the stress

-strain behavior of granular pressure cells, in which they might be used, may differ considerably from the stress-strain behavior of soils in general (Section 2.32). Perhaps, as has been mentioned in section 2.32, a reasonable solution would be to use some resins in external coatings for our pressure cells. At least till an ideal resin to be used as matrix material in granular pressure cells is found (Section 2.32).

2) Granular material : We have seen in sections 6.2 and 7.2 how the physical nature of the surfaces of contact of the carbon grains used in our experiments could influence the behavior under load of a granular pressure cell. The most important step in improving the granular pressure cells to be used in soils would be to arrive at a method of producing rounded or even spherical carbon grains. This could be done probably by grinding existing granules by means of a grinding set-up similar to those used in the ball bearing industry. If spherical grains were used in a granular pressure cell a stable arrangement of the grains in the mass would be reached sooner than with the grains we used in our experiments. Surface contact would be distributed more homogeneously throughout the mass. Thus, we would be certain to obtain a constant electrical resistance-pressure relationship perhaps from the very first loading test on, provided plastic flow of the matrix material were not important.

It might also be interesting in further research to determine what the influence of grain size is on the stress-strain diagram for a granular pressure cell and how it compares to stress-strain diagrams for various soils classified by grain size analyses.

3) Size of pressure cells : It might be of interest to examine what the lower limits to the size of granular pressure cells are (Diameter and thickness especially). It is our feeling that the thinner a pressure cell can be made, the less perturbation it will produce by its presence when incorporated in a soil mass and the more accurate the reading of vertical pressure existing at its location will be. Several pressure cells of varying dimensions ought to be put in identical locations under identical footings on identical masses of soil. These footings ought to be loaded in similar ways. The recordings of pressure for the various pressure cells of similar constitution but of different dimensions could then be compared and perhaps the influence of the dimensions of the pressure cells on the recordings determined.

As a general conclusion to this work, it may be said that if the pressure cells produced to date are not perfect in all respects, we arrived at positive results regarding their production, their constitution, their behavior under load in testing machines and finally in actual laboratory testing.

In view of these results and the important role granular pressure cells may play in the understanding of the behavior of soils under load, we hope, now that the basic problems encountered in the domain of granular pressure cells have been cleared, further developments along the lines of the preceding pages will be carried out in order to provide the field of Soil Mechanics with a very valuable means of soils investigation in a more desirable way than those we have employed to date.

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