A simplified method for analysing the mechanics of clod: clod interactions in topsoils with a wide range of clay content

S. Czarnes\textsuperscript{a,b}, A.R. Dexter\textsuperscript{a,1}, F. Bartoli\textsuperscript{b,*}

\textsuperscript{a}Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK
\textsuperscript{b}Centre de Pédocologie Biologique UPR 6831 du CNRS associé à l’Université Henri Poincaré, Nancy I, BP 5, 54501, Vandoeuvre-les-Nancy, France

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Abstract
Classical concepts of mechanics applied to continuous materials cannot be used directly for associations of soil clods occurring in ploughed and harrowed topsoils. Therefore, we are proposing a new simplified method for analysing the clod : clod mechanics, for a wide range of clay content. We pressed together axially two adherent remoulded soil balls and recorded a dimensionless strain flattening ratio $R_f$ as a function of the compression stress. The strain–stress relationships of the studied adherent soil balls were (i) modeled using either a common statistical curve-fitting approach or the concept of effective stress, and (ii) compared with the strain–stress relationships obtained for the cylindrical counterparts. The axial stress applied on the two adherent soil balls was heterogeneous, ranging from a minimal value to a maximal one, which were both related to the $R_f$ counterpart value. The relationship between the maximal compression stress and the flattening strain was fitted with a power-law equation, with either a negative or a positive power-law coefficient for either the convex stress–strain curve of the plastic clayey soils or the concave stress–strain curve of the friable granular soils, respectively. The internal soil strength, determined as the intercept of the straight stress-suction line for the flattening test ($R_f$ value of 0.47), was of 2.2 and 1.2 kPa (minimal stress), and of 10 and 5.4 kPa (maximal stress) for the silty and the sandy remoulded topsoils, respectively. The minimal axial compressive stress for two adherent remoulded topsoil balls at a flattening strain ratio of 0.47 increased non-linearly as a function of the axial compressive stress for its cylinder counterpart at a volumetric axial ratio of 0.2. The drier and the more cohesive is the soil, the more difficult is the geometrical macroscopic change from a spherical shape to a flattened surface area. The results show the merit of applying the flattening test for two adherent soil balls both for determining mechanical parameters relevant to the behaviour of adherent tilled topsoils. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction
The stress–strain relationships of soil depend on both the stress history and the present stress state (e.g., Mitchell, 1993). They may also vary as functions of time and observation scale.
Classical concepts of mechanics as developed for continuous materials cannot be applied directly to tilled topsoils which have recently been fragmented by ploughing and harrowing, leading to completely separate clods or aggregates. At the other extreme, after drying and wetting cycles, these clods or aggregates may be thoroughly combined together until they become a single continuous piece of soil, characterized by hierarchical structures (Dexter, 1991).

However, there are many important practical cases of an intermediate kind where soil clods or aggregates have been partially combined by pressing them together where they can still be readily separated along the boundaries between the original pieces. In this case, macro-pore volume discontinuity, scale laws and clod to clod adhesion should be taken into account, as well as the fact that stresses applied on clods are heterogeneous. This is why we are proposing a new simplified method for analysing the mechanics of clod : clod interactions.

This paper describes the preliminary application of this new methodology to topsoils with a wide range of clay content. The aim of this study was to model the strain–stress relationships using either (i) a common statistical curve-fitting approach for both granular and plastic remoulded topsoils or (ii) the concept of effective stress (e.g., Mitchell, 1993). A specific objective was to determine the effect of soil water suction (which is the same as water potential but of the opposite sign) on the relationships between the axial compressive stress and the flattening strain ratio for two adherent granular remoulded topsoil balls.

2. Materials and methods

2.1. Topsoils and modelling clay

Selected properties of the four topsoil samples are listed in Table 1. The topsoil samples were collected at 0.2–0.5 m depth. They belong to four types of soils which were (i) a sandy podzolic soil (Podsol, FAO), located near Bordeaux, south-western France; (ii) a silty leached brown soil (Luvisol, FAO), located at Orgeval, Parisian Basin, France (Bartoli et al., 1995); (iii) an alluvial brown soil (Eutric Cambisol, FAO) belonging to the Foggathorpe series, England (Furness and King, 1978) and (iv) an alluvial vertic soil (Vertic Cambisol, FAO) belonging to the Fladbury series, England (Reeve, 1978). A proprietary brand of modelling clay (‘Plasticine’) has also been used as a reference. Although this is not soil, it has a similar plastic cohesive consistency.

Smectites were the predominant clay minerals for the sandy topsoil (Bordeaux), with kaolinite as a secondary clay mineral, and illite and quartz as trace minerals whereas the clay fraction of the silty topsoil (Orgeval) was composed of 35% of <0.1 μm smectites (0.17 nm XRD peak after the ethylene–glycol pretreatment) and of 65% of 0.1–2 μm illite–smectite interstratified clay, illite, vermiculite and kaolinite whose proportions are rather equal (Bartoli et al., 1995; Gomendy, 1996). Predominant clays were illite and interstratified illite–smectite, and smectites for the Foggathorpe and the Fladbury clayey topsoils (Reeve, 1978; Furness and King, 1978).

The studied silty and clayey long-term tilled topsoils were also poor in organic carbon (<10 g kg\(^{-1}\)) whereas the Bordeaux sandy short-term tilled topsoil was rich, with 2.2 g kg\(^{-1}\) organic carbon. Conversely, topsoil organic matter was rich both in nitrogen and in oxygenated functional groups for the silty topsoil (C/N ratio value of 8.4), and probably for the non-analysed clayey topsoils, whereas it was polyaromatic for the sandy topsoil (C/N ratio value of 23.6).

Finally, all the topsoils studied were neutral and mostly calcium saturated, but without calcium carbonates, with pH values of soil suspensions in water of 6.8–7.9 (Reeve, 1978; Furness and King, 1978; Gomendy, 1996), except for the sandy organic topsoil which was relatively acid (pH value of 5.6).

2.2. Atterberg limits and soil activity

The plastic limit was determined as the water content at which a sample of soil can just be rolled into a thread of 3 mm diameter without breaking (Sowers, 1965). The liquid limit was determined by the drop-cone technique (BS 1377, 1975). The plasticity index was computed as the difference between the liquid limit and the plastic limit (e.g., Mitchell, 1993).

Both the type and amount of clay in a soil influences the values of the Atterberg limits. To separate them, the ratio of the plasticity index (%) to the clay fraction
<table>
<thead>
<tr>
<th>Topsoil samples</th>
<th>Soil types</th>
<th>Particle-size distribution (g kg$^{-1}$)</th>
<th>Atterberg limits (g kg$^{-1}$)</th>
<th>Activity (plastic index/clay ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>coarse sand &gt;200 μm</td>
<td>fine sand 50–200 μm</td>
<td>coarse silt 20–50 μm</td>
</tr>
<tr>
<td>Bordeaux</td>
<td>podzolic</td>
<td>857</td>
<td>81</td>
<td>9</td>
</tr>
<tr>
<td>Orgeval</td>
<td>leached brown</td>
<td>13</td>
<td>27</td>
<td>446</td>
</tr>
<tr>
<td>Foggathorpe</td>
<td>alluvial brown</td>
<td>40</td>
<td>370</td>
<td>590</td>
</tr>
<tr>
<td>Fladbury</td>
<td>alluvial vertic</td>
<td>60</td>
<td>220</td>
<td>720</td>
</tr>
</tbody>
</table>

$^a$ Measure not possible.
(%), termed the soil activity (e.g., Mitchell, 1993) has also been used in this study.

2.3. Preparation of cylinders or balls of remoulded topsoils

We first prepared remoulded soil balls in order to homogenise the soil structure (e.g., Monnier et al., 1973) by greatly increasing the number of contacts between particles and micro-aggregates (e.g., Dexter et al., 1984a, b; Mitchell, 1993; Attou, 1996). The experiments required either cylindrical remoulded topsoil samples of initial diameter $D_c$ of 25 mm, with a height/diameter ratio value of 2, or pairs of remoulded topsoil balls of initial diameter $D_b$ values of 20–38 mm, or nearly 30 mm for either Plasticine or remoulded topsoils, respectively. Both remoulded topsoil cylinders and balls were prepared by hand-rolling batch of wet aggregates initially of <4 mm.

The two sandy and silty topsoils were first wetted by hand mixing water and soil, with an excess of water. They were then dried at a matric water potential of $\psi = -5$ kPa for three days on a sand table. Some of them were further dried at matric water potential values of $\psi = -10$ or $\psi = -50$ kPa for one week using ceramic pressure plate extractors (Klute, 1986). In contrast, matric water potential of the studied clayey topsoils has not been controlled. The remoulded soil balls were prepared at different water contents occurring within their plastic domains: 299 and 336 g kg$^{-1}$, or 573 and 635 g kg$^{-1}$ for the Foggathorpe and Fladbury remoulded topsoil balls, respectively.

Each wet remoulded soil ball was weighed, oven-dried at 105°C for 48 h and reweighed again thereafter. Gravimetric water content was computed as the ratio of the weight of water loss to the weight of oven-dried soil. Mean bulk density was determined as the ratio of the weight of oven-dried soil on the volume of the soil ball, assuming it was a perfect sphere. Total soil porosity was calculated, assuming particle densities of 2.65 or 2.7 g cm$^{-3}$ for the granular or the clayey plastic topsoils, respectively.

2.4. Unconfined compressive test

We measured the flattening strain of the interfaces of two adherent remoulded topsoil balls as a function of axial compressive stress in order to simulate, in a very simplified way, the mechanics of adherent topsoil clods such those which occur after cultivation.

The major principal compression stress (axial stress) was determined on the two remoulded granular topsoils using the unconfined compression test (e.g., Watts and Dexter, 1993). Each cylindrical sample of material was loaded axially at a rate of $75 \times 10^{-6}$ m s$^{-1}$ using a loading frame of the type used for triaxial testing of soil core samples. The axially applied force, $F_a$, was recorded as a function of percentage axial strain using a load cell which was calibrated with known weights. The output from the load cell was recorded with a signal analyser (Advantest model R9211B) for subsequent analysis. By definition, the cylindrical compression axial stress, $\sigma_c$, is the ratio between the applied axial force, $F_a$, and the surface area, $\pi D_c^2/4$, of the cylinder disc plane characterized by its diameter, $D_c$.

$$\sigma_c = 4F_a/\pi D_c^2$$

The dimensionless axial strain, $R_a$, is the ratio between the axial strain (mm) and the initial height (mm) of the cylinder of remoulded topsoil. In this study, both $F_a$ and $\sigma_c$ values were recorded at a $R_a$ value of 0.2 as proposed by Watts and Dexter (1993), or, in some cases, for the sandy topsoil, at failure, which was deemed to have occurred when this $R_a$ value of 0.2 was reached.

2.5. Flattening between pairs of balls of remoulded topsoil

The pairs of balls of remoulded topsoil, of diameter $D_b$, were pressed together axially at a constant rate of $75 \times 10^{-6}$ m s$^{-1}$. When each increasing level of applied axial force had been reached, each pair of spheres was pulled apart and the diameter, $D_f$, of the flat interface which had developed between them (Fig. 1) was measured with digital callipers, with a length resolution value of 10$^{-2}$ mm. This enabled the dimensionless strain flattening ratio, $R_f = D_f/D_b$, to be determined.

Two sets of mechanical experiments were done: (i) the step by step record of the dimensionless strain flattening ratio $R_f$ as a function of the compression stress, or (ii) the record of the compression axial stress when a standardized $R_f$ value of 0.47 had been reached.
during continuous compression of the two adherent topsoil balls. These two methods are described as follows.

2.5.1. **Step by step increasing compressive stress method (cyclic loads)**

For each pair of either Plasticine or remoulded topsoil balls, different successive levels of force were applied and their strain flattening ratios, $R_f$, were determined as follows. At the beginning of the experiment, the two remoulded topsoil balls, characterized by either their initial water content or matric water potential, were wrapped in plastic (Cling Film) to keep them moist. Then, each mould was poured with liquid plaster of paris (calcium sulphate with water). Each remoulded topsoil ball was pressed into the mould until about half of the sphere was inside the plaster of paris and so inside the mould (Fig. 1). When the plaster of paris was firm, the upper mould was attached to the cross-beam of the apparatus and the lower mould was placed on a digital balance below it. The step by step compression method was ready to start when the two soil balls were in contact.

The pairs of balls of remoulded topsoil were pressed together at a rate of $75 \times 10^{-6}$ m s$^{-1}$, in the loading-frame. When each increasing level of applied axial force had been reached, each pair of spheres was pulled apart and the diameter, $D_f$, of the flat interface which had developed between them (Fig. 1) was measured. The experiment was stopped when the
flattening diameter reached about one-half of the initial diameter, $D_b$, of the ball.

The possible influence of the water content of the plaster of paris on the water content of the balls (possible soil drying) could not be controlled. However, the time of either putting the balls onto the wet plaster of paris or compressing the adherent balls was very short (nearly 2 min). Then, we assumed that this possible effect of the plaster of paris to partly dry the soil balls was negligible.

In the mechanics of the compression of axial soil cylinders (unconfined compression test), the axial stress, $\sigma_c$, is nearly constant because the surface area on which the applied axial force is applied is almost constant ($\pi D_c^2/4$, $D_c$ being the cylinder diameter). We assumed a negligible increase of the soil cylinder diameter from the beginning to the end of the unconfined compressive test carried out on the slightly plastic silty soil. For the sandy soil, which has a brittle non-plastic behaviour, its cylinder diameter was really nearly constant from the beginning to the end of the unconfined compressive test.

In contrast, in the mechanics of two adherent soil balls, the axial compressive stress, $\sigma_b$, in the soil balls are heterogeneous, with a mean maximal value, $\sigma_{b,\text{max}}$, at the top of the ball, and a mean minimal value, $\sigma_{b,\text{min}}$, on its equatorial plane, as follows:

$$\sigma_{b,\text{max}} = 4F_a/\pi D_c^2$$

$$\sigma_{b,\text{min}} = 4F_a/\pi D_c^2 = R_f^2 \sigma_{b,\text{max}}$$

The strain was also essentially homogeneous in the tests on cylindrical soil samples whereas it was mainly a surface deformation in axial mechanics of two adherent soil balls, at least for $R_f$ values <0.5.

In this study, the $\sigma_{b,\text{min}}$ values so determined on each pair of adherent balls of remoulded topsoil were also compared with the $\sigma_c$ value determined on each remoulded topsoil cylindrical counterpart. For that, we first observed that the axial strain occurred only at the top of the ball, due to the rigidity of the mould containing the plaster of paris, leading to the fact that, for a $R_f$ value of 0.2 (unconfined compression test), the size of the vertical side of this triangle is 0.6 ($D_f/2$). Second, we used the Thales equation within the right-angle triangle drawn in Fig. 1, with its smaller angle $\theta$:

$$(D_b/2)^2 = [0.6(D_b/2)]^2 + (D_f/2)^2$$

leading to a value of ($D_f/2$) of 0.8 ($D_b/2$), that is to say a $R_f$ value of 0.8 for a $R_f$ value counterpart of 0.2 (unconfined compression test).

### 2.5.2. Flattening test

Only the two remoulded granular topsoils were used in this last set of experiments. Here, the pairs of balls of remoulded topsoil were pressed together continuously until their flat interfaces reached about half the initial diameter $D_b$ ($R_f$ value of 0.47), using only one load and not successive increasing loads as previously. The applied axial force was then noted down and the maximal and minimal stresses were computed as above.

### 2.6. Concept and theory used

In this paper, we combined the classical Mohr–Coulomb theory of soil strength with the concept of effective stress (e.g., Mitchell, 1993) to characterize the stress vs. surface deformation by the compression between two spherical soil samples.

According to the Mohr–Coulomb theory of strength, shear failure occurs in a material when some critical shear stress $\tau$ is exceeded, where $\tau$ may be expressed as:

$$\tau = c + \sigma \tan \phi$$

where $\sigma$ is the normal stress, on the plane of the failure and $c$ and $\phi$, the cohesion and angle of friction, are two constants which characterize the material. Following the reviews of Mullins and Panayiotopoulos (1984) and Mitchell (1993), when a saturated porous material is subjected to external stress, the pore water, having no shear strength, is ineffective in mobilizing shear resistance. Thus, ignoring any possible effects due to trapped air, the effective stress $\sigma'$ is dependent on both the applied normal stress $\sigma$ and the pore water pressure or suction, $u$, as follows:

$$\sigma' = \sigma - u$$

Similarly, when the pore water is under a tension $\psi$ (matric water potential), the tension supplements any external applied stress so that, in a saturated soil:

$$\sigma' = \sigma + \psi$$

In an unsaturated soil, assuming that the air in soil pores is at atmospheric pressure, the effective stress is
given by:

$$\sigma' = \sigma + \chi\psi$$  \hspace{1cm} (8)

where $\chi$ is a function of the degree of saturation ranging from 0 in a dry soil to 1 in a saturated soil (e.g., Mullins and Panayiotopoulos, 1984; Young and Mullins, 1991; Mitchell, 1993). The soil strength characteristic is the relation between soil strength and either water suction or water content. It varies with soil type and soil management (e.g., Davies, 1985; Young and Mullins, 1991; Watts and Dexter, 1993). In granular soils in which the long-range interparticle attractions and repulsions are both small, the effective stress corresponds to the true intergranular pressure (Mitchell, 1993).

3. Results and discussion

3.1. Atterberg limits

The values of the Atterberg limits of the remoulded topsoils (Table 1) were plotted as a function of their clay contents, delimiting a plastic domain (dotted area of Fig. 2). In this study, the water contents of the studied remoulded topsoils were within this plastic domain, although the sandy topsoil was non-plastic. Similar observations have been previously observed on quartz which did not develop plastic mixtures with water (e.g., Mitchell, 1993).

As it is usually observed, the increase of the Atterberg limits as a function of clay content was much more pronounced for the liquid limit than for the plastic limit (Fig. 2). This leads to a large increase of the plasticity index as a function of clay content (Table 1), as it is also usually reported (e.g., Smith et al., 1985; Mitchell, 1993). Soil activity also increased as a function of clay content (Table 1) which was attributed to the increase, from the sandy topsoil to the clayey ones, of smectite content within the clay fraction. Smith et al. (1985) have also demonstrated that both Atterberg limits are more closely related to specific surface area, hygroscopic water content and cationic exchange capacity than to clay content, indicating that the clay mineralogy must be taken into account in these Atterberg limits correlations.

3.2. Porosity of centimetric remoulded soil balls

The mean porosities of the sandy and silty remoulded topsoil balls were $0.36 \pm 0.01$ and $0.37 \pm 0.01 \text{ cm}^3 \text{ cm}^{-3}$, respectively (10 replicates), which fit with the porosity value of $0.367 \text{ cm}^3 \text{ cm}^{-3}$ of a random heap of equal spheres, in dense packing (Finney, 1970). Similar porosity values of $0.34$–$0.39 \text{ cm}^3 \text{ cm}^{-3}$ have also been reported by Panayiotopoulos and Mullins (1985) and by Chretien (1986) for a range of compacted sands and sandy soils characterized by quartz grains with rounded shapes similar to those of the two studied granular topsoils.

In contrast, the porosity values of the two studied remoulded clayey topsoil balls were relatively high: (i) $0.43$ and $0.45 \text{ cm}^3 \text{ cm}^{-3}$ for the Foggathorpe remoulded plastic topsoil prepared at gravimetric water contents of 299 and 336 g kg$^{-1}$, respectively and (ii) $0.56$ and $0.64 \text{ cm}^3 \text{ cm}^{-3}$ for the Fladbury remoulded plastic topsoil prepared at gravimetric water contents of 573 and 635 g kg$^{-1}$, respectively. These relatively high porosity values should be attributed to either easy hand-rolling of these plastic clayey topsoils or to shrinkage which occurs during air-drying of the studied remoulded clayey soil balls, leading to growth of intra-balls cracks.

Finally, the pore spaces were nearly water-saturated for both granular remoulded topsoils equilibrated at matric water suctions of 5 kPa and for the very wet clayey soils.
3.3. Stress–strain relationships for two adherent remoulded topsoil balls

In this section, we consider the relationship between the maximal axial compression stress, $\sigma_{h,\text{max}}$, and the dimensionless flattening ratio, $R_f$, for two adherent balls of either modelling clay or remoulded clayey or granular topsoils.

3.3.1. Stress–strain relationships for two adherent modelling clay balls

For modelling clay balls, a diameter effect was observed on the maximal stress–strain relationship, with a tendency for a decrease of surface deformations within the same range of stress values when the diameter increased from 20 to 32 mm (Fig. 3). In the light of these preliminary results, we therefore decided to prepare remoulded topsoil balls with the same range of diameters of nearly 30 mm.

3.3.2. Stress–strain relationships for two adherent clayey remoulded topsoil balls

For the plastic topsoils studied, non-linear convex stress–strain relationships were observed (Fig. 4). Such ductile deformations have been widely described for similar clayey soils (e.g., Tripodi et al., 1992; Mitchell, 1993). For each studied plastic remoulded topsoil, the asymptote value of the stress–strain curve also decreased as a function of its gravimetric water content (Fig. 4).

The first result confirms the fact that compressibility increases as a function of clay content, and the proportion of smectites and interstratified illite–smectites. It was mainly attributed to an increase of clay swelling leading to an increase of both plasticity and creep rate (e.g., Tripodi et al., 1992; Mitchell, 1993). In this study, increase of both clay content and proportion of smectites within the clay fraction and, conversely, of both the plasticity index and the soil activity value, were reported above for the Foggathorpe and Fladbury topsoil. Similarly, the second result confirmed that as the water content of a clayey soil increases, the more plastic it becomes and conversely, the more compressible and the less consolidated it becomes (Mitchell, 1993).

3.3.3. Stress–strain relationships for two adherent granular remoulded topsoil balls

Each granular remoulded topsoil studied was characterized by an important variability of their stress–strain replicate graphs (Fig. 5(a), (b)). This can be interpreted by different types of stress–strain behaviour.

The first was common to the two studied granular remoulded topsoils and was characterized by a rapid
increase of the stress leading to non-linear concave stress–strain relationships (open symbols of Fig. 5(a), (b)). Similar non-linear concave either void ratio change–strain or stress–strain relationships have been previously reported by Mitchell (1993) for granular soils when subjected to cyclic loads. When granular soils are compressed, quartz grains are repositioned into more efficient packings leading to a diminution of both the diameter of water-filled pores and porosity, and, conversely, to an increase of both the water suction and the soil strength, which also may be due to interlocking rough surfaces of compact particles (e.g., Panayiotopoulos and Mullins, 1985; Mitchell, 1993; Horn et al., 1994).

The second type of failure stress–strain behaviour was the brittle one (Mitchell, 1993) which occurred for two sets of experiments carried out on the remoulded sandy topsoil balls (filled symbols of Fig. 5(a)). The stress rised rapidly to a peak value, with increasing deformation, where-upon failure occurred and the stress level dropped substantially to a residual value. Conversely, we have reported in the section on Atterberg limits that it was not possible to measure the plastic limit of this sandy topsoil (Table 1).

A third type of stress–strain relation was a very low increase of the axial compressive stress followed by a rapid increase thereafter. This can be attributed to a metastable fabric as previously suggested by Mitchell (1993). In this study, residual micro-aggregates would still have existed within some remoulded silty topsoil balls. Micro-aggregates are separated by pores which are larger than those occurring between quartz grains and their clay coatings (Gomendy, 1996; Bartoli et al., 1999). Disruption of these micro-aggregates when subjected to the cyclic loads should lead to a reduction of the effective axial compressive stress because of the tendency for the volume to decrease, and the strength is less.

3.4. Modelling of the stress–strain relationship for two adherent remoulded topsoil balls

3.4.1. Statistical modelling of the stress–strain relationship for two adherent remoulded topsoil balls

Three types of mechanical behaviours were characterized using the power-law fitting approach as a common modelling framework for the maximal stress vs. strain curve. These are as follows: plastic for the Fladbury clayey remoulded topsoil ($b$ value of 0.4; convex curve), intermediate but always plastic for the Foggathorpe clayey remoulded topsoil and the plasticine ($b$ value of 0.9–1), and granular for the two sandy and silty remoulded topsoils ($b$ value of 1.6; concave curve) (Fig. 6; Table 2). Conversely, the constant $A$ of the power-law equation $y = Ax^b$, which corresponds to the axial compressive stress at the

![Fig. 5](image)

Fig. 5. Relationships between the maximal axial compressive stress and the flattening strain ratio for two adherent granular remoulded topsoil balls which were prepared at a soil water suction value of 10 kPa, either Bordeaux (19 g kg$^{-1}$ clay) (a) or Orgeval (164 g kg$^{-1}$ clay) (b) topsoils. Each symbol corresponds to an experimental set. Filled symbols correspond to two sets of experiments which characterize either a brittle behavior (a) or a special stress : strain behaviours which can be attributed to a metastable fabric (b).

![Fig. 6](image)

Fig. 6. Mathematical modelling of the relations between the maximal axial compressive stress ($y$) and the flattening strain ratio ($x$) for two adherent remoulded topsoil balls: (i) plasticine (open triangles), Foggathorpe (filled squares) or Fladbury (filled circles) clayey remoulded topsoils which were prepared at 377 and 635 g kg$^{-1}$ water content, respectively (Fig. 6(a)) and (ii) Bordeaux (open squares) or Orgeval (open circles) granular remoulded topsoils which were both prepared at a suction of 10 kPa (Fig. 6(b)). The corresponding power-law equations are reported in Table 2.
flattening strain ratio of 1, increased as a function of this power-law coefficient $b$ (Table 2). These three types of relationships may correspond to the sliding regime (shear residual angle of friction of $<10^\circ$), the transitional regime (residual angle of friction of 10–25$^\circ$) and the rolling shear regime (residual angle of friction of 25–30$^\circ$), respectively. These have been previously described and reviewed by Mitchell (1993) for clayey soils (>550 g kg$^{-1}$ clay), intermediate soils (250–550 g kg$^{-1}$ clay) and granular soils (<250 g kg$^{-1}$ clay), respectively.

On the other hand, all the relations between the minimal axial compressive stress for two adherent soil balls and the flattening strain ratio were characterized by very concave power-law curves (power-law coefficient $b > 2$: Table 2) and, conversely, by very low minimal stress values for flattening strain ratios $<0.4$ (Fig. 7). These results confirm that the strain was mainly a surface deformation in axial mechanics of two adherent soil balls, at least for $R_f$ values $<0.4$.

### 3.4.2. Effect of soil water suction on the stress–strain relationship for two adherent granular remoulded topsoil balls

The minimal axial compressive stress corresponding to the flattening test for two adherent remoulded topsoil balls increased as a function of the initial water suction value, and the increase was much more pronounced for the silty topsoil than for the sandy one (Fig. 8(a)). Similar relationships between shear strength and either the soil water suction or the water content have been previously reported by Spoor and Godwin (1979), Davies (1985), Young and Mullins (1991) and Watts and Dexter (1993). Drying tends to pull the particles together, thus functioning as a cohesive force. So, for a similar flattening ratio, the stress necessary to compress the two remoulded soil remoulded topsoil cylinders also increased as a function of the initial soil water suction value, also with lower stress values for the sandy topsoil than for the silty one (Fig. 8(b)).

![Fig. 7](image)

Fig. 7. Mathematical modelling of the relations between the maximal (filled symbols) or the minimal (open symbols) axial compressive stress and the flattening strain ratio for two adherent granular remoulded topsoil balls: (a) Foggathorpe or Fladburry clayey remoulded topsoils which were prepared at 377 and 635 g kg$^{-1}$ water content, respectively and (b) Bordeaux (open squares) or Orgeval (open circles) granular remoulded topsoils which were both prepared at a suction of 10 kPa. The corresponding power-law equations are reported in Table 2. The filled and the open symbols correspond to the maximal and to the minimal axial compressive stress, respectively.
balls is higher for the drier samples than the wetter ones, as required by Eq. (8).

Although only two sets of experiments were carried out for soil water suction values lower than 10 kPa, in both remoulded topsoil adherent balls and cylinders mechanical tests, the relation between the stress and the suction could at first be linear up to a soil water suction of 10 kPa (saturated remoulded topsoils) as required within a short matric water potential domain by Eq. (8). The intercepts of the straight stress : suction lines with the stress axis could be used in order to know the value of the external axial compressive stress. This is needed to apply either on the diameter areas of adherent remoulded topsoil balls for producing a flattening dimensionless strain of 0.47, or on similar diameter area values of remoulded topsoil cylinders for producing a volumetric dimensionless strain of 0.2.

First, for the flattening test ($R_f$ value of 0.47), this internal soil strength value, determined as the intercept of the straight stress-suction line, was 2.2 and 1.2 kPa (minimal stress) (Fig. 8(a)), and of 10 and 5.4 kPa (maximal stress) for the silty and the sandy remoulded topsoils, respectively. For the unconfined compressive test, this internal soil strength value was of 12.6 and 9 kPa, for the silty and the sandy remoulded topsoil, respectively (Fig. 8(b)). This discrepancy could be attributed to the fact that the $R_v$ value of 0.2 (unconfined compressive test) corresponds to a $R_f$ value of 0.8, which is much more greater than the $R_f$ value of 0.47 (flattening test). It confirms that volumetric deformation was very low, quite negligible, for the balls after the flattening test whereas it was rather important (20% of the initial cylinder volume) for the cylinders after the unconfined compressive test.

Second, the ratio between the calculated applied stress for the silty remoulded topsoil and that for the sandy remoulded topsoil counterpart was 1.8 and 1.4 for the flattening test and the unconfined compressive test, respectively. This confirms that the soil strength characteristic varied with soil type (e.g., Davies, 1985; Young and Mullins, 1991; Watts and Dexter, 1993). This internal soil strength could be mainly attributed to resistances due to interlocking of the rough surfaces of compact particles and to possible grain abrasion (e.g., Fanayiotopoulos and Mullins, 1985; Mitchell, 1993).

For the silty topsoil, and for both the flattening and the unconfined compressive tests, a decrease of the stress : suction slope value was also observed from the 5–10 kPa saturated domain to the 10–50 kPa drained domain, with a stronger effect on the stress for the flattening test than for the uncompressive test (Fig. 8). This observation could be attributed to the fact that the silty remoulded topsoil was partly drained at a suction value of 50 kPa leading to a value of the $\chi$ coefficient (Eq. (8)) <1. In comparison, this $\chi$ coefficient value could be equal to 1 (Eq. (7)) for the near-saturated topsoil which was prepared at soil water suction values of 5 and 10 kPa.

Finally, the relation between the minimal axial compressive stress for two adherent remoulded topsoil balls at a flattening strain ratio of 0.47 increased non-linearly as a function of the axial compressive stress for its cylinder counterpart at a volumetric axial ratio of 0.2, from the sandy to the silty topsoil (Fig. 9). The flattening test therefore appears to be a sensitive tool for characterizing soil plasticity within discontinuous porous media such as adherent tilled topsoil clods.

4. Summary and conclusions

This study was aimed at improving the understanding of mechanics of tilled topsoils which are characterized by discontinuities between adherent soil clods. A device for simulating cyclic or progressive loading on adherent soil clods was designed using
two adherent remoulded topsoil balls with similar diameters. The main results were:

1. A non-linear convex relationship between the axial maximal compression stress and the flattening strain ratio, \( R_f \), was observed for the clayey remoulded topsoils. The results showed that the higher the clay content and the water content of a clayey soil, the more plastic it is.

2. In contrast, a non-linear concave maximal stress–strain relationship, with failure or metastable fabric behaviour, occurred for the granular remoulded topsoils.

3. The maximal stress-flattening strain curve was fitted with a power-law equation, with either a negative or a positive power-law coefficient for either the convex stress : strain curve of the plastic clayey soils or the concave stress–strain curve of the granular soils, respectively.

4. The minimal axial compressive stress corresponding to the flattening test for two adherent remoulded topsoil balls increased as a function of the initial soil water suction value, as required by the concept of effective stress. This increase was much more pronounced for the silty topsoil than for the sandy one. Conversely, the internal soil strength value, determined as the intercept of the straight stress-suction line for the flattening test (\( R_f \) value of 0.47), was 2.2 and 1.2 kPa (minimal stress), and 10 and 5.4 kPa (maximal stress) for the silty and the sandy remoulded topsoils, respectively.

5. The minimal axial compressive stress for two adherent remoulded topsoil balls at a flattening strain ratio of 0.47 increased non-linearly as a function of the axial compressive stress for its cylindrical counterpart at a volumetric axial ratio of 0.2. The drier and the more cohesive was the soil, the more difficult was the geometrical macroscopic change from a spherical shape to a flattened surface area.

In conclusion, the flattening test appears to be a useful tool for characterizing soil plasticity in discontinuous porous media such as adherent tilled topsoil clods. It is also a promising tool for further studies on clod : clod adhesion where two adherent soil balls are pulled apart.

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