Engineering properties of Lucheng Loess in Shanxi
山西潞城黄土的工程特性

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Abstract: The microstructure of a collapsible loess was found to be dominated by the activity of worms to a depth of 26 m. The material was divided into dense and loose areas. The loose areas contained silt-clay aggregates with large voids between them. The presence of large voids permitted collapse to occur. No significant cementation has been found so far, although some of the non-collapsible material contained red-materials. It is suggested that the parent material differs progressively up the profile.

Key words: loess; microstructure; collapsibility
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Biography: BAI Xiao-hong(1959-), female, professor of Department of Civil Engineering, Taiyuan University of Technology. Received her Ph.D. in Geotechnical Engineering from University of Glasgow, UK in 1992. Her research interests including microstructure and engineering properties of soil, soil improvement, and foundation engineering.

摘 要: 通过对山西潞城黄土的微观结构分析研究,得出黄土的微观结构由两部分组成:松散结构和密实结构。松散结构的骨架主要由粉粒构成,粘粒和其它细小颗粒赋着于大颗粒表面,起着胶结作用,结构内部和结构之间存在着较大的孔隙。大孔隙的存在是产生湿陷的必要条件。

关键词: 黄土; 微观结构; 湿陷性

1 Introduction*

The Chinese loess is an extensive and deep deposit, which is naturally partially saturated, and which when wetted tends to settle uncontrollably due to the collapse of its internal structure.

The basic problem was generally thought to be that the material, which is mainly of silt size, was of Aeolian origin and had settled in a dry climate, the particles forming an open framework. Various theories had been advanced to suggest that this open framework had then become cemented, so that it could resist the natural overburden pressures.

The immediate objective was to examine the microstructure and mineralogy of a series of samples taken from Lucheng, Shanxi with a view to providing guidance for an on-going program of research into remedial treatments[1,2]. Although the work reported here was a pilot study, the results so far appear to be of interest.

2 Sampling

A series of good quality block samples was made available to Taiyuan University of Technology from a industrial site in Lucheng, Shanxi. These samples had been taken from a stepped excavation to 26 m depth. Six air-dry sub-samples approximately 100 mm × 50 mm × 50 mm were forwarded to Glasgow University in United Kingdom for microscopical examination. And a second series of samples taken from same site was subsequently brought to Glasgow University for chemical and mineralogical analysis.

Conventional soil mechanics data for these samples was obtained by Taiyuan University of Technology, given in Table 1. In general, the upper soil was collapsible and the lower soil was not.

3 Visual description

The samples were examined under a stereomicroscope at up to but usually less than x63 magnification. In general, the color was a uniform buff, but the samples from the lower depths were slightly redder than those from the shallower depths. The soil appeared to consist mainly of aggregates of fine material up to say 0.3 mm diameter, these aggregates being packed loosely. Holes were seen, usually circular, generally up to 1 mm diameter say, but up to 2 mm diameter at depth 9 m. The material at depth 10 m was distinctive in that it had many white flakes (calcite), which were seen to be composed of small crystals. The material at depth 9m also contained white material, usually as linings to holes. Smaller amounts of white material were found in the lower samples. Due to the semi-disturbed condition of these samples, a fuller inspection could not be made.

Table 1 Data for first and second series of samples

Depth /m	G_N /(kg·m^{-3})	G_s	Pore Ratio	c /%	I_P	w /%	δ_s	w/c /%
4.0	1.44	2.70	1.19	10.9	102	16.4	0.0275	150.4
6.0	1.49	2.70	1.09	9.1	10.4	15.3	0.0291	168.1
7.0	1.52	2.70	1.09	19.3	10.3	19.9	0.0238	103.1
9.0*	1.74	2.70	0.85	25.6	11.0	18.6		72.7
10.0*	1.70	2.70	0.89	24.1	10.8	18.2		75.5
16.0*	1.80	2.71	0.82	24.9	13.3	20.7		83.1
18.0*	1.80	2.71	0.81	24.9	13.1	19.7		79.1
20.0	1.81	2.71	0.78	16.2	11.8	20.0	0.0036	123.5
22.0*	1.88	2.72	0.73	24.9	13.3	19.7		68.4
25.0	1.89	2.72	0.72	32.6	12.2	22.6	0.0038	69.3
26.0	1.96	2.72	0.70	28.3	12.4	22.7	0.0042	80.2

Notes: * - second series of samples; G_N - natural unit weight; G_s - specific gravity of solids; c - clay fraction (< 5μm); w - moisture content; δ_s - index of collapsibility.

4 Optical microscopy

Samples were impregnated using crystal resin after saturation with acetone using the vapor phase transfer

* Received date: 2001-09-23

method[3]. No vacuum was used. One horizontally oriented thin section was made from each of the impregnated samples. These thin sections were approximately 100 mm × 50 mm. Some small vertically oriented thin sections were also made from spare material after the other work had been completed.

All of the thin sections showed a very porous structure.

In general, the samples appeared to be divided into dense and loose areas. A tentative interpretation from the optical microscopy was that the dense areas had resulted from the activities of earthworms or of insect larvae, whilst the loose areas had resulted from the activities of enchytraeid worms. (Enchytreaid worms are active at depth 0–10 cm and are rarely found below 20 cm). Some of the holes had probably been formed by roots.

The three upper samples, at 4, 6, and 7 m depth, contained secondary calcite, presumably precipitated in situ. The biological activity and the precipitation of calcite appeared to have taken place simultaneously, so the structure of these samples seemed to have been formed at an original depth of 0.1 m, i.e. the material was a buried topsoil. Tentatively, the climate would have been wet enough for the worms, and dry enough not to wash the calcite out.

The lower samples, at 20 m and 25 m depth, contained prominent red-materials (i.e. coatings) around the fecal material (worm droppings); these materials are thought to be made of clay, possibly with some iron. This red-stained material is believed to have been deposited after translocation down the profile; and this type of deposition occurs typically at 1.0 m depth. Some black iron–manganese particles were seen, suggesting anaerobic conditions. Tentatively, the climate would have been slightly wetter than that for the upper samples.

The lowest sample, at 26 m depth, seemed to have been formed at an original depth of 0.5 m.

No evidence of frost action was found in any of these thin sections. However the present climate has a cold dry winter, most of the precipitation occurring during spring and summer, suggesting the possibility that the soil was too dry in winter for ice to disrupt the soil structure.

5 Scanning electron microscopy

Two subsamples were cut from each of the impregnated samples to explose one horizontal and one vertical face, respectively. These faces were ground flat, taking care to avoid smearing, and coated with carbon. The back-scattered mode was used, supplemented by X-ray micro-analysis in the SEM.

Before starting this study, it had been expected that the microstructure would fall into one of the three classes suggested by Knight[4], viz: arched silt grains, a few of which had weathered to form unstable clay aggregates; loosely-packed silt stabilized by small bridges of clay or cement; loosely-packed silt grains, all of which were coated with a thin layer of clay. However, the microstructure seen the scanning electron microscope was more complex.

Examination at low magnification in the scanning electron microscope confirmed the observations made in the optical microscope, viz: very porous structure; dense and loose areas; presumed root holes.

Fig. 1 was chosen to illustrate the activity of the enchytraeid worms. Near the top left hand corner, there is an elliptical void 1.3 mm long; and near the bottom there are almost circular voids 0.8 mm and 1.5 mm diameter, respectively. These are becoming filled with fecal material from the enchytraeid worms. Notice also the dense material in the top left of the figure.

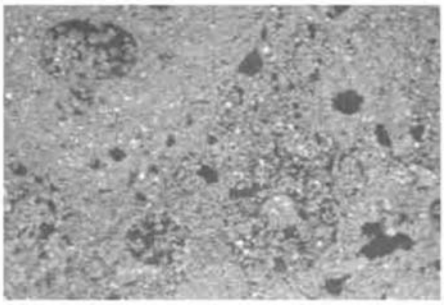

Fig. 1 Depth 7.1 m, vertical face, picture width= 6000 microns

In the dense areas, the silt particles were embedded in moderately compact clay. In the loose areas, the silt and clay combined to form aggregates, in which the silt grains again tended to be embedded in moderately compact clay, although in the uppermost samples there was more bare silt. Figures 2 and 3 illustrate loose areas from depths of 7 and 26 m, respectively. This arrangement is what would be expected of well-mixture well-blended soil; well-blended soil is defined as having just enough fine particles to fill the interstices between the coarse particles[5]. A well-blended mixture of silt and clay would require about 25% clay, which is in line with the quantities reported in Table 1. On this basis, a simple description of structure of the soil would be "a mixture of moderately dense well-blended soil aggregates together with additional large voids".

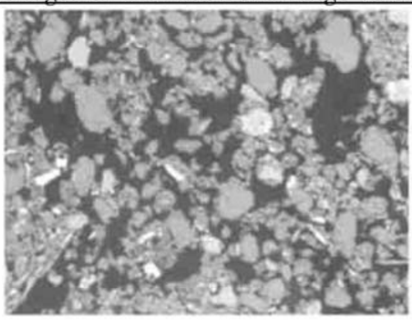

Fig. 2 Depth 7.1 horizontal face, picture width= 600 microns

Many of silt particles seemed to be fresh and un-weathered; but some seemed to be slightly to moderately weathered see the larger particles in Figures 4 and 5. The degree of weathering was possibly greater in the upper samples.

Calcite particles were found amongst both the clay and the silt fractions. Most of this calcite was thought to be of secondary origin, although a few rare calcite particles may have been of biological origin.

During the course of the scanning electron microscopy, the impression was formed that: (1) the size of the largest particle increased from bottom to top of the profile; and (2) the denseness of the packing of the clay increased from top to bottom see Figures 2, 3, 4, and 5. These points will be discussed later.

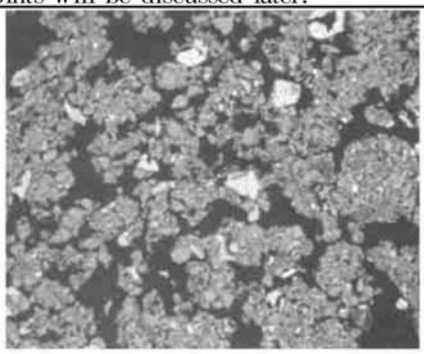

Fig. 3　Depth 26 m, vertical face, picture width= 1200 microns

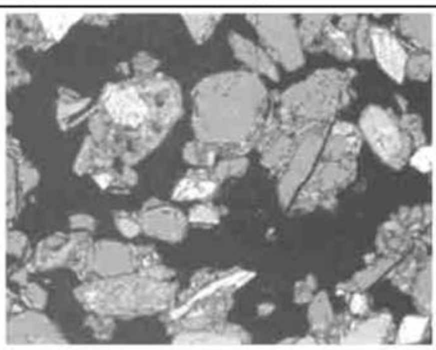

Fig. 4　Depth 4.3 m, horizontal face, picture width= 240 microns

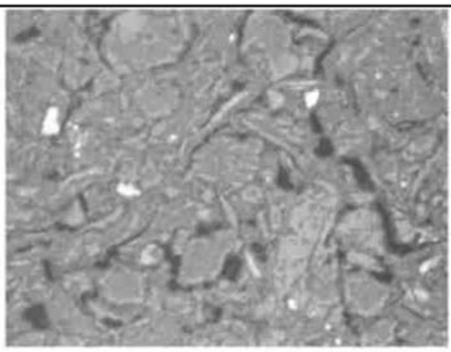

Fig. 5　Depth 26 m, horizontal face, picture width= 120 microns

6　X-ray diffraction

Table 2 shows the results of X-ray diffraction of semi - sedimentary samples of the whole soil under natural conditions, i. e. air-dry power. In addition, the < 20 micro fraction was separated by sieving and analyzed: air-dry; glycolated; after heating to 300 ℃; and after heating to 600 ℃.

Table 2　Mineralogical composition, XRD

Depth/ m	Quartz	Calcite	Feldspar	Clay
9	Mainly	Much	Some	Trace
10	Mainlv	Much	Some	Trace
16	Mainly	Some	Some	Trace
18	Mainly	Some	Some	Trace
22	Mainly	None	Some	Trace
White	Trace	Mainly	None	None

Note: White = white flakes at 10 m depth.

The samples contained mainly quartz, some feldspar, and traces of clay. The upper samples contained much calcite, but this decreased with depth and was apparently absent at 22 m depth. The clays were classified as chlorite (14.3A), and kaolinite (7.1 A). No swelling clay was found. Some of white flakes at 10 m depth were picked out and found to be predominately calcite with traces of quartz.

7　X-ray fluorescence

From X-ray fluorescence analyses, see Table 3, the major difference between the samples was that calcium and loss-on-ignition decreased with depth, some of the other elements then appearing to increase. These changes might have been due to a weathering process which removed the calcium and perhaps caused some of the iron to move down the profile. However, the clay content appears to increase with depth; and there was no indication from the microscopy of a general translocation of clay down the profile, that seen at 20 and 25 m depth being thought to be local. Nor were there indications from the microscopy of widespread weathering of the silt. It seems more likely, therefore, that the parent material changed progressively from being more clayey at the bottom to less clayey at the top. This hypothesis would also explain the suggestion that the size of the silt increased towards the top of the profile.

8　Moisture content and void ratio

As expected, the natural moisture content increased, and the void ratio decreased with depth, see Table 1.

Now, the microscopy had suggested that the soil consisted of three components: silt particles, which cannot hold water; aggregated clay, which readily hold water; and large voids, which might allow water to pass through readily. On this basis, all of the water held by the soil would be held within the aggregated clay. Therefore, a nominal moisture content, m_c, was calculated for the aggregated clay from:

$$m_c = w / c, \tag{1}$$

where w is the moisture content of the soil, and c is the clay content. The nominal moisture content of the clay appeared to decrease with depth, see Table 1. Taking probability, $P = 92.5\%$ as significant, regression analysis, see Fig. 6, suggested that this trend was significant despite wide scatter. If the nominal moisture content of the clay does decrease with depth, this would be consistent with the hypothesis that the soil is consolidating, some at least of the settlement being accommodated within the clay aggregates; and this would be consistent with the suggestion from scanning electron microscopy that the denseness of the packing of the clay increased from top to bottom.

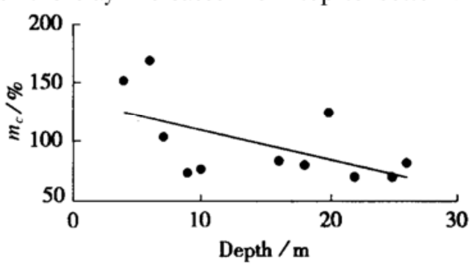

Fig. 6　The nominal moisture content- depth relations

Table 3 Chemical composition, XRF %

Depth/m	SiO_2	Al_2O_3	MnO	MgO	K_2O	Na_2O	CaO	TiO_2	P_2O_5	LOI
9	50.90	11.49	4.48	0.078	1.964	0.95	13.57	0.592	0.107	13.58
10	58.26	13.29	5.22	0.091	2.352	1.30	7.17	0.690	0.088	8.87
16	62.96	14.96	5.88	0.104	2.738	1.04	2.78	0.761	0.107	5.81
18	62.37	14.50	5.71	0.106	2.662	1.07	3.67	0.748	0.117	6.31
22	64.32	16.04	6.42	0.114	2.963	0.91	0.89	0.809	0.086	4.70

Two alternative hypothesis should be considered. (1) the clay was blown in in the form of aggregates, and those which arrived in the earlier period and now at the bottom of the deposit were originally denser than those which arrived later. (2) The climate was wetter when the lower material was deposited than later, so that the earlier material to be deposited formed plastic aggregates, whereas the later material broke down into dust. However, the optical microscopy suggests that almost all of the material had been processed by at least one worm. On this basis, the initial state of the clay would have been effectively as left by worms, and this was presumably the same from top to bottom of the profile. This in turn favors the hypothesis of consolidation.

9 Collapsibility

Four factors, which might affect the collapsibility of the soil, are: organic cements; inorganic cements; moisture tension; void ratio.

On the basis that almost all of the material had been processed by at least one warm, it seems probable that organic cements were present. These cements would be invisible in most optical and electron microscopy; and the simpler methods of measuring organic cement would be invalidated by the large amounts of calcite present. Presumably, the amount of organic material is small, and it is only a weak cement; on which basis, this factor is perhaps not a major one.

Samples at 20 and 25 m depth appeared to be cemented by the red material. Otherwise, no organic cements were found; but so much clay was present, that clay particle would have had to be cemented to clay particle. The size of the probe during X-ray microanalysis in the SEM was about 1 micron diameter; but the size of cementitous bonds between clay particles would be much smaller. Thus, this point could not be resolved directly. Although much of the calcium was found to occur in discrete calcite particles, it is possible that some of the silt-clay aggregates were cemented by calcium carbonate. On the other hand, Feda[6] suggested that calcium carbonate must be present for collapsibility.

Since the soil is partially saturated, the silt-clay aggregates will be subjected to high pre-moisture tension, which will tend to stabilize them until excess moisture is supplied, when this stabilization will be lost, and collapse will occur. However, if the soil structure is only just stable under the present pore-moisture tension and over-burden pressure, then, by implication, either: (1) the moisture content has never been higher than present; or (2) the over-burden pressure has decreased; or (3) some cementitious material has been lost. The first two possibilities seem unlikely. Three hypotheses arise concerning the third: (a) organic cements have decayed; (b) cementitious calcium has moved into the calcite crystals (and possibly been translocated up the profile as the soil has dried); (c) the cation exchange complex of the clay has been altered.

A high void ratio, e, is a prerequisite for collapsibility, because the particles must have room to move. for example, Feda[6] suggested that the porosity should be greater than 40% for collapsibility. This is equivalent to a void ratio of 0.67. All of the soils here had high void ratio; but the non-collapsible soils at the bottom of the profile had $e > 0.67$, suggesting that for the present material a higher limit, perhaps as high as $e = 1$, is necessary for the soil to be collapsible.

10 Conclusions

In the upper samples, many of the voids were sufficiently large to permit the silt-clay aggregates to move; so, to a certain extent, the question of whether these aggregates are cemented is immaterial. Also there were fewer silt-clay aggregates in the upper samples. The combination of these two factors, large voids and few aggregates, appears to be the controlling mechanism of collapsibility.

The lack of collapsibility lower in the profile appears to result from: the lower void ratio; the higher clay content, which leads to plasticity; and in some of the samples, cementation by the red materials.

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