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COMPRESSIBILITY CURVES AS A QUANTITATIVE MEASURE OF SOIL TILTH

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(With Plates VIII and IX and Four Text-Figures)

Introduction

There is at present no quantitative measure of soil tilth. If the farmer is asked to express an opinion on the tilth of a field, he generally presses the soil with his foot and notes the compressibility, the ease with which the lumps of soil disintegrate, the stickiness, and possibly the tendency to recoil elastically when his weight has been removed from the soil. These properties are judged at a compressive stress considerably less than that obtaining in normal cultivation processes. Thus a man weighing 150 lb. if he puts the whole of his weight on his one foot, assuming the area of contact to be 35 cm.^{2},[1] will exert a stress on the soil of less than 200 g./cm.^{2} whereas, in practice, he seldom shifts more than half his weight on to the foot with which he is testing, so that a stress of the order of only 100 g./cm.^{2} is probably applied. Ballu (1) calculates that an ordinary farm horse exerts, under its own weight, compressive stresses of the order of 2000–4000 g./cm.^{2} if the ground is hard enough for the whole weight to be taken by the shoes, that tractor tyres produce a stress of 1000–3000 g./cm.^{2}, and caterpillar wheels of the order of 250 g./cm.^{2}, though these stresses are only exerted for very short periods of time. The stresses produced on the mouldboard of the plough are very variable. Nichols (2) has worked over a stress range from about 350 to 2000 g./cm.^{2}, and points out that the lower part of this range, although more complex than the upper part, is, "from a practical point of view... quite important, as pressures are far above the average pressure exerted by the plow". Nichols worked on soil carefully prepared in "a fluffy finely divided state, without the formation of lumps or puddled particles".[2] Work by other authors has generally been confined to soil removed from its natural environment.

In designing an apparatus to measure quantitatively and imper-

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[1] Estimated by observing the "wear" on a pair of old rubber boots.

[2] For a complete account of the development of cultivation processes see Keen (3).

sonally what the farmer gauges by his skill and experience, it is advisable that the weight to be applied to the soil should be considerably larger in area than any soil lumps likely to be encountered. If stresses of the order of 1000 g./cm.^{2} are to be applied, this would involve the transportation and manipulation of many hundredweights of metal, and in practice a compromise must be reached, both stresses and areas being smaller than those theoretically most desirable.

THE FIELD APPARATUS

For this purpose the apparatus shown in Pl. VIII was constructed. The weight consists of four cylinders of iron *A*, diameter 15 in., laid one above the other, each weighing about ½ cwt., the whole weight being hung from a point just above its centre of gravity, so that unevennesses in the soil surface only produce very small restoring forces. This weight is hung from a spring balance *B*, which can be raised or lowered by a windlass *C* operating through a worm, the whole being supported by a tripod fastened by iron pins to a triangle of iron resting on the soil surface. At each corner of this triangle is brazed a circular disk, 8 in. in diameter, to prevent the base from sinking into the soil. This apparatus can be placed in position without any disturbance of the soil beneath its centre, over which the weight initially hangs. The weight is lowered until its surface just touches the topmost summits of the lumps of the soil surface. A duralumin rod *D* is pivoted to the suspension between the spring balance and the weight, and is suspended on a hardened steel knife-edge attached to an independent iron rod *E* bent at right angles at both ends so as to penetrate the soil, and likewise fitted with 8-in. disks. The further end of the duralumin rod is ground to a point, which is trained on to a vertical millimetre scale held by another independently "disked" iron stand *F*.

The weight (approximately 230 lb.) is lowered on to the soil by stages; the effective load on the soil is thus 230 lb. minus the spring-balance reading. The increments of load are applied at ¼-min. intervals, and, immediately before each increment, the reading, *L*, of the spring balance and σ, that on the deformation scale, are recorded. The increments of load are made as nearly equal as possible. Two operators are required for the tests. The principal operator calls the ¼-min. intervals from a stop watch, reads the σ-scale, and records all the data, while an assistant gives a turn to the windlass when instructed, and calls out the spring-balance readings.

Interpretation of the significance of the data obtained will be largely reserved for a later section, but it will be advantageous at this stage to examine a single experimental curve, such as that shown in Fig. 1. As the load is increased, the deformation increases at first fairly rapidly, and later more slowly. By the time the whole load is resting on the soil, a total compression *A* has been produced (circles on Fig. 1). This is partly elastic (recoverable) and partly plastic (non-recoverable) (*vide* Schofield &

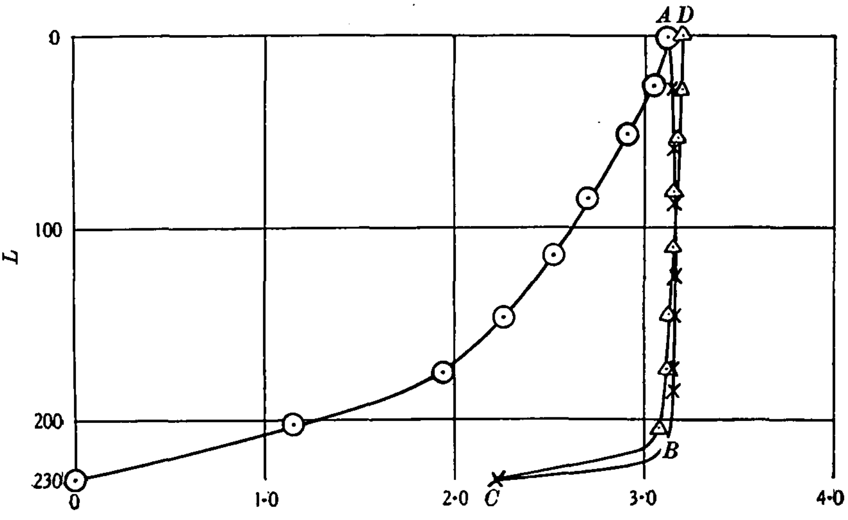

Fig. 1. Load-deformation curve for a field soil.

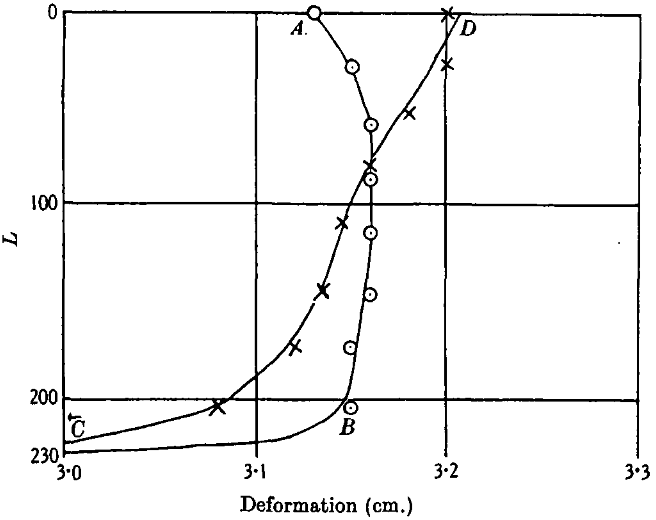

Fig. 1 *a*. Replotting of data given in Fig. 1 to show elasticity effects.

Blair (4); Nádai (5)). If the load is removed from the soil by stages at the same rate as it was applied (crosses in Fig. 1), the soil surface actually rises very slightly. That this effect is real has been checked by doing tests on hard incompressible surfaces. These tests show that any elastic "give" in the apparatus itself must be exceedingly small. The loading curve, *OA*, is complex in shape, and its form will be considered later. It is by no means invariably of the form shown in the figure, but in all soils investigated the permanent plastic deformation is large compared with the recoverable elastic deformation shown in the unloading arm of the curve *AC*. The tailing off of the curve from *B* to *C* is apparent rather than real, and depends simply on the unevenness of the soil surface and consequent difficulty in assessing a correct zero. In Fig. 1*a*, the scale has been increased so as to magnify the hysteresis loop. The amount of flow which takes place during the unloading and subsequent second loading of the soil (triangles in Fig. 1, crosses in 1*a*) is largely determined by the moisture content, whereas the steepness and shape of the first loading curve depend more on the looseness of tilth of the soil. These latter factors may be subdivided into (*a*) flow and rupture properties of individual soil lumps or crumbs, and (*b*) capacity of these lumps to alter their packing under load. Although the elastic properties of the soil in tilth are interesting, the recoverable deformations are so small (of the order of a millimetre in the experiments shown) that their practical interest is not so immediate as that of the plastic deformations. Nichols (2) has pointed out the difficulties involved in fitting any equation to the part of the compression curve when stresses are relatively low, and before attempting any complete treatment to actual experimental results it seemed advisable to evolve some method of plotting the data which should give a straight line as the ideal case, divergencies from linearity then being treated as a measure of abnormality of one sort or another.

THE "IDEAL" RELATIONSHIP BETWEEN STRESS AND DEFORMATION IN COMPRESSION OF A CRUMB-STRUCTURED MATERIAL

This problem has been touched on by Terzaghi (6) and treated much more completely by Pokrowski & Bulytschew (7). These latter authors point out that in compression, the soil particles become increasingly disturbed out of their original structural formations and suggest an equation in which the stress gradient $dS/d\sigma$ is proportional to the stress at any point on the loading curve, multiplied by the difference between this stress and the limiting stress at which the disturbance of structure is complete. For small stresses, this equation reduces to $dS/d\sigma \propto S$, in which limiting case straight lines should be obtained by plotting log S against σ. This treatment has been applied to some of the data from an experiment described in a later section, and the curves, which show a fair linearity, except in cases where the soil is very incompressible (1), are given in Fig. 2. The numbers refer to the treatments described later.

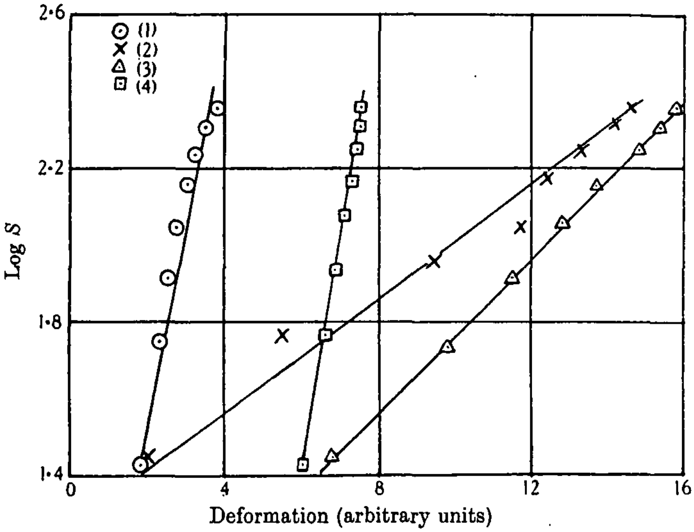

Fig. 2. Data from field soil compression tests plotted according to simplified Pokrowski equation.

It would seem more logical, however, to relate the stress gradient to deformation rather than to stress. The change in structure on compressing the soil may be regarded as a type of work-hardening and certainly depends more on the amount of compression than on the stress, and the total load exerted on the weight by the soil will rise proportionally to the area of contact as the area increases with the sinking of the weight. At first, the area of contact will increase rapidly, whereas repacking and shear effects will be slight. As compression proceeds a region will be reached in which the two processes will have about an equal importance, and here the stress might be supposed to vary ideally with the square of the deformation—varying directly with the deformation for each of the two factors, increased surface of contact and packing and shearing.[1]. This is equivalent to assuming that $dS/d\sigma \propto \sigma$ for a crumb-structured material.

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[1] The shearing properties of the soil are being very thoroughly investigated by Pigulevski and his colleagues (8).

For an elastic solid[1] $dS/d\sigma$ = constant, or S increases proportionally to σ, and an approximation to this condition occurs for very hard dry soils, or at the top of the stress-strain curve, when compacting is considerable. (Experimental evidence for this will be given in a later section.) For a soil the loading curve is thus sigmoid in shape, for, in the lowest stress region, the stress varies as a power of the deformation greater than two, and at the high stress range it varies more nearly as σ. The intermediate region is that in which the repacking, shear, and rupture of the soil crumbs are principally taking place, and this region, where S varies approximately as σ^2, is in general the more marked the better the tilth of the soil.

It is clear that a very great many data will have to be examined before it can be established as a certainty that this treatment, which is partly empirical, gives the nearest approximation to agreement with the experimental figures. As Nichols rightly says, no true soil will conform exactly to any simple equation. A simple flow equation presupposes that the fine structure of the material is of such an order that statistical laws can be applied. The laws of flow for a true fluid depend on the great number and small size of the shearing units. In the flow of pastes complications arise due to size and shape of the shearing units (9) and, in natural soil, where these become of the same order of magnitude as the apparatus, individual particles may show their effects on the curves (*vide infra*). Before any information can be obtained as to the individual eccentricities of particular samples, the curves must be reduced to a form where the gross effects of compression have been as far as possible reduced to order. For this reason it seemed good to design an apparatus in which curves could be obtained, giving the deformations plotted against the square root of the stress, the deformation being given at a constant rate. Partly because such an apparatus would be difficult to construct on a field scale, and partly because it was desired to investigate conditions of tilth, some of which could not be conveniently obtained on the farm, the apparatus was made for use in the laboratory. The technique is subject to the criticism applicable to all laboratory tests that the soil is liable to some changes in condition in the process of transferring to the laboratory, however carefully the operation is done. The problems are therefore being studied at the same time by both methods: first, the field soil loading apparatus already described in which loads are applied as far as possible in equal increments after equal intervals of time, the rate of deformation being increased and elastic as well as plastic deformations being considered;

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[1] For a true fluid, the stress would be proportional to the *rate* of deformation and independent of the absolute deformation, so that $dS/d\sigma$ would be zero.

and secondly, the laboratory method, in which deformations are given at a carefully controlled constant rate, the square root of the stress built up being automatically plotted against deformation. In this latter method, elastic hysteresis phenomena are not studied.

THE LABORATORY APPARATUS[1]

The apparatus is shown in Pl. IX. *A* is an enamelled metal tray (20 × 15 cm.) containing a layer of soil 2·5 cm. deep. (The effect of depth of layer has been investigated and the depth here quoted has been found satisfactory.) This tray is hung by four chains and counterpoised by a bucket *B*, containing water. A constant speed motor *C*, operating through a suitable worm gearing, causes the tray to rise at a constant and very slow rate of about 2·35 mm./min. A lead weight *D* (= 1670 g.) is hung from the beam *E* of a counterpoised balance resting on knife edges *F*. The weight is a cylinder of diameter 6·0 cm. It is hung from a point just above its centre of gravity, the suspension passing upward through a wide enough hole to allow for a maximum of about 10° of tilt if the surface of the soil is uneven. The force tending to right the weight is extremely small. Except at the lower end, the suspension is of steel wire to avoid errors due to elasticity in the suspending thread.

As the rising soil surface tends to take up the load of the weight, the beam of the balance rises, thereby opening a valve *G* which allows mercury, stored in the container *H* and kept at a constant head by adjustment of the tap *J*, to run into the bucket *K* which is hung on the same arm of the balance as *D*. This compensates for the change in load produced by the gradual lifting of *D*. The bucket *K* has two of its sides parallel and two sloping, so that the height of the mercury collected is proportional to the square root of its mass, and hence to the square root of the load pressing on to the soil. The bottom of *K* is made flat, and before each test, 2·5 c.c. of mercury are run in from the burette *L* to cover this flat bottom. On this layer of mercury floats a small steel weight attached by means of a cotton passing over pulleys to a pen *M*, the other end of whose holder is again attached to a smaller counterpoise weight *N*. As the mercury lifts the weight in *K*, *N* pulls the pen *M* across the paper which is attached to a glass sheet by two rubber bands. The glass sheet is driven in a direction at right angles to the movement

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[1] This apparatus was described, with special reference to its application to soil amelioration problems, at the Conference of the Sixth Commission of the International Society of Soil Science, held at Zürich, August 1937. The author is indebted to Mr D. Morland for much help in the construction of the apparatus.

of M by a second gearing from the motor C, and as D does not move appreciably M traces a curve whose ordinate is proportional to the square root of the load on the soil, and whose abscissa is proportional to the amount of deformation. The two axes are drawn, one by raising and lowering N before the test, and the other by the second pen O attached rigidly to the frame, which is aligned so that the two lines so produced are at right angles. The total load represented in the diagrams amounts to 59 g./cm.^{2}, though, since only a part of the surface of the weight is in contact with the soil during much of the run, much higher local stresses must be produced. Work with a larger weight has also been carried out, but it is difficult to prevent weights giving high loads per cm.^{2} from becoming unduly top-heavy. Once the motor has been started, it will be observed that the whole process, including the drawing of the curves, is automatic, except only for the adjustment of the tap J, which is a matter of secondary importance.

Data obtained from laboratory apparatus

A number of curves obtained with this apparatus are given in Fig. 3: (1) is that for a dry sand, (2) for a wet sand in such a condition that the material coheres into a loose kind of structure, and (3) the same sand wetted to such an extent that the structure again disappeared. It is clear that in the two cases in which there is no crumb structure, the curve is concave to the deformation axis throughout, and calculation shows that the stress varies approximately as the deformation, whereas where there is a structure the curve is predominantly convex, the strain varying with some power of the stress higher than 2. Intermediately, approximately straight-line curves may be obtained. A "step-ladder" formation just visible at the lower end of curve 2 indicates the disintegration of individual crumbs. In Fig. 4*a* values of S calculated from $\sqrt{S}$ readings read off the dry-sand curve are plotted against σ. It is clear that under the circumstances of this test the "elastic" law is approximately obeyed.[1] For comparison, curve 4 (Fig. 3) shows a test made on an ordinary rubber sponge. This is more or less elastic, as is shown from the S/σ curve (Fig. 4*b*). The modulus is not quite constant for low stresses due to peculiar surface properties.

A curve for a wet, structureless soil is shown in Fig. 3, 5, and may be

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[1] The laboratory apparatus is not designed to study elastic phenomena, and it is known that there is some "give" in the apparatus itself. For this reason reliable elasticity moduli could not be calculated from these curves.

compared with that for a soil in fairly good tilth (Fig. 3, 6). The significance of the differences in form will be discussed later.

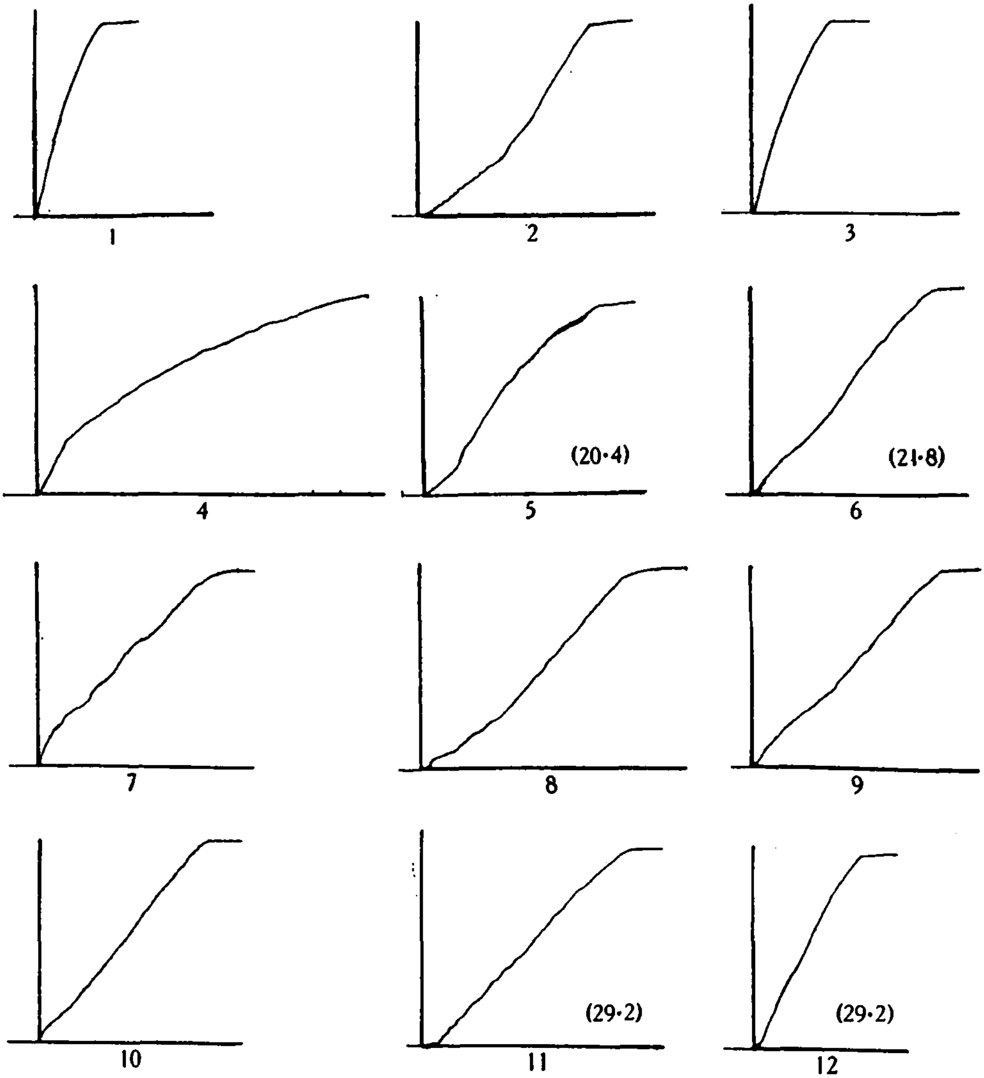

Fig. 3. Compressibility curves from self-recording laboratory apparatus. Ordinate is square root of the load, and abscissa is deformation. Moisture contents are given as numbers in brackets.

It is natural to enquire how far the size of lumps of soil affects the shape of the curve. In order to study this point, the soil used for Fig. 3, 6 was sieved into a series of fractions, curves for the individual fractions being taken. These are shown in Fig. 3, 7 particles > $\frac{1}{2}$ in., 8, $\frac{1}{2}$–$\frac{1}{4}$ in., 9, $\frac{1}{4}$–$\frac{1}{10}$ in., and 10, < $\frac{1}{10}$ in. The differences are surprisingly slight.

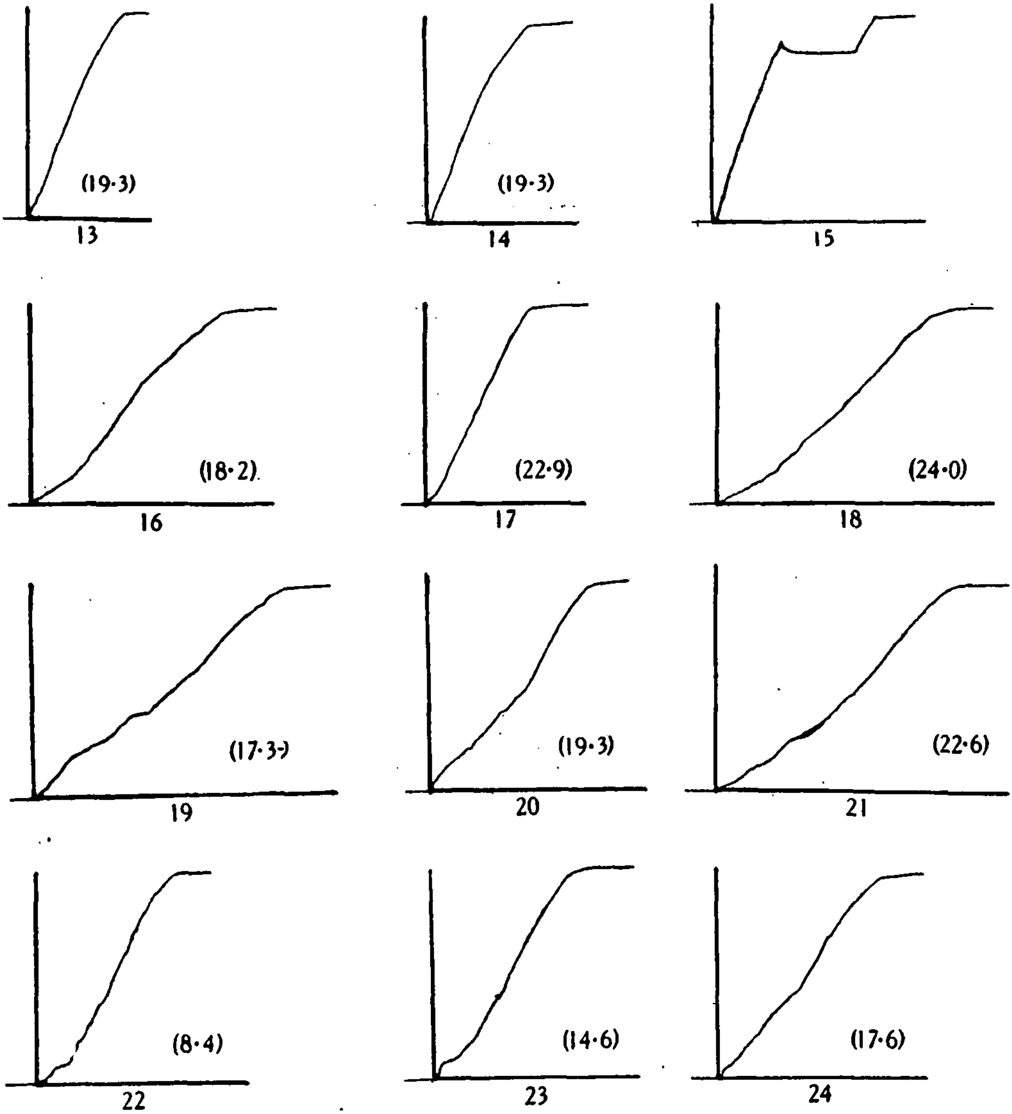

Fig. 3. (Continued).

Except in the case of the smallest fraction, there is a general tendency for the total compressibility to increase with decreasing size of particle, and the biggest particles not only tend to give a somewhat erratic curve, but the stress clearly varies as some power of the deformation less than 2. This leads to the question as to how far the compression observed is due to shear or crushing of individual lumps, and how far to packing effects. Although local stresses must sometimes be much higher than the mean value of 59 g./cm.^{2}, not very many crumbs are actually crushed, except in the case of soils having artificially prepared very soft crumbs. We are mostly concerned with the distribution of deformation between shear and repacking. Mr G. H. Cashen suggested that experiments might be done on the compression of three crumbs chosen as far as possible to be of the same size (about 2 cm. diameter), and that comparison should be made with the curves for the complete soil from which the crumbs were selected. The results of these experiments are shown in Fig. 3, 11–15. Fig. 3, 11, is a curve for a surface soil obtained from a wood where the soil condition was kept good by natural processes. The soil lumps were small, and three of the largest of them had to be selected to obtain curve (12). Curve 13 is for a complete soil from the same neighbourhood, but taken from a nearby waterlogged cultivated field which had not been ploughed for some time. The soils had both been somewhat dried out in the laboratory before testing, and the latter soil had set into large hard lumps, three of the smallest of which had to be selected for the test 14. It is clear that the compressibility of the larger lumps from the good soil and that of

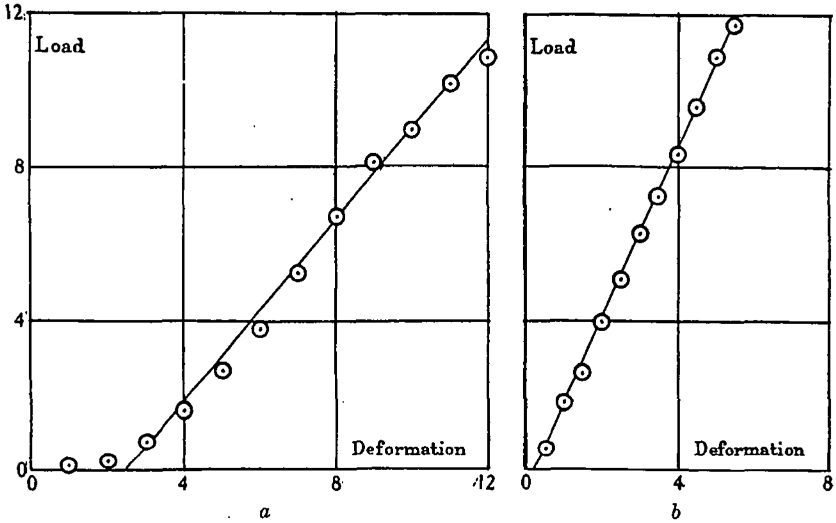

Fig. 4. Compressibility curves plotting deformation against load directly. *a*. Dry sand (calculated from Fig. 3, 1). *b*. Rubber sponge (from Fig. 3, 4).

the smaller lumps from the bad soil were very similar, though in the former case this compressibility represented only a small fraction of the total compressibility of the soil, whereas in the latter, repacking can have played hardly any part in the building up of the composite curve. In none of these three-crumb tests did the crumbs crush completely. In order to show the effect of such a collapse on the curve, a soil made into very brittle crumbs in the laboratory was selected, and three crumbs tested. The curve is numbered 15. The apparent fall in stress immediately after the breaking of one of the crumbs (the only complete break during the test) is due to an upsetting of the surface tension conditions round the weight floating on the mercury surface.

EFFECT OF CHANGES OF TILTH ON THE CURVES

If the line of argument followed in this paper has been cogent, it should be possible to follow changes in tilth produced by natural processes by means of the laboratory technique described. Certain effects, such as slight surface "capping", may be incapable of preservation during the process of transferring the soil from the field to the testing tray. If these effects are to be studied the field technique must be used; but many of the changes produced by climatic or cultural processes on the soil-crumb structure will readily survive transportation. The effect of a spell of frosty weather is shown in Fig. 3, 16–21. Curves 16–18 are for the samples taken from three locations before the frost: (1) the top of a furrow on ploughed land in fair tilth, though over-wet, (2) a nearby depression where the lack of drainage had produced a really bad condition, (3) an allotment whose soil had been well cared for and suffered only from excessive moisture. (Moisture figures are given in brackets on the figure, and refer to the percentage moisture on a wet basis determined by drying the soil at 110° C. for 24 hours.)

Following a few days of frost, further samples were taken from the same three places. A considerable improvement in tilth is shown in the case of the soil from the top of the furrow, a greater retentive improvement for the waterlogged sample, but little change is found for the soil already in good condition (curves 19, 20 and 21 respectively). A test designed to demonstrate the effect of freezing in the laboratory on a really good garden soil gave a completely negative result, the only changes produced in the curve being explainable by the slight drying out.

Although space considerations preclude the publication of all the curves, the above soils were all tested not only soon after being brought to the laboratory, but frequently for a period of some days during the drying-out process. After each test the soil was dug carefully to restore the uncompressed condition of the surface and, although the continuous pressing and digging is bound in the long run to affect the course of the drying process, experiments repeated immediately after such treatment agree very closely with the initial tests. It is therefore believed that the results of following such a drying out in this way are of interest. Three curves obtained after considerable drying are shown in Fig. 3, 22–24, which were obtained from the corresponding dried samples used for 19–21. During the same period of time (about 4 days) the better field soil had dried most, the waterlogged soil, on account of its bad structure, had dried least, and the good garden soil intermediately, due, no doubt, to the very large amount of organic matter which it contained. The decrease in total compressibility is clearly marked in all three cases. The shape of the curves has not been greatly affected, except for a slightly increased step-ladder structure in the case of Nos. 22 and 23 where somewhat hard intractable lumps are formed when the soil is dried.

Sticky points and lower plastic limits were determined (Atterberg) on many of these soils, and it was observed that the latter, which is known to correspond reasonably closely to that moisture most suitable for cultivation, also in many cases corresponds approximately to the point at which a well-marked step-ladder formation is observed in the compression curves. Such conclusions must, however, be treated with caution, since the moisture is often not very evenly distributed throughout the soil mass, and a small number of large lumps having a moisture content differing from the mean for the whole sample may affect the fine structure of the curve quite appreciably.

CONCLUSIONS ON INTERPRETATION OF CURVES FOR EVALUATION OF TILTH, AND APPLICATION TO FIELD EXPERIMENTS

The process of compression is not yet sufficiently understood for a full and complete interpretation of the curves in terms of tilth to be possible. In the field experiments, it is not known how the stresses in the soil vary with depth, though preliminary experiments (conducted in co-operation with Mr Cashen) in which closed rubber tubes attached to manometers were buried at different depths in the soil, indicate that although there is probably a time-lag, the compression effect goes down at least as far as the soil has been cultivated. It is intended to extend these experiments and to publish the results in a later paper. In the laboratory technique the situation is somewhat different. Here, the effect of depth of soil layer is surprisingly slight, and the deformations are partially restricted by the proximity of the sides of the tray.

Even before the laboratory apparatus had been designed, interesting semi-quantitative results had been obtained in the field by testing areas within a small space which had been (1) dug once and rolled, (2) dug once not rolled, (3) dug twice and not rolled, and (4) dug twice and rolled. Tests were done at different spots on these plots chosen in a random manner, and the total compressibilities (arbitrary units), taken from the best straight line on a $\sqrt{S}/\sigma$ basis to eliminate surface unevenness effects, were as follows:

	Days after cultivation treatment				
Treatment	0	6	11	21	38
1	2·7	4·4	5·5	6·5	4·7
2	14·2 (?)	11·1 (?)	21·5	18·1	15·6
3	11·6	9·0	15·9	16·1	16·3
4	1·9	2·5	3·7	3·7	6·7

(Figures marked (?) were not as accurate as could be desired.)

The first of these experiments (0 days) provides the data used to test the validity of the (log S)/σ equation, and shown in Fig. 2. Only the first loading figures are given. The complete data for No. 3 are those used to show, in Figs. 1 and 1*a*, the general shape of the curves. A number of other factors as well as total compressibility were considered, and certain regular effects noted, but it seems wiser to confine our attention at this stage to the broadest outlines, since the experiments have not yet been repeated, and it is hoped to undertake further field experiments, which, from the experience already gained, should be of a higher order of accuracy.

It is clear from the above table that, for all treatments, the soils have become more and not less compressible during the first few weeks of digging, an effect probably due to an increase in moist content from 16 to 26 per cent. When the soil has been rolled, this "lifting" effect is very marked. Digging the soil twice in succession has not made it any more but rather less compressible, whether the soil is afterwards rolled or not.

These preliminary results indicate the kind of information which such experiments should give. The following interpretation of the different characteristics of the curves will serve as a working hypothesis, and may be followed with reference to Fig. 3:

(1) Soils in good tilth show a long deformation range in which the $\sqrt{S}/\sigma$ curves are approximately linear. Upward curvature (increasing

$d(\sqrt{S})/d\sigma$) is preferable to the reverse, and a big total compressibility is generally a sign of good condition.

(2) A long initial range where $d(\sqrt{S})/d\sigma$ is low, especially if the curve is irregular, indicates an uneven surface of rather intractable lumps.

(3) Very wet or very dry soils give curves concave to the deformation axis for most or all of their lengths. The latter usually give big step-ladder effects. A very light powdery soil may give a fairly high compressibility, but the curve is invariably concave.

(4) Some step-ladder effect is advantageous—a perfectly smooth curve indicates a poor structure.

(5) All data are best interpreted in the light of the moisture content of the soil when tested in relation to its Atterberg constants.

These conclusions are derived largely from experience in the laboratory tests. It remains to be seen how far the differences in the method of stress application will cause them to require modification before application to the field data.

SUMMARY

1. A preliminary account is given of experiments on the compressibility of soils in field condition, and two methods for obtaining compressibility curves, one for the field and one for the laboratory are described. The laboratory apparatus automatically draws a curve relating deformation to the square root of the load built up.

2. The theoretical relationship between load and deformation is discussed, the conclusions reached being at this stage semi-quantitative.

3. Laboratory compression curves are shown to indicate the characteristics of soils in various states of tilth, and the effects of drainage condition, frost action, etc. are discussed.

4. Such factors as size of soil crumb, depth of layer tested, and moisture content of soil samples for laboratory studies are considered.

5. Preliminary field experiments are described in which the effect of simple cultivation processes on soil compressibility were measured.

6. Tentative conclusions about the significance of the differences in the shape of the laboratory curves are given, though these may need to be modified, and will certainly be extended following further experimentation.

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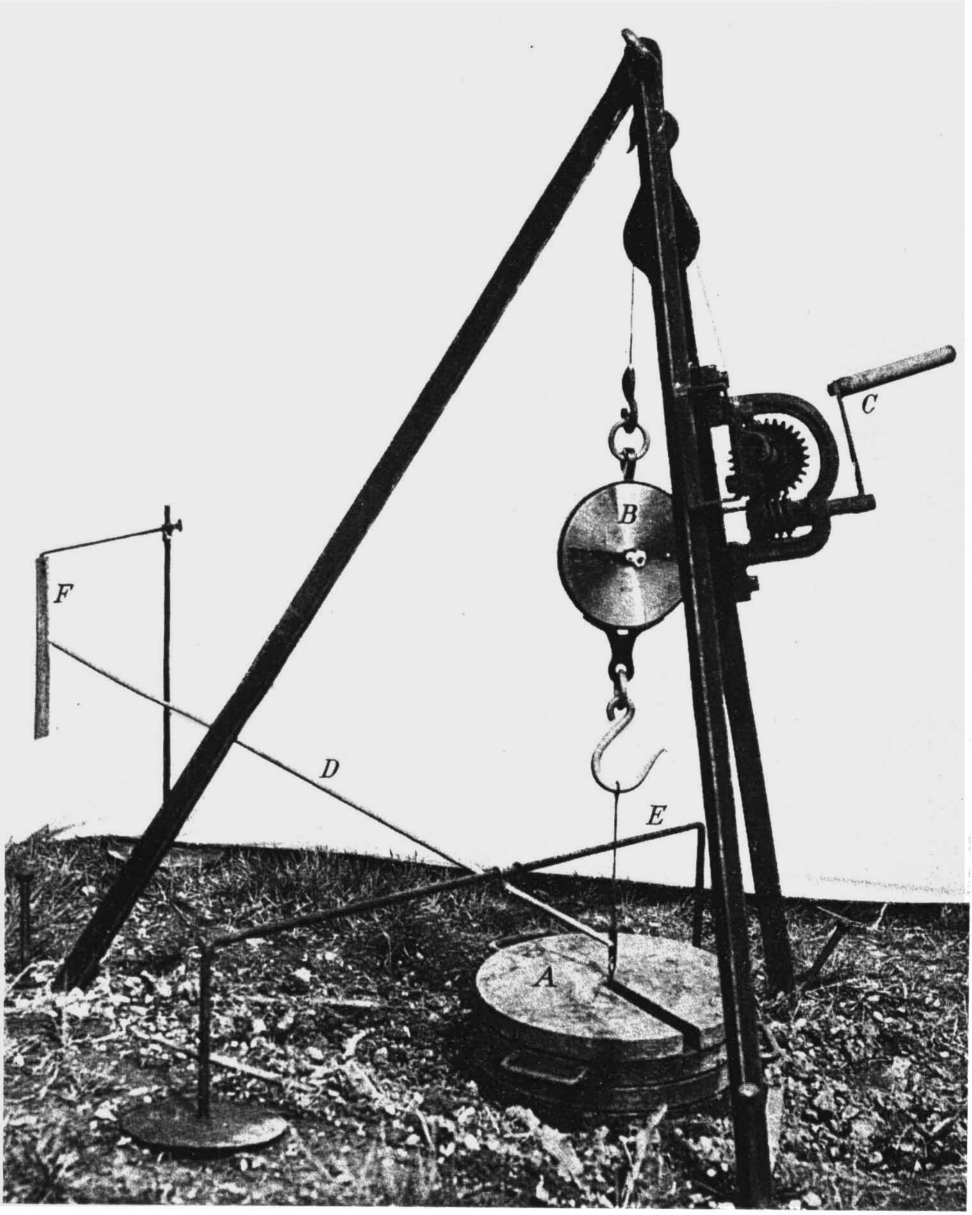
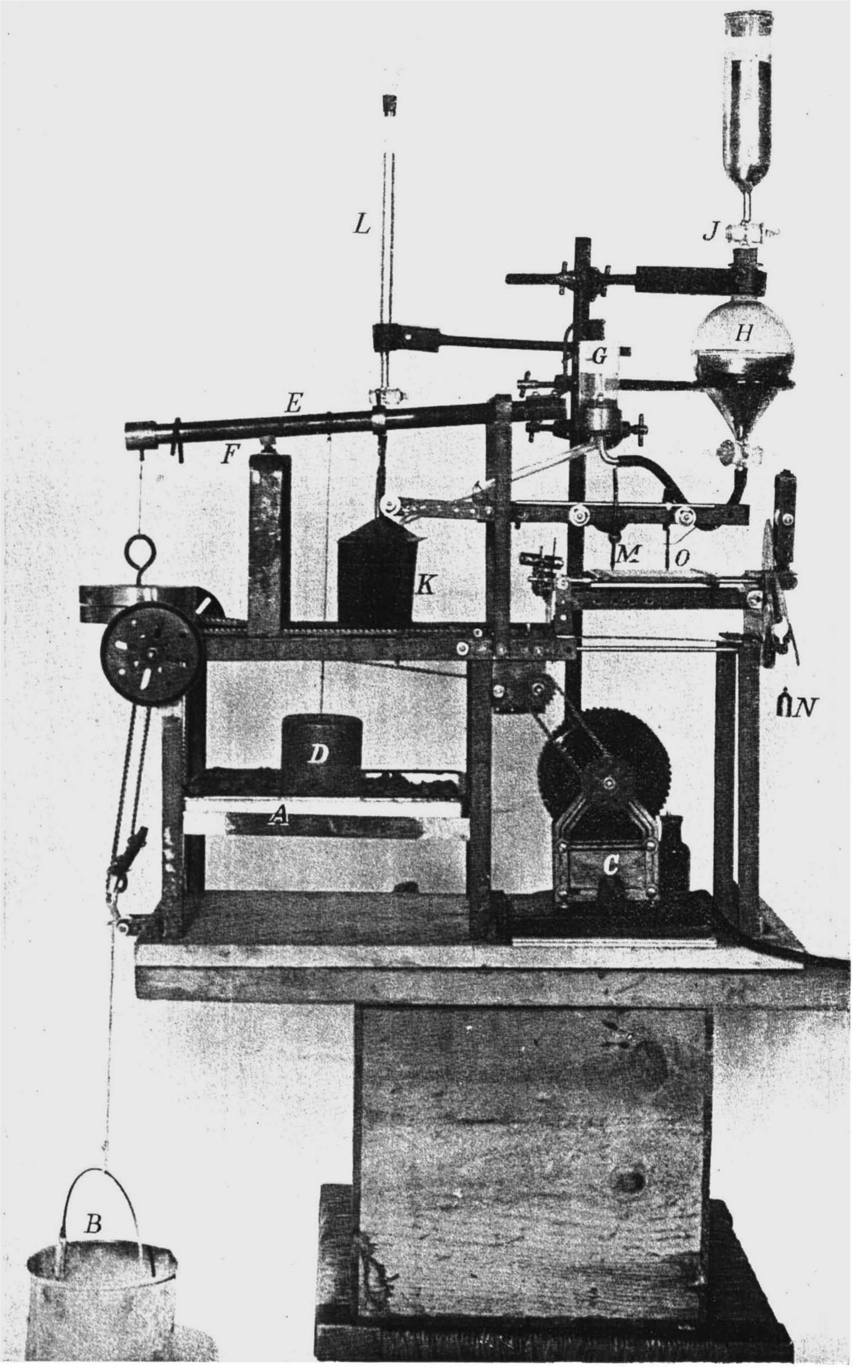


Field apparatus.



Laboratory apparatus.