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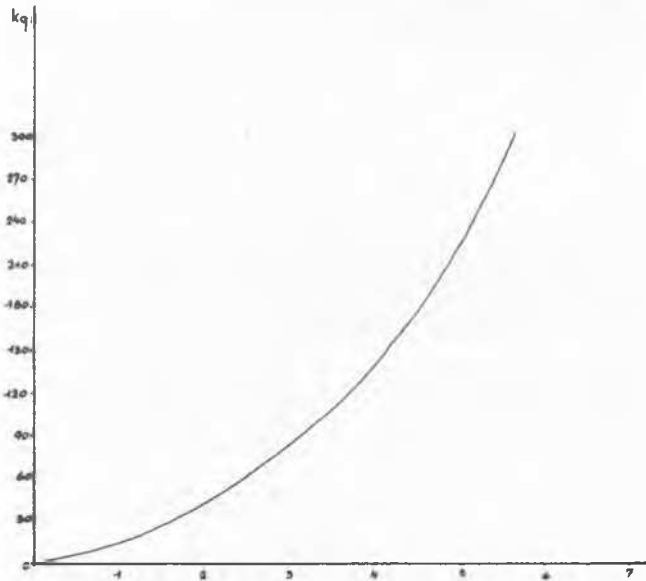


FIG.4

-o-o-o-o-o-o-o-

The practical value of these experiments exists therein, that the bearing capacity of a pile can easily be established thanks to the above described examinations. In ramming a pile into the ground, the same conditions result in the ground as we saw in our above described researches. It is easily comprehensible that under a rammed pile a condensation occurs underground. Although this condensation generally is not axial, conditions in deeper ground come more and more close to the axial. Adding to that the strong condensation at the surface of the pile nearly occurs in deeper ground in the same way as it does in the oedometer apparatus. With the aid of a pile the ground is cut through similar to the stamping of metal and by simultaneous condensation tested for shearing stress. The work which occurs in ramming the pile is the result of the condensation- and shearing-work. To state the real bearing-power (transverse strength) of the pile it is necessary to analyse this condensation- and shearing-work. It is also necessary to take into consideration the contents of moisture of the soil, that is to say not the casual but the most unfavourable one which may occur.

## II e 5

### SOIL FRICTION COEFFICIENT AS A FUNCTION OF WATER CONTENT

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#### 1. SCOPE OF INVESTIGATIONS

The earth structures which are of interest to road building specialists (subgrades, earth fills, dirt roads) are not ordinarily saturated with water, but their pores are more or less filled with air.

On the other hand, knowledge of the cohesion and of the angle of internal friction of these soils presents a great interest. However, these characteristics, as determined by Casagrande's method, i.e. with the pores initially saturated with water and left saturated during the shearing test, correspond to a condition found only exceptionally in road construction.

Therefore, it was logical to wonder how the cohesion and the angle of internal friction vary as a function of the water content. To solve this problem, it was necessary to determine the shearing strength of a number of mixtures with different water contents, for various pressures, and to find the water content of the rupture zone at the time of shearing. Then, the curve of shearing strength vs. water content for various pressures had to be drawn, to arrive at the relation between shearing strength and pressure for various water contents, in other words, the value of these coefficients had to be computed.

#### 2. APPARATUS

It was deemed advisable to perform shearing tests by translation as well as by torsion on confined samples. Other tests are under way with the triaxial apparatus (with lateral strain).

For the former tests, the apparatus shown on Fig. 1 (photograph) was used. Its detail is shown on Fig. 2.

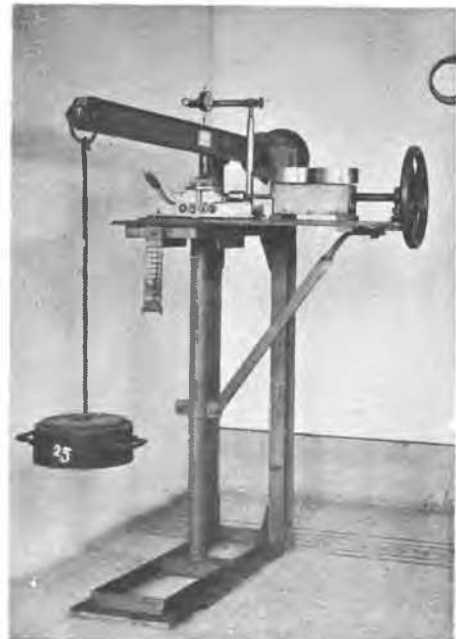


FIG.1

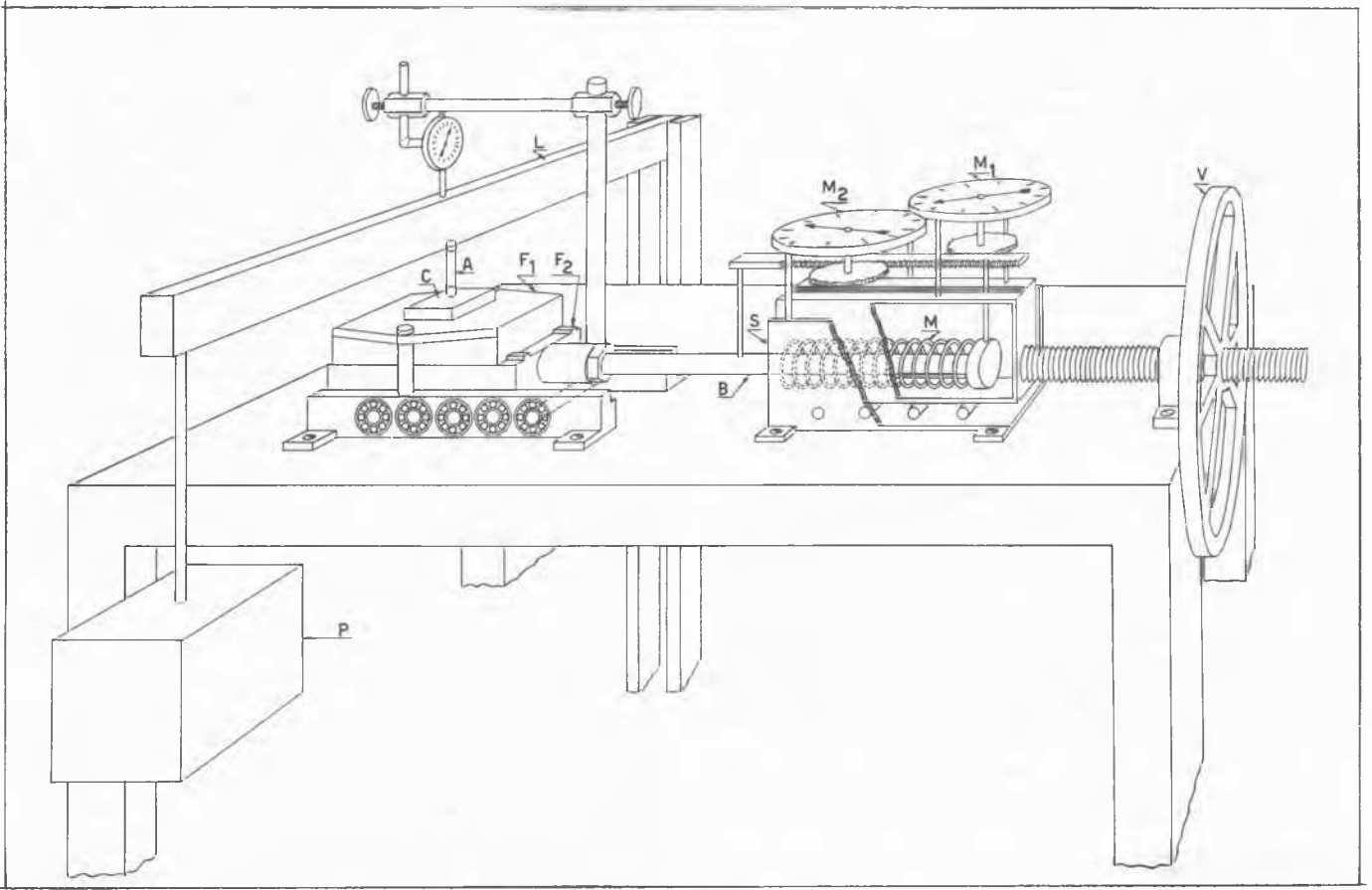


FIG.2

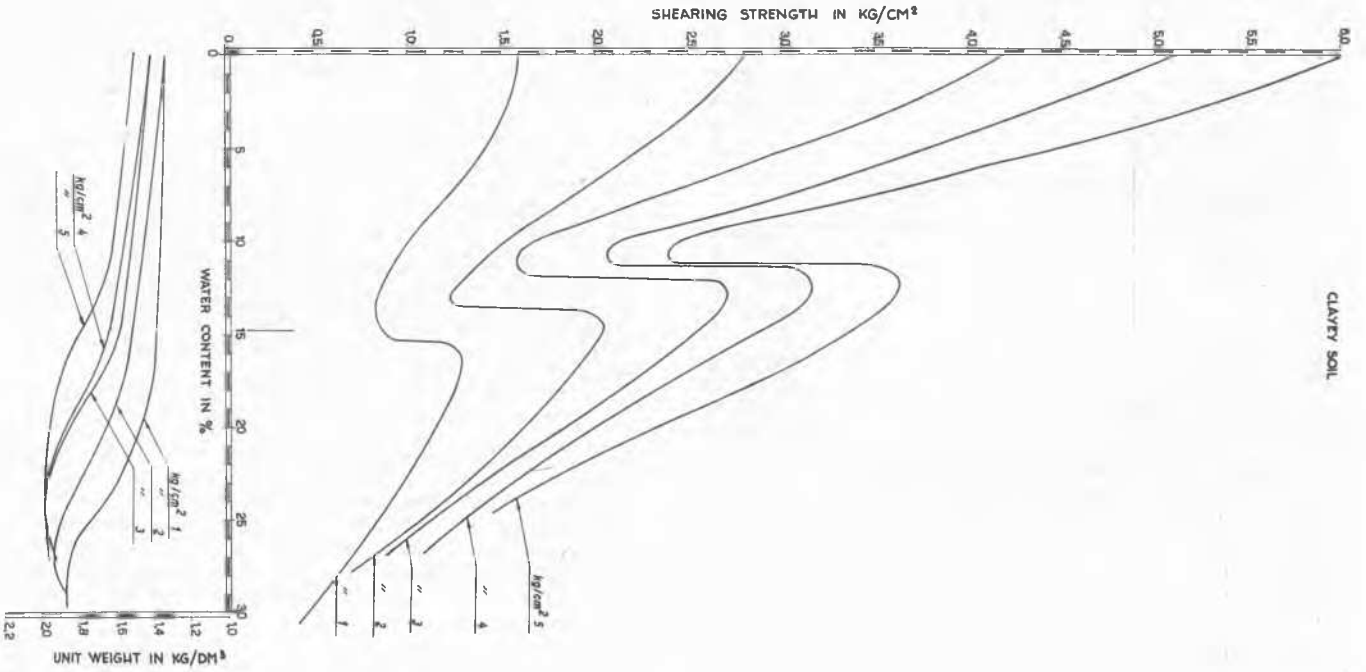


FIG.3

The soil and water mixture is placed in a frame made up of 2 parts F1 and F2. The lower frame F2 can be displaced with respect to the upper frame F1 by means of a pull exerted by the arm B which is operated by the wheel V. The displacement is transmitted through a box S which operates a compression dynamometer M, the strains of which - and therefore the stresses - are indicated at all times on M1 while the displacements of F2 are measured by M2.

The pressure is obtained by means of the weights P multiplied by the lever arm L which transfers the load through rod A. This rod is provided at each end with a sphere. One of these balls is set in a spherical cavity of the lever arm, and the other in a similar cavity of the lever arm, and the other in a similar cavity of plate C which, guided by F1, moves vertically to press upon the soil.

Porous stones were not used and the sample did not come into contact with water.

F2 is set on rollers with ball bearings at each end.

The consolidation is measured by an extensometer dial graduated in 1/100 mm divisions. Its tip rests on the lever arm at a point located on the vertical axis passing through the center of rod A.

After completion of the shearing test, a small soil sample is taken in the vicinity of the rupture surface, and its water content is determined by weighing before and after drying. On Fig. 1 one can see the side tubes through which water is introduced when performing the normal tests.

For the torsion shearing tests, the well known Hvorslev apparatus was used, omitting, however, the insertion of water during the test.

### 3. SOILS TESTED

The tests were performed on 3 soils having the following characteristics.

#### A) Clayey soil (designated by No. 03246)

Mechanical analysis (by sedimentation using Boyoucos' Hydrometer x)

Coarse sand (2 - 0.25 mm):.....	4.35 %
Fine sand (0.25 - 0.050 mm):.....	7.75 %
Silt (0.050 - 0.005 mm):.....	44.85 %
Clay (0.005 - 0.001 mm):.....	31.15 %
Colloids (< 0.001 mm):.....	9.9 %
Liquid limit:	63.05 %
Plastic limit:	31.49 %
Plasticity index:	31.56 %
Shrinkage limit:	14.75 %

#### B) Silty soil (designated by UL)

Mechanical analysis:

Coarse sand:	3.60 %
Fine sand:	12.40 %
Silt:	64.75 %
Clay:	14.25 %
Colloids:	5 %
Liquid limit:	33.37 %
Plastic limit:	21.70 %
Plasticity index:	11.67 %
Shrinkage limit:	18.48 %

#### C) Sandy soil (designated by ULSTL)

Mechanical analysis:

Coarse sand:	51.50 %
Fine sand:	6.10 %
Silt:	32.40 %
Clay:	6.50 %
Colloids:	3.50 %
Liquid limit:	31.15 %
Plastic limit:	20.35 %
Plasticity index:	10.80 %
Shrinkage limit:	18.84 %

### 4. TEST PROCEDURE

Due to the large number of tests required to reach a conclusion, the consolidation time had to be shortened. After a few preliminary tests which showed that consolidation of a short duration did not materially affect the strength of low water content mixtures, the duration of the consolidation time was set, as a general rule, at 24 hours for the shearing tests by translation, and at 72 hours for the Hvorslev tests. Nevertheless, the values obtained for complete consolidation, that is after a minimum of 7 days, were taken into account when the curves were plotted.

The results of shear tests are particularly unreliable for very low water contents (0 to a few %) and for water contents between the maximum and the minimum strengths which will be discussed further.

For the former, the curve was passed through the closest points, omitting those showing large deviations. It is natural that with a relatively dry soil, the compaction should be erratic (vehicle's vibration, probable arrangement of sand grains with respect to the walls of the box, etc.). These are causes of possible variations in consolidation and therefore in shearing strength.

The latter are accounted for by fact that a very small variation in water content, smaller than 1%, can lead, owing to the shape of the curve, to large differences in strength. Moreover, it is possible that the water content could be distributed unevenly over all the shearing sections. However, it was not convenient to determine the average water content of the whole sample since the moisture may differ between the inside and the surface.

The unit weight of the wet mixture was determined by weighing the samples taken, and by measuring their dimensions with a caliber (the sample for the translation shear test had a 50 cm<sup>2</sup> cross-section).

### 5. SHEAR TEST RESULTS

Results for soils 03246, UL and ULSTL are shown on Fig. 3, 4 and 5. The upper curves indicate the shearing strength as a function of water content, and the lower ones, the unit weight vs. water content; each curve corresponds to a consolidation pressure equal to that of the test xa).

It is noted that:

- the variations of unit weight with water content are small over a fairly long range for the clayey soil, over a shorter one for the silty soil and over a lesser distance yet for the sandy soil. Then the unit weight increases until a maximum is reached for the optimum water content which varies with the pressure and, in particular, decreases as the pressure increases. This last observation is logical enough; however, to the writer's knowledge, it has not been made by others.
- starting with a dry soil, the shearing strength decreases rapidly with an increas-

x) All soils were dispersed by addition of 20 cm<sup>3</sup> of sodium silicate. For the influence of dispersion time and of the variation of the quantity of deflocculating agent, see the writer's paper: L'analisi granulometrica dalle terre eseguita per sedimentazione da sospensione", in "L'Ingegnere", 1946, No.7, 8 and 9.

xa) Similar curves were drawn for consolidation pressures differing from those of the tests. The test pressures are shown next to the curves.

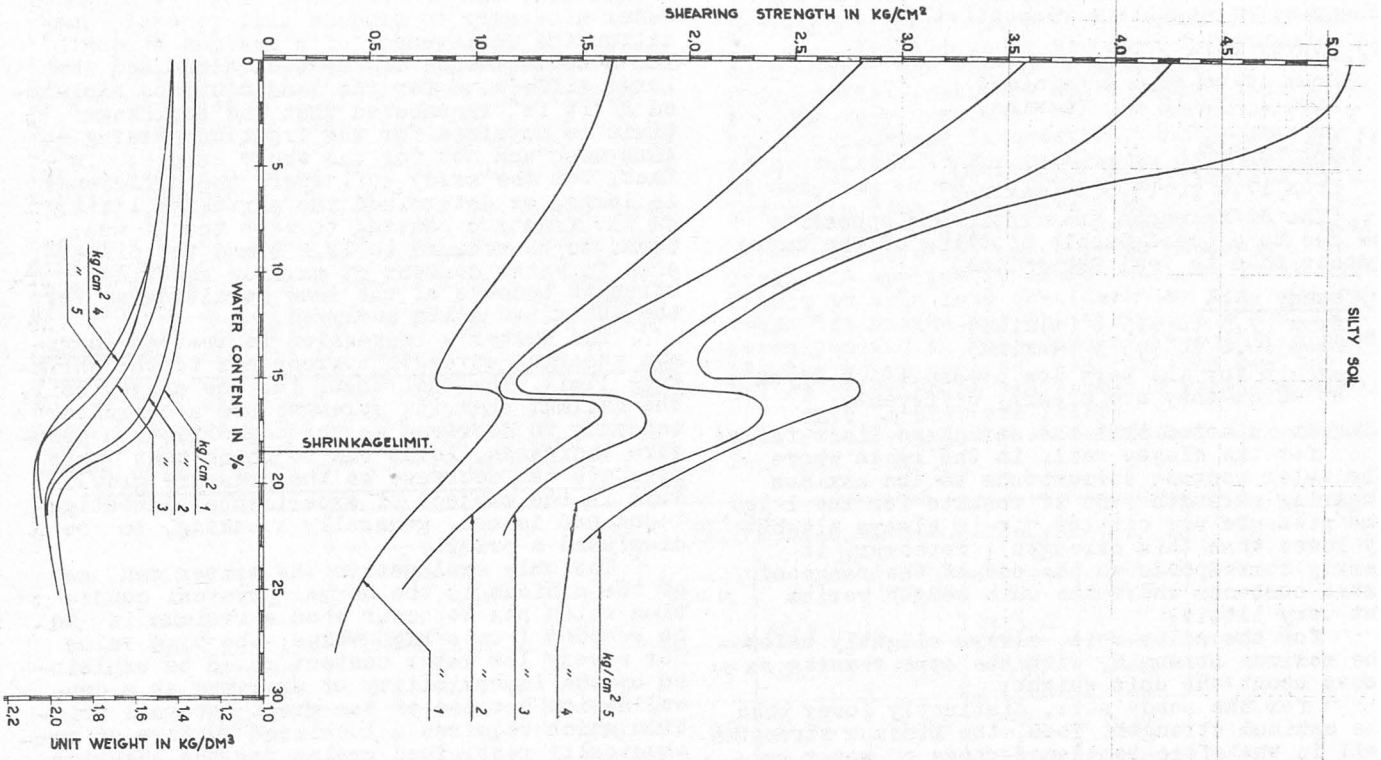


FIG.4

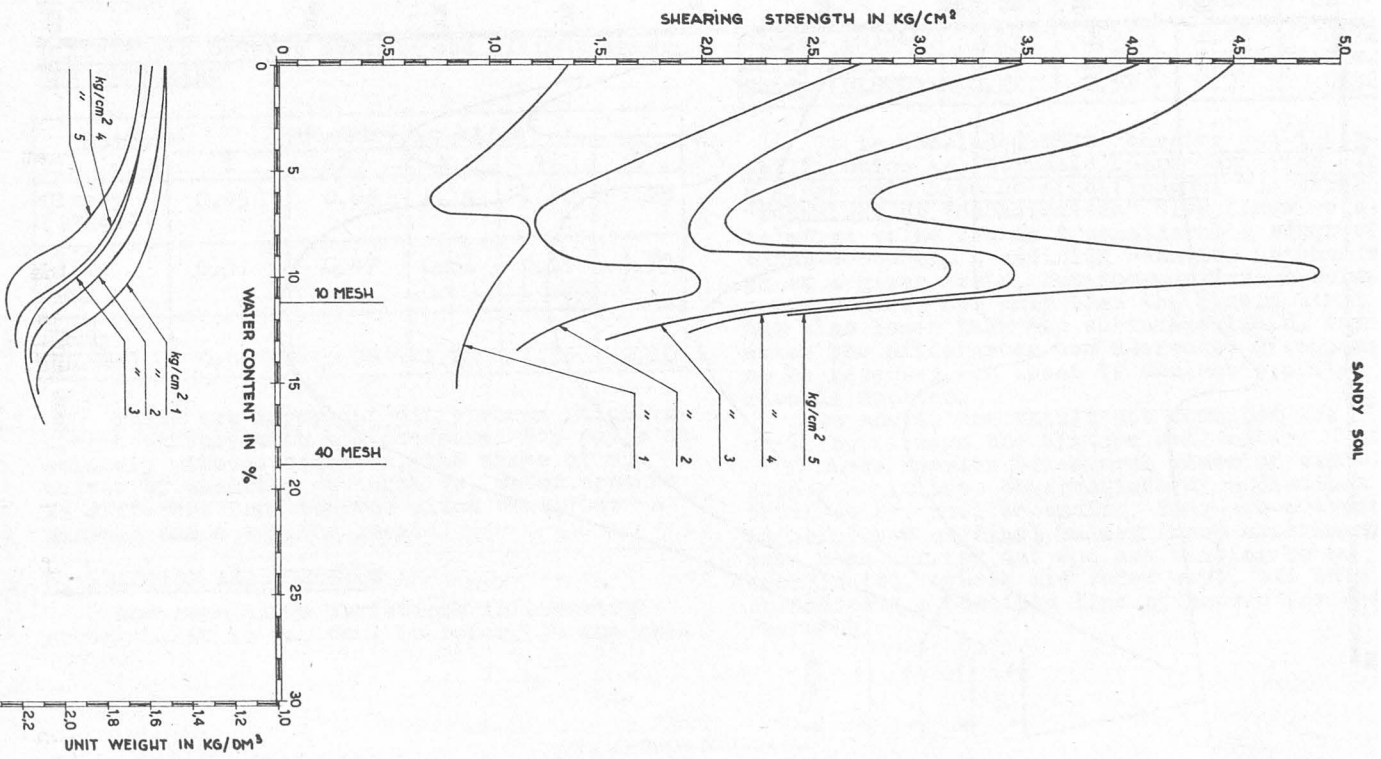


FIG.5

ing water content to reach a minimum, then increases very quickly to a maximum, and finally declines rapidly.

Water contents of minima and maxima of shearing strength are respectively:

a) clayey soil

from 14 to 10,6 % (minima)  
from 16 to 12 % (maxima)

b) silty soil

from 15,5 to 14,5 % (minima)  
from 17,0 to 15,5 % (maxima)

(The differences are erratic and appear to be due to a questionable plotting of the curve rather than to real variations)

c) sandy soil

from 7,5 to 6,5 % (minima)  
from 10,0 to 9,5 % (maxima)

except for the very low pressures (1 kg/cm<sup>2</sup>) at which they are clearly different.

It is noted that the shrinkage limit falls:

for the clayey soil, in the range where the water content corresponds to the maximum shearing strength (and if results for the 1 kg/cm<sup>2</sup> pressure are omitted, it is always slightly lower than this strength); moreover, it nearly corresponds to the end of the range of water contents where the unit weight varies but very little;

for the silty soil, always slightly below the maximum strength, with the same remarks as above about the unit weight;

for the sandy soil, distinctly lower than the maximum strength. Then, the minimum strengths fall in the afore-mentioned range of water contents where unit weights begin to decrease appreciably. Furthermore, the maximum strengths correspond to the portion with rapid variations of unit weight while remaining always below the optimum water content.

The relation between shrinkage limit and maxima of shearing strength is rational: it seems understandable that the complete removal of the air, and the presence of the minimum of water necessary to produce this removal, condition the achievement of a maximum strength. The noncoincidence of the two values and the large difference for the sand could be explained if it is remembered that the shrinkage limit is obtained for the fraction passing 40 ASTM mesh and not for the whole sample. In fact, for the sandy soil where the difference is large, we determined the shrinkage limit on the fraction passing 10 mesh and it was found to be reduced to 11.2 % and the difference in water content at maximum shearing strength becomes of the same magnitude as for the other two soils analyzed.

The writer's impression is that the maximum shearing strength corresponds to the shrinkage limit. The fact that, for the clayey soil, the maximum shearing strength has a definite tendency to decrease as the consolidation pressure increases, leads one to think that this strength can decrease as the pressure grows. This is the subject of experimental investigations and is not, generally speaking, to be dismissed a priori.

The only explanation the writer can see of the minimum is the normal physical condition which has to occur when a maximum is to be reached from a high value; the high value for a very low water content could be explained by the impossibility of arriving at a consolidation because of the great internal friction which requires a localized rupture of mechanically restrained grains for the shearing to occur.

The determination of shearing strength by torsion gave results only partly in agreement with those previously indicated. The results for the silty soil are given in fig. 6. One notices the presence of a maximum and of a

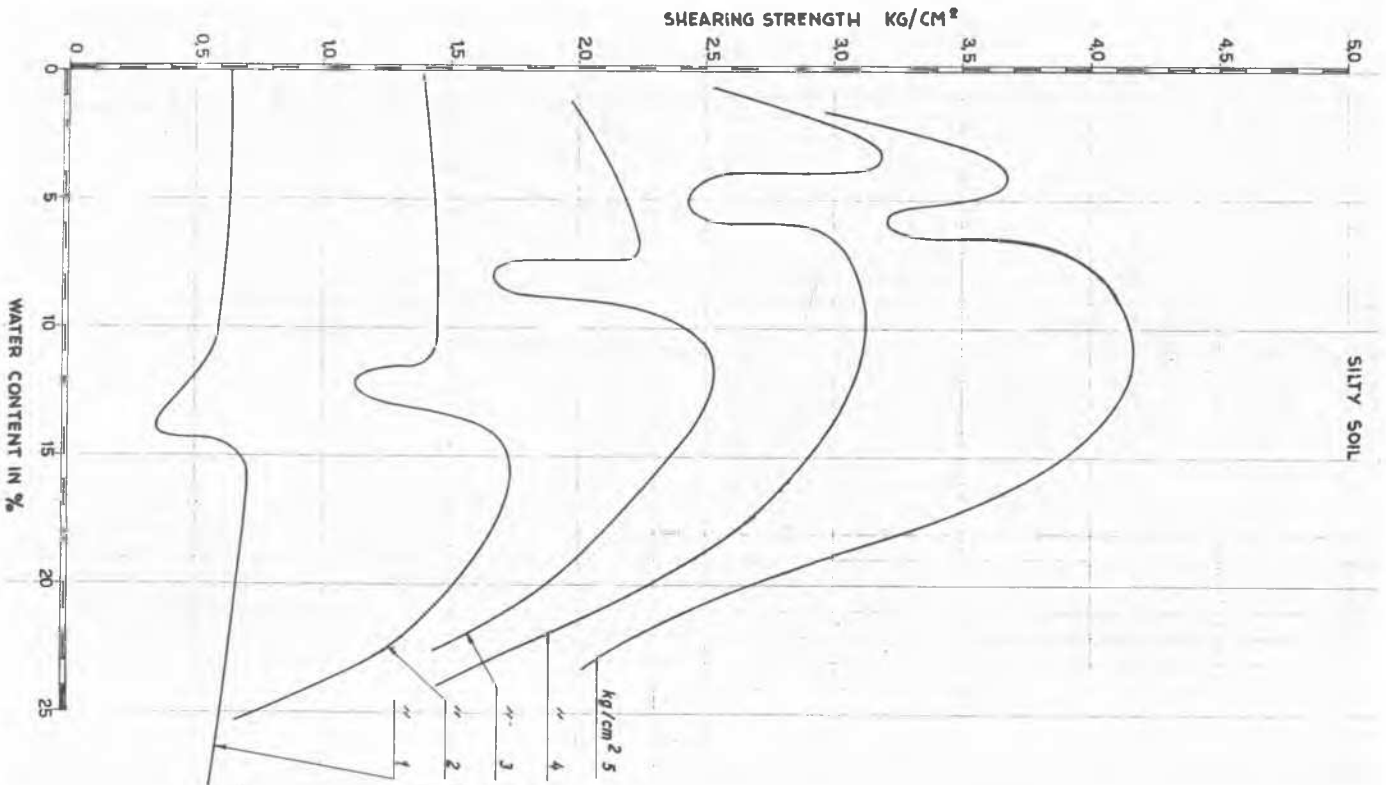


FIG.6

minimum as was found for the translation test, but the abscissa of the maximum is the same for the 1 and 2 kg/cm<sup>2</sup> pressures and much smaller for greater pressures. Furthermore, the transition from the maximum to the minimum is abrupt, the ordinate differences between the two are important and increase with the pressure, as was the case in shearing by translation, but the maximum is less sharp and a new maximum appears in the dry zone. The maximum shearing strengths obtained for soil UL with the torsion apparatus are higher.

In short, the significant and qualitative features of the phenomenon are confirmed, but differences appear in the numerical values and in the shape of the curves. These differences are subject of investigations now under way.

A last remark deals with the differences between the maximum and minimum values of shearing strength obtained by translation, for the various soils and for the different pressures. They are given in the following table and should be considered not as results of accurate measurements but as indications of or-

ulation of the friction and of the cohesion, to the same water contents.

For, if one follows the normal procedure of starting with the soil at a water content corresponding to the liquid limit, and becoming consolidated under the load in contact with water, the values of shearing strength found differ sometimes appreciably. This fact renders very uncertain the determination of the 2 parameters in question, and it appears to be related to the occurrence, in consolidated samples, of water content differences of a few % (in some cases more than 2 %).

If in the graphs, the strengths for equal water contents are used, it is necessary to limit the applicable range because it is difficult to take into consideration the zone between the maxima and the minima. The values corresponding to them were analyzed, disregarding the water content, and for each one the values of friction and cohesion were computed.

This is what was found:  
(c = cohesion;  $\tan \phi$  = coefficient of internal friction)

Soil	Water content							
	2.5 %		5 %		10 %		20 %	
	c kg/cm <sup>2</sup>	$\tan \phi$	c kg/cm <sup>2</sup>	$\tan \phi$	c kg/cm <sup>2</sup>	$\tan \phi$	c kg/cm <sup>2</sup>	$\tan \phi$
Clayey (O3246)	-	-	0.58	0.79	0.70	0.35	0.90	0.26
Silty (UL)	-	-	0.70	0.75	0.78	0.43	0.55	0.28
Sandy (ULSTL)	0.46	0.76	0.39	0.57	-	-	-	-

ders of magnitude. The uncertainty of the plotting of the curves because of the strong dispersion of the test results has already been mentioned

#### Differences between maximum and minimum shearing strengths

Soils	Pressure in kg/cm <sup>2</sup>				
	1	2	3	4	5
Clayey (O3246)	0.45	0.83	1.14	1.10	1.25
Silty (UL)	0.31	0.47	0.61	0.53	0.77
Sandy (ULSTL)	0.46	0.78	1.22	1.36	2.10

These are important differences which increase notably with the pressure. For soils absolutely without cohesion, the shape of the curves of shearing strength vs. water content is different from the one given here, but a minimum and a maximum remain.

#### 6. FRICTION AND COHESION

For such large variations in shearing strength, it is rational to refer, in the cal-

Soil	Shearing strength			
	Minimum		Maximum	
	c kg/cm <sup>2</sup>	$\tan \phi$	c kg/cm <sup>2</sup>	$\tan \phi$
Clayey (O3246)	0.25	0.49	1.03	0.72
Silty (UL)	0.49	0.3	0.75	0.40
Sandy (ULSTL)	0.22	0.52	0.2	0.92

It is concluded that cohesion and internal friction as intrinsic characteristics of a given soil have no significance. The terms "cohesive" or "cohesionless" have likewise a relative value within a considerable range of water contents. A definite behavior is observed at a given state, but there exists a water content lower not only than the liquid limit but also lower than the shrinkage limit, for which the differences can decrease, disappear or be reversed, at least if Coulomb's criterion is applied.

In short, one should not consider the soil, but always the mixture soil-water.

These results of several years of experience contribute observations of a distinct interest for soil mechanics. They are presented here, not as final values (many experiments have been carried out and are waiting to be coordinated, others are under way), but only to indicate a possible line of action for new research.