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Compaction and Shear Characteristics of Remoulded Negev Loess

La Compaction et les Caractéristiques de Cisaillement d'un Loess du Néguev remoulé

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Summary

In conjunction with the design and construction of embankments for various purposes in the arid loessial region of Israel, the Negev, a study of the compaction and shear behaviour of remoulded loess was made.

The compaction characteristics of the material were evaluated from tests by two types of compaction procedures, the impact and the kneading compaction procedures. The kneading compaction resulted in flatter curves, a behaviour which does not stand in agreement with some other studies of compaction characteristics by the kneading action. As a result of this study a quick method for measuring the compactive effort exerted on the soil by the kneading compaction is suggested.

The shear strength of the compacted loess was investigated by a triaxial shear apparatus, with pore pressure measurements. The strength characteristics of the material in partial and full saturation conditions are discussed, and a significant relationship between the compressive strength, the major effective principal stress and the void ratio at failure for both conditions is shown. The pre-stress effect on the shear behaviour was determined and found to increase the cohesion of the soil appreciably.

Sommaire

A l'occasion de la construction de remblais dans la région aride loessique d'Israël le Néguev, une étude a été effectuée sur le compactage et le cisaillement d'un loess remoulé.

Les caractéristiques de compactage du sol ont été évaluées à partir d'essais employant deux types de compactage: compactage au choc et pétrissage.

La présente étude a suggeré une méthode rapide pour mésurer l'effort appliqué au sol compacté par pétrissage.

La résistance au cisaillement du loess compacté a été étudiée avec l'appareil triaxial, en mesurant en même temps la pression interstitielle.

Les caractéristiques de la résistance du sol sont discutées pour la condition saturée aussi bien que pour saturation partielle. Il a été présenté pour ces deux conditions une relation significative entre la résistance à la compression, la contrainte principale effective et l'indice des vides au point de rupture.

L'effet de la précontrainte sur le cisaillement a été determiné et on a trouvé qu'elle a pour résultat une augmentation appréciable de la cohésion du sol.

Introduction

In the Negev, which constitutes the southern arid part of Israel, loessial soils predominate, varying in texture from sandy to clayey loess. In connection with the vital importance of developing the Negev for Israel's economy, embankments of the native loess are being built in this region. These embankments are constructed for various purposes, mainly for water storage reservoirs, as well as for highways and railroads.

In dealing with loess embankments, a different approach in design and construction is required for foundations than for the embankment. The natural undisturbed material exhibits extremely different behaviour than the remoulded compacted loess. The major problems arising from erecting a structure on dry loess foundations are those of high permeability, high settlement and hazardous decrease in strength when subjected to moisture increases. However, when the material is remoulded and compacted in an embankment it behaves as an impervious and stable material with a larger strength and a considerably lesser tendency to consolidate, both at partial and full saturation. Nevertheless, the problem of retaining the shear strength of compacted loess upon saturation still exists, since the material tends to lose a large portion of its strength in this moisture condition.

The following study deals with the compaction and shear strength characteristics of a typical remoulded Negev loess. Analysis and interpretation of test results presented herewith enables better understanding of the behaviour of compacted loess in engineering structures.

Description of Loess Studied

The physical characteristics of particular importance for identifying the loess studied are shown in Table 1.

Table 1

Gradation %			*Specific gravity*	*Atterberg limits %*			*Soil group**
Sand	*Silt*	*Clay*		*LL*	*PL*	*PI*	
10	65	25	2·74	20	15	5	ML–CL

* Based on the *Unified Soil Classification System* (1953).

Compaction Characteristics

Testing programme—The testing programme included investigation of the compaction behaviour of the loess by two types of laboratory procedures, namely the 'impact compaction' and the 'kneading compaction'. With each type a variety of compactive efforts were used.

Investigation by the impact compaction—The test procedure involved generally followed the standard compaction test (ASTM D-698-42T) using 1/30 cubic foot mould. Dry density *versus* moisture content curves obtained by using four different compactive efforts are shown in Fig. 1a. The line of optimums found is approximately parallel to the zero air voids curve and corresponds to the 80 per cent saturation curve. The relatively high densities obtained indicate that the Negev loess, although possessing very low natural densities, may be compacted into a dense mass under properly controlled field conditions.

Investigation by the kneading compaction—In recognition of the objections which have been recently raised to the impact compaction test procedures, it was considered desirable to investigate the compaction characteristics of the loess studied by the kneading compaction, in order to provide a better evaluation of field compaction. The kneading compaction apparatus and test procedure used were developed by S. D. WILSON (1950). The device, which is called 'Harvard Miniature Compaction Apparatus', has been found to reproduce more closely the kneading action of sheepsfoot rollers. It has also the advantage of saving time, effort and quantity of material required to obtain the moisture–density curve.

The compaction characteristics of the loess under the kneading action are illustrated in Fig. 1b. The four variations in procedure which were chosen resulted in consistently flatter moisture-density curves than those obtained by the impact compaction for the same density range. However, the line of optimums obtained and the relation of the curves to the zero air voids curve are almost identical to the impact compaction curves. This behaviour does not show the differences between compaction methods to the extent reported by McRae and Rutledge (1952) and Wilson (1950) for similar soils.

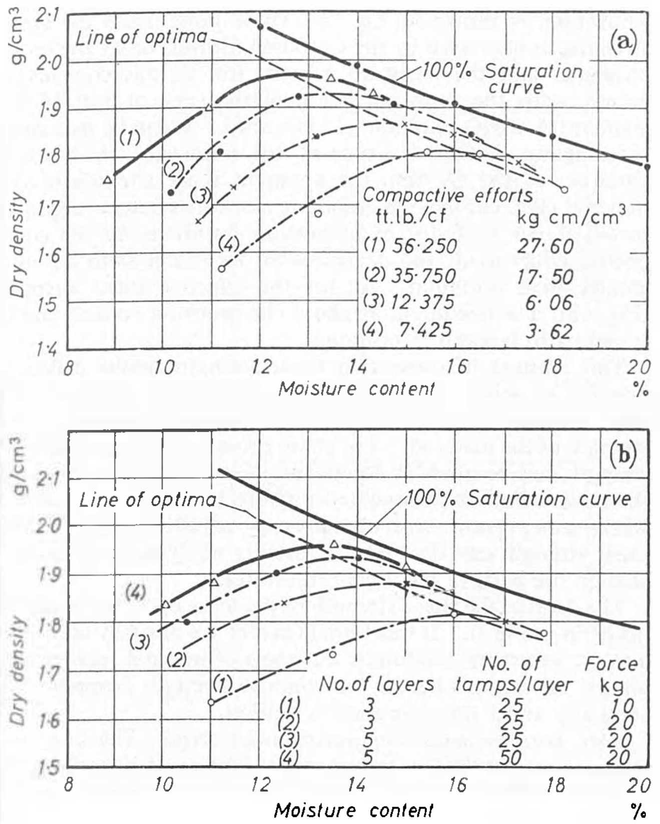


Fig. 1 (a) Compaction curves obtained by impact compaction procedure
Courbes de compactage obtenues par compactage au choc
(b) Compaction curves obtained by kneading compaction procedure
Courbes de compactage par pétrissage

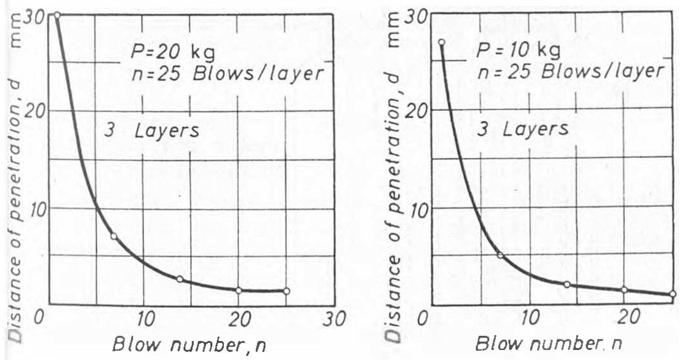


Fig. 2 Distance of penetration *versus* number of tamp curves
La pénétration en fonction du nombre de chocs

Comparison of compactive efforts—Since the optimum lines obtained by the two compaction methods were almost identical, it was desirable to establish the compactive effort put into the loess by the kneading compaction.

A modification of the Proctor needle was used to measure the distance of penetration, d, of the tamper rod. A sliding ring was attached to the bottom end of a rod of the same diameter as the tamper rod. When the desired force, P, was obtained by pressing the tamping rod into the soil the ring slid on the needle and stayed on the surface of the soil, thus allowing the measuring of d. The measurements resulted in curves of d *versus* number of tamp n, see Fig. 2. The integration of these curves expresses the cumulative distance of penetration for each layer. In order to determine the average force exerted on each layer, P *versus* d curves were drawn for each measured tamp number, n, see Fig. 3. The average force is equal to a coefficient μ times the maximum force P, where μ is the ratio of the integral of each curve to the total area enclosed by P and maximum d. It follows then that the compactive effort E

$$E = \frac{\text{No. of layers} \times \text{total distance} \times \text{average force}}{\text{Volume of mould}}$$

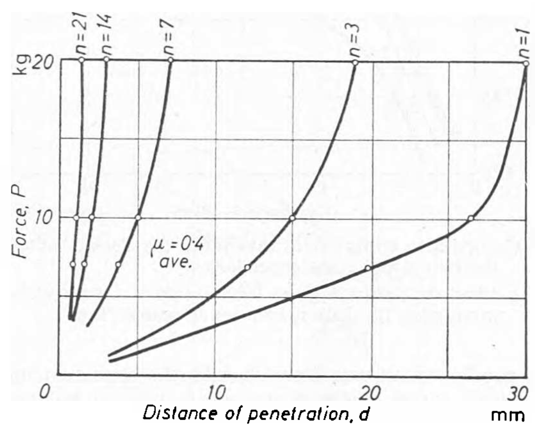


Fig. 3 Force *versus* distance of penetration curves
La force en fonction de la pénétration

The results are presented in Table 2.

Table 2

Kneading compaction procedure					*Compactive effort*		*Maximum densities*	
No. of tamps	*Force*	*No. of layers*	*Total distance*	*Average force*	*Kneading*	*Impact*	*Kneading*	*Impact*
	kg		cm	kg	kgcm/cm³	kgcm/cm³	g/cm³	g/cm³
25	10	3	13·0	4	2·5	3·6	1·82	1·81
25	20	3	16·5	8	6·4	6·1	1·88	1·87
25	20	5	9·6	8	6·9	17·5	1·94	1·94
50	20	5	12·6	8	9·1	27·6	1·96	1·98

A graphical comparison of the compactive efforts by the two compaction procedures *versus* maximum dry densities is given in Fig. 4. It should be noted that the points on the kneading compaction procedure curve fall in fairly close to a straight line although the maximum densities were obtained by using many variables.

Shear Strength Characteristics

Testing programme—The investigation of the shear behaviour of the remoulded loess included triaxial testing with pore pressure measurements of nine sets, of three identical specimens each, at various placement conditions corresponding to the lower three compaction curves (Fig. 1). The 15 and 2 per cent drier and 1·5 per cent wetter moisture contents were selected to serve as moisture conditions. The material was tested both at initial placement conditions and after saturation at test pressure in order to evaluate the shear strength of the loess during the various stages of the life of the embankment.

Equipment—The schematic diagram of the piping system of the triaxial shear apparatus and the pore pressure device used in this study are shown in Fig. 5. The pore pressure device operates according to the principle of preventing the pore water from draining from the specimen by maintaining a counter air pressure equal to the pore water pressure. It consisted of a

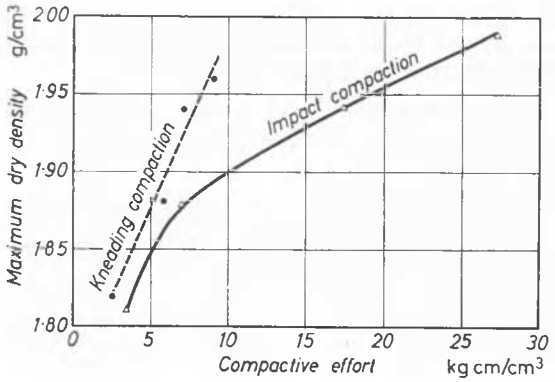


Fig. 4 Compactive effort *versus* maximum dry density obtained by the two compaction procedures
L'éffort de compactage en fonction de la densité sèche maximum pour les deux méthodes de compactage

porous needle which was inserted into the specimen near the failure zone and transmitted the pore pressure by means of water to a capillary tube.

Specimen preparation and test procedure—Large specimens, 7·2 cm in diameter and 15·2 cm high, were prepared at predetermined densities. The specimen was subjected to the final test lateral pressure by increments without allowing drainage. Volume changes and pore pressures were recorded. Saturation, when desired, was started under a pressure less than one-half of the lateral pressure. At the end of the 'pre-consolidation', or the saturation, time was allowed for stabilization of pore pressures, which usually took less than ½ hour. The axial load was then applied at a rate of 1·25 mm per min. holding the ateral pressure constant until failure occurred. The maximum effective principal stress ratio (σ_1'/σ_3') was used as the failure criterion.

Factors governing selection of shear strength—The influence of the compactive effort on both the effective and apparent shear strength of the loess, at placement moisture and after saturation, is shown in Fig. 6. These plots relate the shear strength, as expressed by the Coulomb formula or by the Mohr envelope, and the moisture content for various compactive efforts, with the moisture being plotted dry or wet of the standard AASHO optimum (15 per cent). It can be seen from these figures that for the type of test employed, which was a variation of the *Qc* test, the apparent shear strength of the material (Fig. 6a) is a maximum at moisture contents approximately 1 per cent dry of laboratory optimum for the compactive effort used, and decreases for moistures both less and greater than optimum. As for the effective shear strength (Fig. 6b), it is maximum at about the moisture content corresponding to laboratory optimum.

This manner of presenting shear strength results makes it possible to select placement moisture contents and required field densities for embankments in respect to total shear strength of the material. For small projects the apparent shear strength may be used for design and its selection is governed by the range of moisture feasible for control. For large projects, where pore pressure computations may be justified, the effective shear strength can be used for stability analyses, and selected also on the basis of placement moistures.

The drop in the shear strength of the loess upon saturation is noted from Fig. 6. It was found that for the partially saturated and the saturated conditions the angle of internal friction was almost the same, whereas the cohesive strength dropped substantially under the saturation condition.

Pore pressure behaviour versus *total stress*—The chamber pressure was applied in increments to obtain data pertinent to the behaviour of the pore pressure and volume changes occurring in the loess under the applied loads. Fig. 7 presents the relationship of the applied total stress (gauge reading) and the induced pore pressure measured. Each curve was constructed for a set of three identical specimens, using the average pore pressure readings obtained by the incremental loading. It is noted that the shape of the measured (Fig. 7a) curves is very similar to the shape of pore pressure *versus* total stress curves obtained by using the theoretical formula (Hilf, 1948), com-

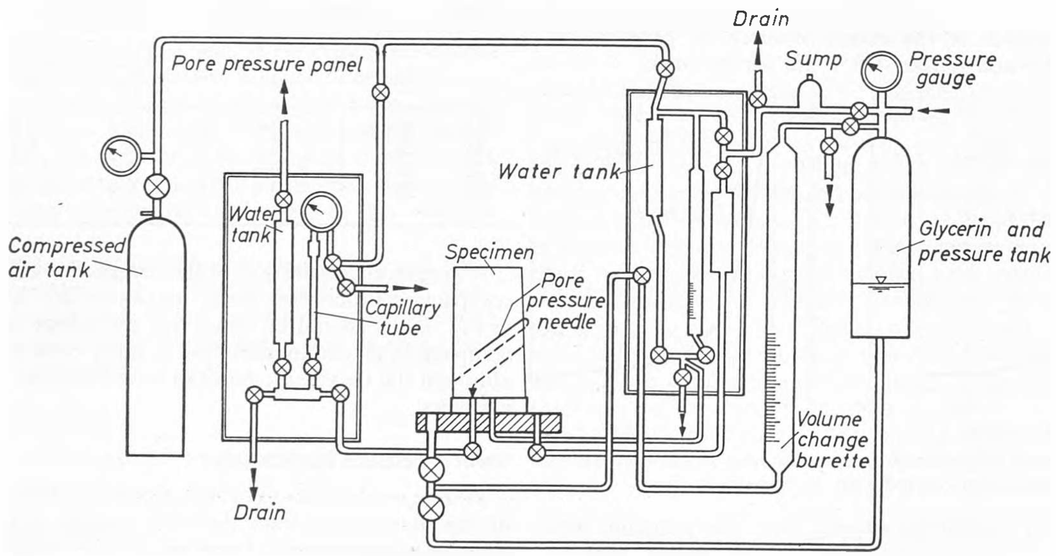
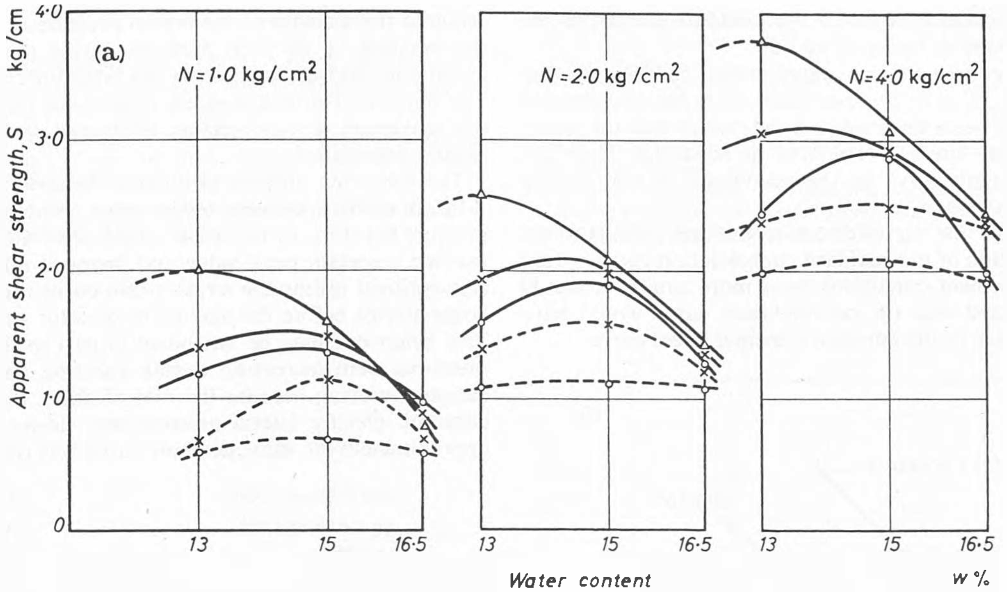


Fig. 5 Piping system of the triaxial shear machine and the pore pressure device
L'arrangement des tuyaux dans l'appareil triaxial et le mécanisme à mesurer la pression interstitielle



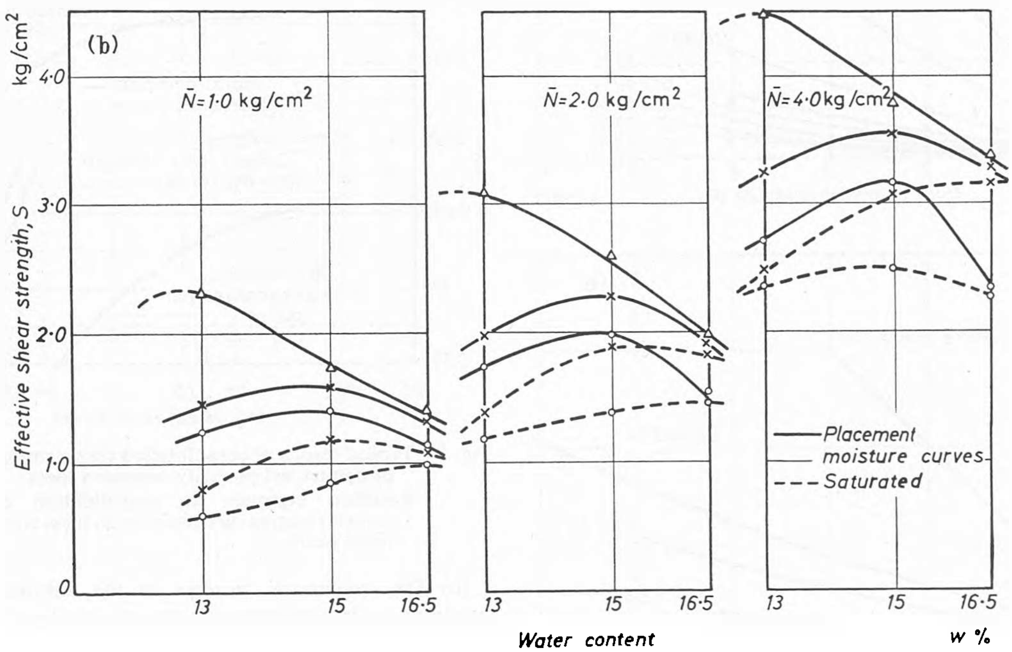


Fig. 6 (a) Moisture content *versus* apparent shear strength for placement moisture and saturation conditions
La teneur en eau en fonction de la résistance apparente au cisaillement pour les conditions de placement et pour saturation
(b) Moisture content *versus* effective shear strength for placement and saturation conditions
La teneur en eau en fonction de la résistance au cisaillement pour les conditions de placement et pour saturation

puted on the basis of volume change data taken from a standard consolidation test.

A comparison of curves for pore pressure *versus* total stress obtained during consolidation (Fig. 7b) and during triaxial shear tests (Fig. 7a) shows fairly close agreement except for differences caused by the placement conditions not being identical. Comparison on the basis of degree of saturation shows the closest correspondence.

Strength versus *consolidation characteristics*—It has been found on many homogeneous saturated clays (Rutledge, 1947), that a linear relationship exists between the logarithm of the compressive strength and the void ratio at failure of the given clay. There is little published literature showing the same behaviour for compacted partially saturated soils.

Fig. 8 presents typical results of tests in terms of e — log *p* curves for the following conditions:

(a) standard consolidation tests of compacted partially saturated loess in which the major principal stress is the applied vertical pressure after completion of consolidation under each increment of load; the consolidation pressure is considered intergranular and plotted on the basis of effective pressures;

(b) preliminary consolidation of triaxial specimens placed at comparable initial conditions, also plotted on the basis of effective stress, since the pore pressure was measured;

(c) quick triaxial test of the same specimens in which the major principal stress is determined on the basis of effective stress, as follows:

$$\sigma_1 = \sigma_3' + (\sigma_1 - \sigma_3)_f$$

Various relationships may be observed in these plots.

(1) The preliminary triaxial consolidation curves, for the lateral pressures used, show a similar behaviour to ordinary

e – log p curve. Their prolongation tends to parallel to the other curves plotted in the same figure.

(2) There are consistent linear relationships between the void ratio at failure of triaxial specimens and the compressive strength, and between the void ratio at failure and the major effective principal stress. The latter is separated from the compressive strength curve by the magnitude of the effective minor principal stress, σ_3'.

(3) The straight line curves discussed in 2 are parallel to the straight line portion of the standard consolidation curve. Had their initial placement conditions been more similar it would have been expected that the consolidation curve would have been located closer to the effective principal stress curve.

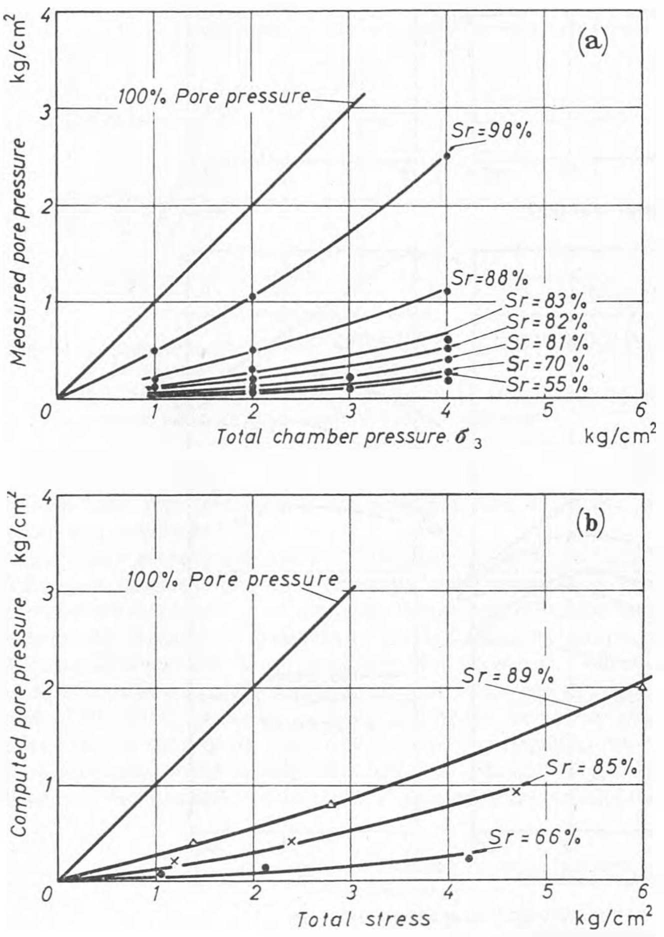


Fig. 7 (a) Pore pressure *versus* total triaxial chamber pressure
La pression interstitielle en fonction de la préssion totale dans la cellule triaxiale
(b) Pore pressure *versus* total stress, computed from consolidation test
La pression interstitielle en fonction de la contrainte calculée à base des essais de consolidation

The behaviour discussed above was found true also for compacted specimens tested after saturation.

Pre-stress effect on the shear strength of compacted loess—Since in a Qc test the effective lateral stress at failure is usually reduced by positive pore pressures developed since the start of the test, it follows that the specimen is being tested in a range of pre-stress. The resulting strength is high in proportion to its normal pressure and the resulting Mohr circle envelope is too high (Casagrande and Wilson, 1953). In the shear strength evaluation of the Negev loess the effect of this factor was studied by adjusting conditions in a special test series so that the *effective* lateral stress remained constant during the test. This required the increase of the lateral pressure at the same rate as the building up of pore pressure during the test, above the initial pore pressure induced by the preliminary 'consolidation'. The maximum principal stress ratio point thus coincides with the maximum deviator stress point and the failure point is readily determined.

The following differences in shear behaviour were noticed:

(a) In all the specimens tested under constant *effective* lateral pressure the slope of the stress–strain curve was relatively steep, reached a certain peak value and dropped off, whereas in the conventional testing the stress–strain curve was flatter showing larger strains before the maximum deviator stress was reached. This behaviour may be attributed in part to the fact that total pressures were increasing during shearing and some consolidation occurring because the rate of shear strain used for the constant *effective* lateral pressure was slower. In both cases approximately the same deviator stress was reached.

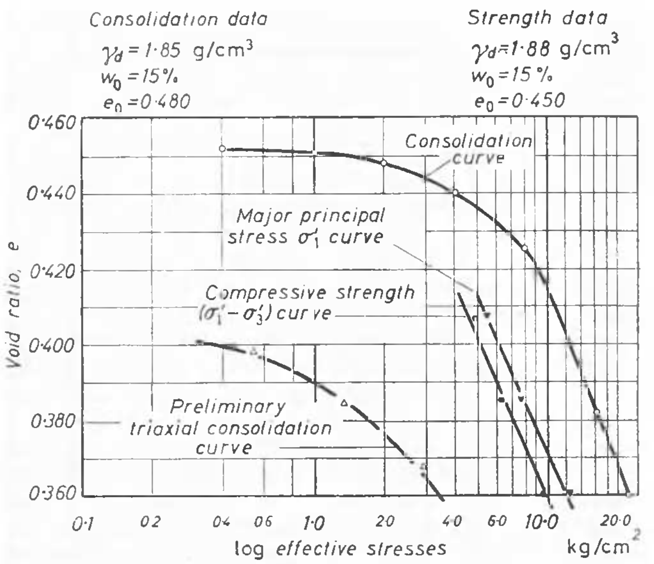


Fig. 8 Typical results of consolidation *versus* strength characteristics of compacted partially saturated loess
Résultats typiques de consolidation en fonction des caractéristiques de résistance du loess compacté et partiellement saturé

(b) The maximum decrease in the volume change of the specimen in the constant *effective* lateral pressure testing occurs at less strain.

(c) As a result of the early decrease in volume, there is a distinct difference in pore pressure–strain relationship. The pore pressure, although relatively low in magnitude, builds up to a definite maximum at lesser strains.

(d) In comparing the effective shear values obtained by triaxial testing under constant *applied* lateral pressure with the values accomplished under the constant *effective* lateral pressure for the same placement conditions, it is found that the slope of the Mohr envelope is practically the same, whereas the intercept called cohesion dropped quite appreciably under the latter testing conditions. It may be concluded, therefore, that for this type of soil the pre-stress effect tends to increase the cohesion value and results in unsafe values of shear strength.

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