Abstract

Preliminary results from a study of collapsible loess from Xi'an suggested that the material consisted of two types of structural units: crumbs, i.e. irregular aggregates less than 100 microns ‘diameter’; and larger aggregates sized 300 microns upwards. There appeared to be about 5 types of voids: (1) invisible intra-aggregate voids too small to be resolved in the electron microscope used; (2) small, mainly intra-aggregate voids; (3) relatively large voids in the larger aggregates; (4) inter-crumble packing voids; (5) relatively large irregular voids. Measuring the visible porosity allowed the invisible porosity to be calculated by subtraction from the total porosity. Few traces of biological activity have been recognised; suggesting that physical phenomena also operated. The observations raise the question of the relative importance of inter-crumble and intra-aggregate porosity in controlling the stability/collapsibility of the material.

Keywords: loess, collapsibility, soil structure, electron microscopy

1. Introduction

Collapsibility of soil can be defined as susceptibility to a large and sudden loss of volume when either water is added or the stress is increased. A high initial void ratio is necessary for the loss of volume to be large; and a high initial air-voids content is necessary otherwise slow consolidation results. It is also necessary that the structure of the soil should remain stable under the in situ conditions; so it has been suggested that the soil particles are cemented together, for example by: organic matter; clay; calcium carbonate; silica; iron hydroxides; or inter-particle welding. [1]

The idea that loess is an aeolian sediment has led to the idea that it is composed of air-blown silt particles stabilised in an open framework by bridges, buttresses, or coatings of cementitious material similar to the structure reported by Knight [2]; and this model seemed to be applicable to loess from Baotou [3]. However, loess from Lucheng was different [4]; and much of the Chinese loess has a high clay content: so other ideas are considered here.

This paper presents the preliminary results obtained using electron microscopy. The qualitative and quantitative results are reported separately below, followed by some discussion. The preparatory work is reported first.
Fig. 1. Sample 1; vertical section. (A) Back-scattered scanning electron micrograph.
(B) Segmented; pores are black. There are loosely packed small aggregates to top and left and part of an atypically large aggregate to right and bottom. Picture width 1.08 mm.
Fig. 2. Sample 2; vertical section. (A) Back-scattered scanning electron micrograph.
(B) Segmented; pores are black. Picture width 1.08 mm.
2. Preparatory work
Two sites were selected about 1 km apart in Xi'an City, Shaanxi Province, P.R. China. Undisturbed block samples were excavated by hand; and conventional geotechnical observations were made in accordance with the Chinese National Standards.

Table 1. Geotechnical data.

<table>
<thead>
<tr>
<th>Sample depth</th>
<th>Size*</th>
<th>$G_s$</th>
<th>$w_L$</th>
<th>$w_P$</th>
<th>$w$</th>
<th>$n$</th>
<th>$\delta_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>%</td>
<td>%</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>5.10</td>
<td>42</td>
<td>43</td>
<td>15</td>
<td>2.71</td>
<td>30</td>
<td>19 20</td>
</tr>
<tr>
<td>2</td>
<td>8.08</td>
<td>41</td>
<td>44</td>
<td>15</td>
<td>2.71</td>
<td>30</td>
<td>18 26</td>
</tr>
</tbody>
</table>

*Particle size, %: a >0.75 mm; b 0.75-0.05 mm; c <0.05 mm.

$G_s$ = unit weight of solids; $w_L, w_P$ = Atterberg Limits;

$w$ = natural water content; $n$ = porosity;

$\delta_s$ = Index of Collapsibility.

For the work presented here, one block sample was selected from each site. Sample 1 was from a shallower depth and more collapsible than was Sample 2, see Table 1. These samples were transported to Taiyuan University of Technology; air dried; and impregnated with Colophony. From each of these original samples, one horizontal and one vertical thin section and one horizontal and one vertical ‘polished’ cross-section were prepared for microscopy and transported to Glasgow University. The cross-sections were coated with carbon and examined in an FEM Quanta 2000 F scanning electron microscope. Supplementary observations were made using a Zeiss optical microscope.

Table 2. Quality control, number of micrographs.

<table>
<thead>
<tr>
<th>Class</th>
<th>Definition</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>At specified position</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>Near specified position</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>First area seen</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Additional micrographs</td>
<td>155</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>368</td>
</tr>
</tbody>
</table>

After some initial experiments, it was decided to take concentric sets of back-scattered electron micrographs at standard magnifications with a view to choosing the best magnification for future work. The magnifications used were from x55 up to the highest useful magnification, sometimes up to x2000; all magnifications quoted here and marked on the micrographs refer to the original display in the SEM. From the vertical cross-sections, 9 sets of micrographs were taken on a 3 x 3 grid; and 7 similarly arranged sets were taken from the horizontal cross-sections. (For future work, at least 25 sets per cross-section are recommended.) The grid spacing should have been 10 mm x 6 mm precisely; but adhering to this would have resulted in some of the high magnification images showing only void space; so adjustment to fill the field of view at high magnification was permitted. The resulting micrographs were placed in Class 1. Sometimes, further adjustment was required to avoid small patches of grit left from the grinding; if so, the micrographs were placed in Class 2. Additional micrographs were taken of the first area seen, Class 3, and to show interesting features, Class 4. These scores are in Table 2. The proportion of Class 2 images is as expected when establishing a new laboratory; and the proportion of Class 4 micrographs is as expected at the start of a new project: both these proportions should decrease as skill improves and experience with the material increases.
3. Qualitative observations

The scanning electron micrographs were re-examined at leisure using image analysis software written using the Salford FTN95 compiler in order to check and refine the observers’ notes. In general terms, the material was aggregated, being divided into:

1. crumbs, i.e. small irregular aggregates less than 100 microns across;
2. larger aggregates, greater than 300 microns across;

see Figs. 1 and 2. There were 5 sets of voids:

1. very small voids, invisible at x250, in both types of aggregate; the pixel size was 1.06 microns.
2. small pores, visible at x250, in both types of aggregate.
3. medium sized pores seeming to pass through the larger aggregates.
4. inter-aggregate pores between the crumbs: so that the structure could almost be said to be divided into loose and dense areas. The distinction between the loose and dense areas was clearer in Sample 1 than in Sample 2.
5. large pores disrupting the structure: these varied in their size; they varied from almost circular or almost square, to elongated, to long and irregular; and some had smooth boundaries whilst others had rough boundaries (at x250).

The small crumbs might have had a faunal origin; and the rounded voids might have had faunal or floral origins: but the relative importance of biological and of physical factors is yet to be established. (Occasionally, the micrographs suggested that the soil structure had been disturbed naturally, not during sampling; but this point remains open. Another point yet to be resolved is the relationship between the conventional particle size analysis and the microscopical observations.)

4. Quantitative observations

The scanning electron micrographs at x250 magnification showed the void structures clearly; so the Class 1, 2 and 3 images at this magnification were segmented to distinguish ‘visible voids’ from ‘pseudo-solids’: the pseudo-solids contain voids which are too thin to be seen. (Two micrographs showed patches of grinding grit overlying voids; so these were first corrected by hand.) Attempting to segment by eye took too long; and the result was subjective. Therefore, the histograms of grey levels were examined. Most showed two peaks, void and pseudo-solid, with a distinct inter-peak minimum; and, for these micrographs, segmentation was at this minimum. In difficult cases, reference was made to the sets taken immediately before and immediately after. For each sample, the ‘visible porosity’ was calculated from the numbers of pixels attributed to the visible pores; then the ‘inter-aggregate porosity, i.e. that of the pseudo-solids, was estimated by subtracting the visible porosity from the total porosity found conventionally.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total</th>
<th>Visible</th>
<th>Invisible</th>
<th>Air</th>
<th>Water</th>
<th>$\delta_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.543</td>
<td>0.340</td>
<td>0.203</td>
<td>0.292</td>
<td>0.251</td>
<td>0.207</td>
</tr>
<tr>
<td>2</td>
<td>0.523</td>
<td>0.195</td>
<td>0.328</td>
<td>0.175</td>
<td>0.348</td>
<td>0.021</td>
</tr>
</tbody>
</table>
The visible and invisible porosities are, respectively, estimates of the inter- and intra-aggregate porosities; because there were small pores in the aggregates, the intra-aggregate porosity is slightly higher than the invisible porosity. Thus, the aggregates in the more collapsible Sample 1 appear to have been denser, and presumably stronger, than those in the less collapsible Sample 2; and, conversely, there was more space between the aggregates in Sample 1. This suggests the hypothesis that, in these samples, during initial collapse of the structure, the small aggregates would not themselves deform but would slip over each other to pack more densely. Somewhat similar slippage of aggregates seems to have occurred during low-pressure consolidation of flocculated kaolin [5].

Table 3 also shows the air- and water-filled porosities calculated conventionally. The water-filled porosity is very little larger than the invisible porosity. On this basis, the inter-aggregate pores were air-filled; and the intra-aggregate pores were water-filled. This suggests the hypothesis that, under natural conditions, the surface tension of the water tended to stabilise the aggregates.

5. Conclusions
The structure of two samples of loess has been examined using back-scattered scanning electron microscopy. The void patterns were seen clearly; and analysis of these patterns suggested that, in these materials, collapsibility is associated with slipping of small aggregates of soil into relatively large inter-aggregate voids rather than with slipping of individual particles.

Acknowledgements
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References
[1] These remarks are based on a very voluminous literature.