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The Nature of Changes in Bulk Density with Water Content in a Cracking Clay

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Abstract

The effect of changing water content on the bulk density of undisturbed cores of a cracking clay was examined in laboratory experiments. The results were compared with the relationship between bulk density and water content established by core sampling the same soil in the field.

Over the water content range measured in the field soil, the laboratory cores shrank three-dimensionally and normally. Small departures from normal shrinkage were attributed to the formation of cracks within the cores, and to the occurrence of some structural shrinkage in cores previously wet to high water contents. Swelling of cores was approximately three-dimensional, except for some unconfined swelling which occurred in the core surface. Unidimensional swelling was induced by confining dry cores to reduce the void ratio before wetting. Subsequent shrinkage was three-dimensional, indicating that the soil particles were reoriented during the unidimensional swelling phase.

While the laboratory measurements showed that the soil volume changes were essentially three-dimensional and normal, the field data indicated that unidimensional shrinkage occurred at water contents greater than $0\cdot47$ g g^{-1}. These field results were attributed to sampling inaccuracies associated with the use of a small-diameter core sampler, the actual field bulk density relationship being considered three-dimensional.

Introduction

A number of workers have studied the swelling and shrinkage properties of clay soils. 'Structural', 'normal' and 'residual' phases of shrinkage have been measured in laboratory studies using unconfined moulded soil blocks (Haines 1923; Holmes 1955) and natural clods (Johnson and Hill 1944; Stirk 1954). In the normal shrinkage phase, the loss of soil volume equals the volume of water lost, while in the structural and residual phases, volume changes are less than normal.

Field investigations of the volume-change process in cracking clay soils have produced conflicting results. Aitchison and Holmes (1953) observed changes in surface elevation of a black earth soil near Adelaide which could be explained by volume changes of slightly less than three-dimensional normal. Similar results have been obtained on cracking clays around Emerald, Qld. (Yule and Shaw, personal communication). In contrast, the bulk density results obtained by Fox (1964) from a black earth on the Darling Downs indicate that 60% of the variation in bulk density at water contents greater than the wilting point could be explained by volume changes which were unidimensional normal. These changes in soil volume in the vertical direction were explained on the basis of water films changing dimensions only in horizontal interstices, after vertical cracks had closed.

Because these field results conflict, the specific relationship between bulk density and water content must be defined for any cracking clay under investigation. This necessitates the measurement of bulk density throughout the field water content range, and, if unidimensional volume change occurs, the determination of the point of transition from the unidimensional to the three-dimensional phase. It is often impractical to obtain these field data for cracking clays, due to the need to sample at a wide range of water contents and the difficulties imposed by crack geometry.

An alternative approach may be to obtain the required data by studying the volume changes of soil cores in the laboratory. If such cores were confined in the same manner as field soils, and possessed field structure, they should exhibit field behaviour. The undisturbed core technique described by Berndt *et al.* (1976) appears to provide suitable core samples.

In examining the nature of bulk density changes of field soils, this paper compares the bulk density results obtained from a laboratory study using undisturbed soil cores with those obtained from field sampling.

Materials

Soil

The soil examined, a Waco black earth as described by Thompson and Beckmann (1959), was located near Mt. Tyson on the Darling Downs, Queensland. Some properties of the soil are listed in Table 1. This soil exhibits gross swelling and shrinkage with changing water content, resulting in the formation of large vertical cracks on drying (Swartz 1966).

Table 1. Some physical characteristics of the Waco black earth soil used in this investigation

Particle size distribution (%)				Water retention ($g\ g^{-1}$)			Oven-dry clod bulk density ($g\ cm^{-3}$)	Density of soil solids ($g\ cm^{-3}$)
				Potential ($J\ kg^{-1}$)				
Coarse sand	Fine sand	Silt	Clay	−0·1	−30	−1500		
2	11	9	78	0·70	0·60	0·37	1·80	2·66

Experimental

Laboratory experiments

Undisturbed soil cores, 10·9 cm in diameter, were obtained as described by Berndt *et al.* (1976). The cores were taken from the 20–60 cm depth at an average water content of $0{\cdot}49\ g\ g^{-1}$. The mean bulk density of the cores was $1{\cdot}08\ g\ cm^{-3}$. No shrinkage cracks were evident in the samples or the field soil. The cores were transported to the laboratory in sealed polyvinyl chloride tubes and cut into sections approximately 10 cm long.

Experiment 1: Unsupported Cores—Drying

Five cores were removed from their supporting tubes and placed on rigid bases. These laterally unsupported cores were kept at their initial water content for 7 days, then allowed to dry slowly by restricted exposure to the atmosphere.

The resultant average drying rate was $0 \cdot 0025 \mathrm{~g~g^{-1}~day^{-1}}$. When the experiment was terminated, the cores had reached a mean water content of $0 \cdot 23 \mathrm{~g~g^{-1}}$.

Core dimensions and weights were monitored during the experiment to measure volume and water content changes. Core volumes were calculated from height and diameter data. Core heights were measured with a dial guage incorporating an electrical contact indicator. Diameters were calculated from the core circumference, measured with a flexible rule. The density of soil water was assumed to be unity in all calculations.

Experiment 2: Supported Cores—Wetting and Drying

Twelve cores were retained in the tubes of 10·9 cm diameter which were then cemented to rigid bases. A hole of 2 mm diameter was drilled in the base of each tube to allow drainage. The experiment proceeded in two phases:

(*a*) An additional piece of tube 10·9 cm in diameter was cemented to the tops of four of the supporting tubes to allow for vertical swelling. The cores were wet to the maximum water content, by ponding 10 ml of water on the soil surface daily until each addition was lost as drainage. The cores were then dried to below their initial water contents.

(*b*) The remaining eight cores were allowed to dry slowly to water contents less than $0 \cdot 30 \mathrm{~g~g^{-1}}$. The cores were then removed from their supporting tubes and four put aside for experiment 3. The remaining four were reinserted into 10·9 cm tubes, of greater height than their original tubes. The new supporting tubes were cemented to rigid bases and drainage holes were inserted. Water was added daily in 20 ml increments into the space between the cores and the tube, until the macro air space was filled by the swelling core. The water was then ponded on the soil surface until the maximum water content was reached, as in experiment 2(*a*). The samples were dried to a mean water content of $0 \cdot 30 \mathrm{~g~g^{-1}}$ at a rate of about $0 \cdot 002 \mathrm{~g~g^{-1}~day^{-1}}$.

Experiment 3: Confined Cores—Wetting and Drying

The four cores, retained after the first drying phase of experiment 2(*b*), were transferred into tubes of 10·0 cm diameter. This effectively reduced the volume available to the cores for horizontal expansion. These confined cores were wet to the maximum water content, and dried, as described for experiment 2(*b*).

In experiments 2 and 3, bulk densities of the cores were determined on the basis of the cores representing field units. The cores were assumed to effectively occupy the supporting or confining tubes in the horizontal direction. Core heights alone were measured, the diameters being taken as 10·9 or 10·0 cm, the internal diameters of the tubes.

Field bulk density measurements

Field core samples, 4·5 cm in diameter, were obtained from the 30–60 cm layer using an hydraulically inserted tube sampler (Stace and Palm 1962). Samples were obtained over a gravimetric water content range of $0 \cdot 33$–$0 \cdot 59 \mathrm{~g~g^{-1}}$. Bulk densities were determined from the oven-dried core mass contained in the field volume of the sample.

Results

Laboratory experiments

Experiment 1: Unsupported Cores—Drying

The dimensions of the five unsupported cores did not change after being removed from their supporting tubes, or while held at their initial water contents for 7 days. This suggests that the samples were physically stable, and that water was not redistributed when the support was removed.

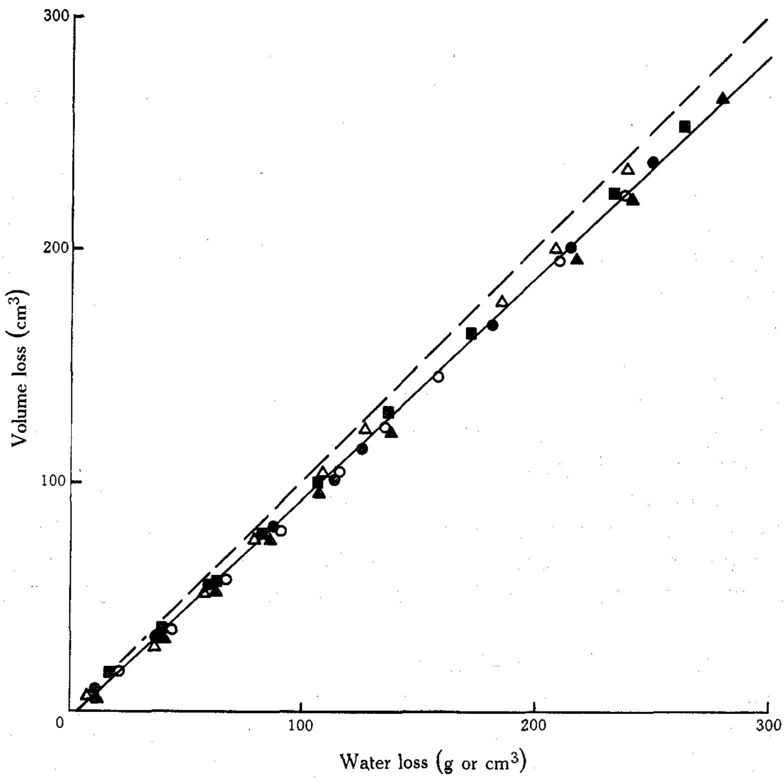

Fig. 1. Relationship between volume loss and water loss for five soil cores in experiment 1.
Solid line: $Y = -2 \cdot 391 + 0 \cdot 949X$, $r = 0 \cdot 999$ ($P < 0 \cdot 001$).
Broken line: $Y = X$.

Core symbol	Water content range ($g\ g^{-1}$)
●	0·52–0·25
○	0·50–0·24
▲	0·49–0·24
△	0·48–0·24
◧	0·46–0·20

The relationship between volume loss and water loss, for the five unsupported cores, is shown in Fig. 1. These two variables are highly correlated, with correlation coefficients of 0·994–0·999 for individual cores. The linear regression of the grouped data and the 1 : 1 relationship are also shown in Fig. 1. The regression coefficient of 0·949 is significantly less than 1·0 ($P < 0 \cdot 01$), thus indicating that the loss of soil volume was approximately 5% less than the volume of water lost.

The relative changes in height of the unsupported cores on drying are highly correlated with the relative changes in diameter ($r = 0 \cdot 999$), as shown in Fig. 2. The linear regression of the grouped data is not significantly different from the 1 : 1 relationship ($P > 0 \cdot 05$). Shrinkage of the unsupported cores was approximately equal in the vertical and horizontal dimensions.

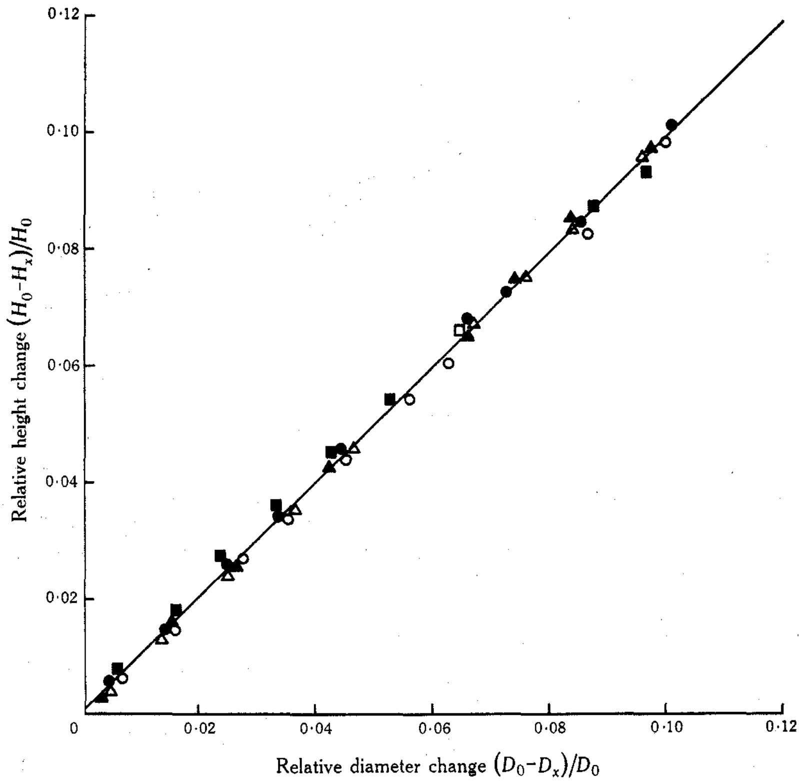

Fig. 2. Relationship between change in height ($H_o - H_x$) relative to initial height (H_o) and change in diameter ($D_o - D_x$) relative to initial diameter (D_o) for five soil cores drying in experiment 1.
$Y = 0 \cdot 001 + 0 \cdot 981X$, $r = 0 \cdot 999$ ($P < 0 \cdot 001$). Legend as for Fig. 1.

Experiment 2: Supported Cores—Wetting and Drying

The mean bulk densities of the supported cores during the wetting and drying phases of experiment 2 are plotted in Fig. 3. The arrows on the lines of best fit of data indicate the wetting and drying phases. Three-dimensional and unidimensional normal shrinkage curves from the maximum water content are presented for comparison. These curves theoretically relate field bulk density to water content for three-dimensional normal changes in volume of the soil matrix between cracks, and for unidimensional normal changes in the soil volume when cracks are closed (Fox 1964).

The cores in experiment 2(*a*) reached a mean water content of $0\cdot55\ g\ g^{-1}$, and exhibited changes in bulk density with water content which were similar to those of the three-dimensional relationship. Shrinkage during drying to $0\cdot47\ g\ g^{-1}$ was also approximately three-dimensional.

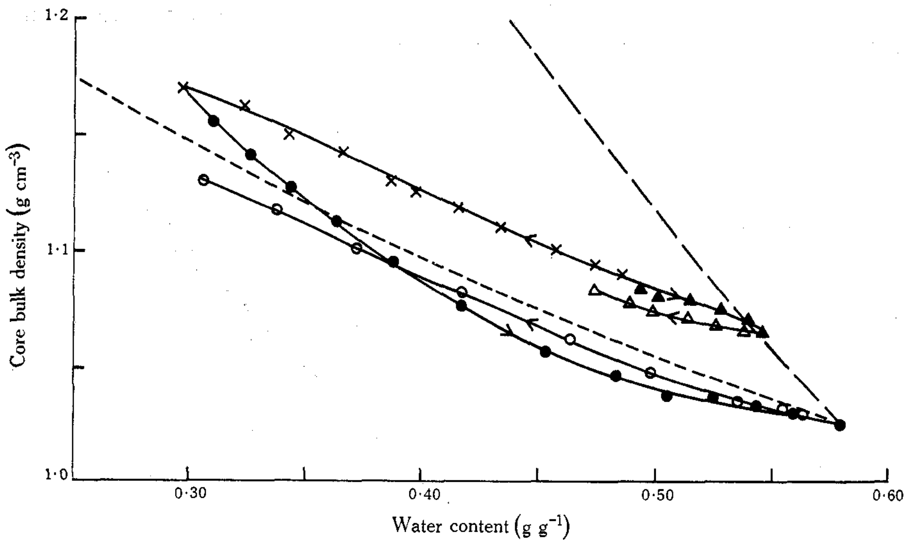

Fig. 3. Bulk density changes in supported soil cores sampled at a mean water content of $0\cdot49\ g\ g^{-1}$ and subjected to wetting and drying treatments. Experiment 2(*a*), ▲ wetting, △ drying. Experiment 2(*b*), × drying, ● wetting, ○ drying. ——Freehand lines of best fit. – – – Unidimensional normal shrinkage curve. - - - - - - Three-dimensional normal shrinkage curve.

During the initial drying phase of experiment 2(*b*), to a mean water content of $0\cdot30\ g\ g^{-1}$, shrinkage was essentially three-dimensional. Swelling of these cores during subsequent wetting tended to be initially greater than three-dimensional, and less than three-dimensional as the maximum water content was approached. The mean maximum water content of $0\cdot58\ g\ g^{-1}$ is significantly higher ($P < 0\cdot05$) than that reached by the cores in experiment 2(*a*).

The final drying phase of experiment 2(*b*) produced bulk density changes similar to those predicted for three-dimensional shrinkage. The bulk densities of the cores in this phase indicate that a mean increase in sample porosity of $0\cdot03\ cm^3\ cm^{-3}$ occurred during the wetting phase of experiment 2(*b*).

Experiment 3: Confined Cores—Wetting and Drying

Mean bulk density and water content data for the confined cores during the wetting and drying phases of experiment 3 are presented in Fig. 4. For comparison, theoretical unidimensional and three-dimensional normal shrinakge curves from the maximum water content are also presented.

The confined cores were at a mean water content of $0\cdot26\ g\ g^{-1}$ when wetting commenced. Swelling was approximately three-dimensional at water contents less than $0\cdot31\ g\ g^{-1}$, then unidimensional up to water contents of $0\cdot41$–$0\cdot45\ g\ g^{-1}$. As the maximum water content of $0\cdot57\ g\ g^{-1}$ was approached, bulk density changes were slightly less than those expected from unidimensional expansion. The final drying phase of the confined cores, to a mean water content of $0 \cdot 30 \text{ g g}^{-1}$, was accompanied by three-dimensional shrinkage throughout.

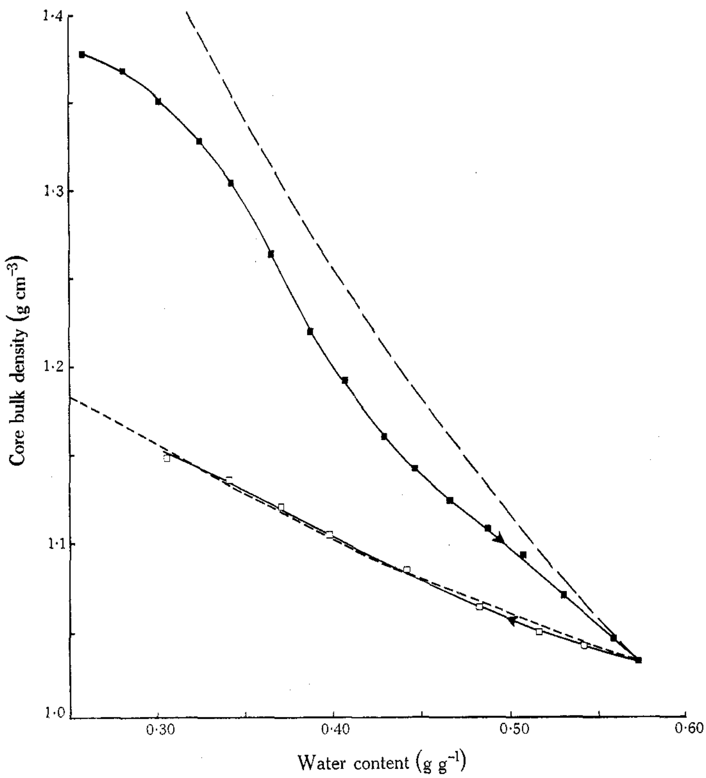

Fig. 4. Bulk density changes in confined soil cores subjected to wetting and drying treatments. Experiment 3, ■ wetting, □ drying. —— Freehand lines of best fit. – – – Unidimensional normal shrinkage curve. - - - - - Three-dimensional normal shrinkage curve.

The core surfaces were observed to remain intact during wetting in experiment 2(*a*), while considerable surface disruption occurred during wetting in experiments 2(*b*) and 3.

Field data

The field bulk density data were divided, at approximately $0 \cdot 01 \text{ g g}^{-1}$ water content intervals, into groups of 10 samples. The mean bulk densities of each group, and the 95 % confidence limits, are presented in Fig. 5. The theoretical unidimensional and three-dimensional shrinkage curves, for the soil drying from the maximum water content observed, are also shown. At water contents greater than $0 \cdot 47 \text{ g g}^{-1}$, measured bulk density is consistent with the unidimensional volume change theory. At lower water contents, bulk density falls below the unidimensional curve, and variability increases markedly.

The maximum water content observed in field sampling was similar to those reached by the cores in experiments 2(*b*) and 3.

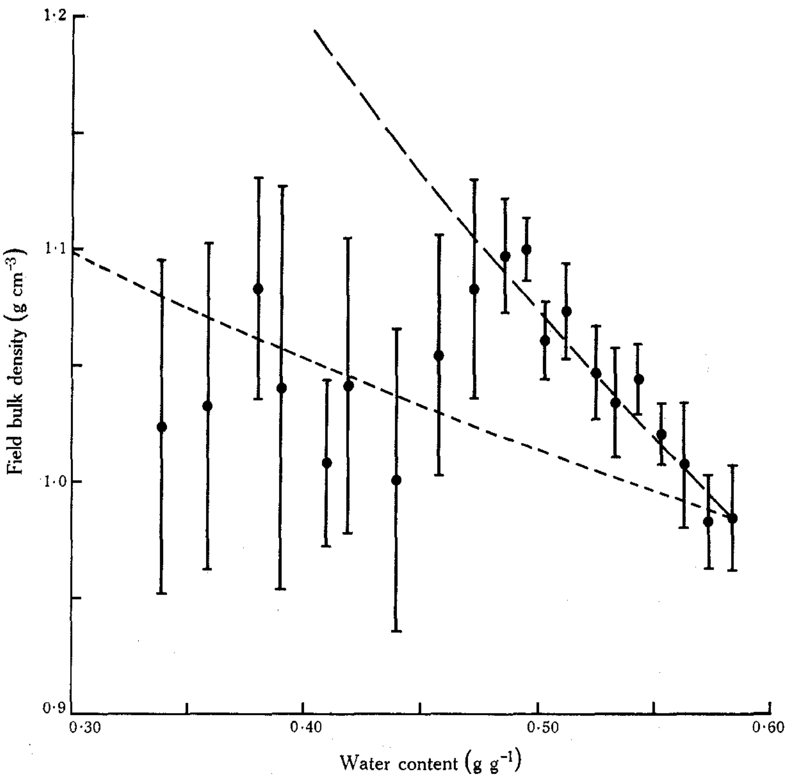

Fig. 5. Means and 95% confidence limits of field bulk density samples at different soil water contents. – – – Unidimensional normal shrinkage curve. - - - - - Three-dimensional normal shrinkage curve.

Discussion

Changes in volume of the unsupported cores during drying were approximately 95% of those expected from normal shrinkage (Fig. 1). The water content range sampled extends well below the minimum water content observed in field sampling (Fig. 5), or the $-1500\ \mathrm{J\ kg^{-1}}$ water content (Table 1). The nature of shrinkage observed conforms to that reported by Stirk (1954) and Holmes (1955) over similar water contents. The 5% departure from normal shrinkage in the unsupported cores can be attributed to either air entering voids, or cracks being formed within the cores on drying. As shrinkage was three-dimensional and equi-dimensional (Fig. 2), this air porosity must have been equally distributed, both horizontally and vertically. Small internal cracks, with no apparent preferred orientation, were observed in the dry cores and could explain this departure from normal shrinkage.

Shrinkage from the maximum water content reached by the suppported cores (Fig. 3) was also three-dimensional normal, but with a tendency to depart from the theoretical relationship between water contents of 0·53 and 0·58 g g^{-1}. A small amount of structural shrinkage may have occurred at high water contents, as reported by Stirk (1954). Irrespective of the reason for the 5% departure from normal shrinkage, or the occurrence of some structural shrinkage at high water contents, the errors involved in the use of the three-dimensional normal shrinkage theory would not be great.

Swelling of supported cores was approximately three-dimensional, but with some variation from the theoretical relationship in cores wet from low water contents (Fig. 3). The rapid reduction in bulk density on initial wetting cannot be attributed to unidimensional expansion, since vertical cracks were present around the cores at this stage. It may, however, be associated with the unconfined swelling and disruption of the core surfaces observed in experiment 2(*b*). The surface disruption could have resulted from the high swelling pressure on wetting at low water contents, combined with the absence of the field overburden pressure. This explanation is consistent with the higher maximum water contents in experiment 2(*b*), and the small reversible bulk density change at high water contents. Water content changes above $0\cdot53$ g g^{-1} could be largely associated with filling and draining of structural pores formed during unconfined swelling.

Laboratory experiments 1 and 2 have shown that volume changes in this soil are essentially three-dimensional and normal over mean water contents of $0\cdot23$–$0\cdot58$ g g^{-1}. This is in contrast to the field bulk density data (Fig. 5), which indicate unidimensional volume change over water contents of $0\cdot47$–$0\cdot58$ g g^{-1}. According to Fox (1964), the transition from three-dimensional to unidimensional volume change is dependent on the void ratio at zero water content. The void ratio of the cores in experiment 3 was artificially reduced by confining the shrunken samples in $10\cdot0$ cm tubes, thus increasing the bulk density. Wetting of these samples would theoretically produce three-dimensional swelling up to a water content of about $0\cdot36$ g g^{-1}, followed by unidimensional expansion to the maximum water content. This is basically what happened, as shown in Fig. 4. Comparing these results with those obtained in experiment 2(*b*), two surprising points emerge:

(1) The confined cores, swelling mostly unidimensionally, reached the same maximum water content as the supported cores, swelling three-dimensionally;

(2) shrinkage of the confined cores was three-dimensional, as for the supported cores.

For these results to have been obtained, surface areas available for water absorption and water film thicknesses on clay surfaces must have been equal in both confined and supported cores at the maximum water content. These conditions could have been achieved only if particle reorientation occurred in the confined cores. Swelling pressure in these cores at the onset of unidimensional expansion could have been approximately 1500 kPa (Table 1), since for normal expansion, swelling pressure should equal soil water potential. This could cause particle reorientation. There was visual evidence of reorientation in the confined cores, where resultant structure was platy or lenticular, in contrast to the blocky structure of the supported cores. This effect is shown, for individual aggregates, in Fig. 6.

In practice, field bulk density is measured only during the drying cycle (Fox 1964). The field data presented in Fig. 5 therefore indicate unidimensional shrinkage over water contents of $0\cdot58$–$0\cdot47$ g g^{-1}. This is in direct contrast to the laboratory results, where shrinkage was, without exception, three-dimensional. There are two possible explanations for these contradictory results, based on errors in the field data. Firstly, distortion of samples may occur using small-diameter core samplers (McIntyre 1974). If the field bulk density samples were compacted to a uniform air content, they would appear to fit the unidimensional shrinkage curve in Fig. 5, which is similar to the bulk density relationship of a soil–water system containing 5% air. Soil compaction to a constant air content above an optimum water content for compaction is shown by Inglis (1968, Fig. 1.10). Below this water content compaction is lower and the core samples may be representative of the field soil.

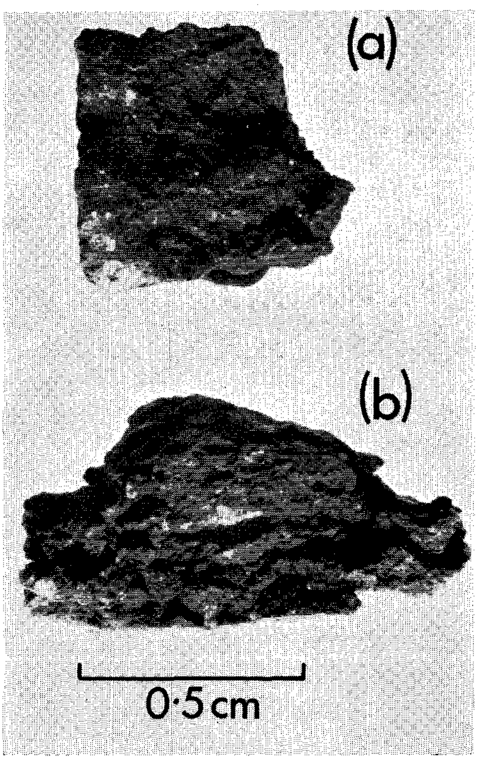

Fig. 6. Side elevation photograph of clods from (*a*) supported core showing blocky structure and (*b*) confined core showing lenticular structure.

Secondly, the unidimensional curve is essentially the bulk density relationship of a soil where volume change is normal, with no cracks occurring. These conditions apply to the soil matrix between field cracks. Thus if the soil matrix alone were sampled, the bulk density data obtained would fit the unidimensional relationship, yet would not be representative of the field soil. This could occur at high water contents where cracks are infrequent, and small core samplers have a high probability of sampling between cracks. As water content decreases, the frequency of soil cracks should increase, and the probability of sampling cracks consequently increases. At some stage it may be possible to representatively sample the field soil, including cracks, with a small core sampler. In Fig. 5, this could be the case at water contents below $0 \cdot 47$ g g^{-1}, where measured bulk density approximates the three-dimensional curve. As expected, bulk density variability is considerably greater at lower water contents.

Both explanations put more reliance on the field data at low water contents, which are consistent with three-dimensional volume change. We therefore suggest that the unidimensional results shown in Fig. 5 are a product of the sampling technique, and that the volume-change process in the field soil examined is essentially three-dimensional and normal. This is in agreement with the laboratory results, and the field volume changes of slightly less than three-dimensional normal reported by Aitchison and Holmes (1953) and Jamison and Thompson (1967).

Although field sampling inaccuracies may explain some unidimensional volume changes measured with small-diameter core samplers, they do not satisfactorily explain the results of Fox (1964). At no water content did his measured bulk densities approach those expected for three-dimensional contraction from the maximum water content. Either true unidimensional contraction was measured, or the sampling inaccuracies were not overcome at any water content. Further work with a range of soils is needed to clarify the situation and to determine a satisfactory technique for establishing the bulk density relationships of cracking clay soils.

Acknowledgments

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