1 INTRODUCTION

After heavy rains, extensive structural damage on buildings has occurred. Up to 10 cm settlements in buildings are the results of the water content plasticity of this kind of loess soil. These incidents, as well as similar problems during the building of the high speed railway in West China, show us the necessity of an extensive research program in this field of geotechnical engineering.

Up to now, a lot of research about loess soils and their settlement behaviour have been done by different scientists (Derbyshire 1995). But often chemical aspects are a bit neglected.

To get more knowledge about the settlement behaviour of loess soils, the research program is divided into three parts.

The first part is to understand the collapse behaviour under static loads. For this, modified compression tests were performed according to the Chinese standard GBJ 123-88. Particular attention was paid to changes in microstructure, because of loading and watering.

In a second step, which is also the second part of this study, the chemical properties were covered. Especially the chalk and salt content and its influence on the water dependent susceptibility to collapse were analyzed.

The third step is the research of collapse behaviour under dynamic loads, with the objective of developing a new estimation method for earthquakes.

Up to now the first two steps of the study have been done and the results can be presented.

2 LABORATORY TESTING

To improve the understanding of the complex mechanical properties of this kind of soil, initial laboratory tests (index tests) were carried out. These tests are necessary to get an impression of the particle density of the soil, the bulk density of soil, the natural water content, grain size, liquid and plastic limit. To get the optimum water content with the associated density, compaction tests were made. The knowledge about the optimum water content bears relevance to the collapse behaviour under static, as well as under dynamic loads.

2.1 Index tests

The density $\rho$ of soil particles of the loess soils from the three trial pits were determined according to Germany Standard DIN 18124. The test results are listed in Table 1 (MP = point of measuring and taking samples). The average value of the particle density is $\rho_p = 2.72$ g/cm$^3$, which is the typical value of clay containing silt. The natural water content $w$ of the samples was measured in laboratory. The values of natural water content are listed in Table 1 as well. The average value of the natural water content $w$ decreased with increasing depth. The average value of the natural water content $w = 4.77 \%$, which is a typical value of loess soils in dry areas. The bulk densities $\rho$ of the undisturbed soil samples with natural water content were measured in laboratory. The dry densities $\rho_d$ of the soil samples are calculated by bulk density $\rho$ and natural water content $w$. Their values are listed in Table 1. The dry density with the average value of $\rho_d = 1.46$ g/cm$^3$ is relatively low. The
calculated values of void ratio ε of the most samples are higher than 0.8, which is relatively high for silts. The calculated degree of saturation S, ranges between 10% and 30%. The liquid limit wL and plastic limit wP of the loess soils were determined in the laboratory according to Germany Standard DIN 18122. The liquid limit wL ranges between 26% and 28%, the plastic limit wP between 13% and 19%, thus the plasticity index Ip ranges between 8% and 14%. With the measured natural water content w, liquid limit wL and plastic limit wP the consistency index IC was calculated. According to Germany Standard DIN EN 14688-2 the loess soils are in a “very stiff” state. The grain size distribution fractions of the loess soils were determined according to Germany Standard DIN 18123. The optimum water content wopt, and maximum dry density ρdmax of the loess soils are given in Table 2. The range for water content for the degree of compaction Dc > 95%, obtained from the compaction curves is relatively large.

### Table 1. Optimum water content w_{\text{opt}} and maximum dry density ρ_{\text{dmax}}

<table>
<thead>
<tr>
<th></th>
<th>MP1</th>
<th>MP2</th>
<th>MP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>density of soil grain ρ_s [g/cm³]</td>
<td>2.73</td>
<td>2.72</td>
<td>2.71</td>
</tr>
<tr>
<td>water content w [%]</td>
<td>5.00</td>
<td>8.13</td>
<td>4.41</td>
</tr>
<tr>
<td>wet density ρ [g/cm³]</td>
<td>1.59</td>
<td>1.56</td>
<td>1.47</td>
</tr>
<tr>
<td>dry density ρ_d [g/cm³]</td>
<td>1.51</td>
<td>1.45</td>
<td>1.41</td>
</tr>
<tr>
<td>void ratio ε [-]</td>
<td>0.80</td>
<td>0.88</td>
<td>0.94</td>
</tr>
<tr>
<td>degree of saturation S [%]</td>
<td>17.93</td>
<td>22.95</td>
<td>11.50</td>
</tr>
<tr>
<td>liquid limit wL [%]</td>
<td>27.30</td>
<td>26.20</td>
<td>27.00</td>
</tr>
<tr>
<td>plastic limit wP [%]</td>
<td>13.50</td>
<td>14.50</td>
<td>18.20</td>
</tr>
<tr>
<td>plasticity index Ip [%]</td>
<td>13.80</td>
<td>11.70</td>
<td>8.80</td>
</tr>
<tr>
<td>consistency index IC [-]</td>
<td>1.63</td>
<td>1.43</td>
<td>2.55</td>
</tr>
<tr>
<td>grain fractions: sand [%]</td>
<td>16.50</td>
<td>70.00</td>
<td>13.50</td>
</tr>
<tr>
<td>silt [%]</td>
<td>25.00</td>
<td>56.00</td>
<td>19.00</td>
</tr>
<tr>
<td>clay [%]</td>
<td>17.00</td>
<td>69.00</td>
<td>14.00</td>
</tr>
</tbody>
</table>

*average values of 3-sample-testing  
**average values of 2-sample-testing

### Table 2. Optimum water content w_{\text{opt}} and maximum dry density ρ_{\text{dmax}}

<table>
<thead>
<tr>
<th></th>
<th>MP1</th>
<th>MP2</th>
<th>MP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>w_{\text{opt}} [%]</td>
<td>13.7</td>
<td>14.0</td>
<td>16.2</td>
</tr>
<tr>
<td>ρ_{\text{dmax}} [g/cm³]</td>
<td>1.90</td>
<td>1.86</td>
<td>1.79</td>
</tr>
</tbody>
</table>

Ranges of water content for Dc > 95%: 10 – 18 10 – 18 12 – 20

### 3 COLLAPSE UNDER STATIC LOAD AND CHANGES IN MICROSTRUCTURE

Modified compression tests, so called collapse tests, were carried out, to identify the compaction behaviour as a function of changes in moisture content and load level.

To get an impression of what had happened to the microstructure of the soil, microscope pictures have been made before and after the collapse.

#### 3.1 Collapse tests

In order to study the sensitivity of the loess soils in Mazar-e-Sharif to water, so called collapse tests were performed in laboratory according to Chinese Standard GBJ 123-88. For the tests, undisturbed loess samples with natural water content were compressed at first in an oedometer under different vertical pressures P. Then the samples were watered, and at the same time the vertical deformations of the samples were measured (Lutenberger, A.J. & Hallberg G.R. 1988). After watering the saturated samples were further compressed with increasing load (150, 200, 400, 800 kN/m²). The relative deformations of the samples before, during and after the watering in relation to the vertical pressures P were noted. Figure 1 shows the relative deformations εc (collapse deformation) during the watering in relation to the vertical pressure P for three different samples (MP1, MP2 and MP3). The collapse deformations εc increase with increasing vertical pressure P. The collapse deformations εc of the samples MP1, MP2 and MP3 for p = 160 kN/m² are larger than 7%. Thus, the loess soils belong to “highly collapsible loess soils” according to the Chinese Standard. The in-situ overburden pressure of the samples is p = 16.0 kN/m² approximately. The collapse deformation εc of the sample MP3 for p = 16.0 kN/m² is smaller than 1.5%, thus the sample is “not collapsible loess under overburden pressure” according to the Chinese Standard. Because the collapse deformation εc of the samples MP1 and MP2 for p = 16 kN/m² is larger than 1.5%, the two samples belong to “collapsible loess under overburden pressure” (Boley & Zou 2007).

![Figure 1. Collapse deformation of loess samples](image-url)
3.2 Microstructure

The microstructure of the loess soils was observed under the microscope. The observed changes in structure are evidence of the collapse settlement.

Figures 2 show the honeycomb structure of the loess soil before the collapse in the modified oedometer-test.

Figure 2. Loess sample before collapse; 100x magnification

Figure 2 shows a typical loess soil, which is characterized by an open structure with large pores. Bonding forces, which are responsible for the strength of the structure, are more mechanically than chemically founded (B. M. Schulz 2008).

After watering the sample under a defined load, the microstructure of the soil changed into a clearly denser system (Figure 3).

Figure 3. Same loess sample after collapse; 100x magnification

As can be seen in Figure 3, the poresystem of the loess has changed. Pores become smaller and the structure of the grains becomes more compressed.

At the beginning of the study, it was assumed that the main reason for the collapse is the dissolving of salt and lime (Figure 4) bounds by the added water.

Figure 4. Loess with high salt and lime contents, 2000x magnification

To confirm or confute the theory, that the solution of salt and lime is responsible for the collapse deformation, further research was necessary.

4 CHEMICAL ANALYSES

In order to study the binding effects between silt grains the lime contents $V_{Ca}$ of the loess soils were determined by laboratory tests according to Germany Standard DIN 18129. The lime contents $V_{Ca}$ in the loess soils are listed in Table 3. Their values are above 23%, which is very high.

Table 3. Lime Content V<sub>Ca</sub>

<table>
<thead>
<tr>
<th></th>
<th>MP1*</th>
<th>MP2**</th>
<th>MP3*</th>
</tr>
</thead>
<tbody>
<tr>
<td>lime content $V_{Ca}$ [%]</td>
<td>23.90</td>
<td>24.70</td>
<td>34.60</td>
</tr>
</tbody>
</table>

*average values of 3-sample-testing

**average values of 2-sample-testing

Table 3 is based on an analyses, which measured the gassing. This gassing is the result of a chemical reaction between hydrochloric acid and lime. As it is known, lime is not the only soil component which reacts with hydrochloric acid. So it was necessary to confirm the reliability of the results (Table 3) on the basis of a second independent method. For this the content of carbon dioxide was determined. Afterwards carbonate content was calculated with the help of molar masses.

\[
\begin{align*}
V_{CO_2} &= MC + 2 \times MO \\
&= 12.0107 \text{ g/mol} + 2 \times 15.9994 \text{ g/mol} \\
&= 44.0095 \text{ g/mol} \\
V_{CO_3} &= MC + 3 \times M \\
&= 12.0107 \text{ g/mol} + 3 \times 15.9994 \text{ g/mol} \\
&= 60.0089 \text{ g/mol} \\
\frac{V_{CO_3}}{V_{CO_2}} &= \frac{60.0089 \text{ g/mol}}{44.0095 \text{ g/mol}} \\
&= 1.36354 \\
\end{align*}
\]

From this follows:

\[
V_{CO_3} = 1.36354 \times V_{CO_2} \\
(4)
\]

With a determined $V_{CO_2}$ content of about 22.2%, the content of carbonate $V_{CO_3}$ comes to 30.27%, which confirms the results from the gassing test.

To figure out, if it is really lime ($CaCO_3$), comprehensive ion exclusion was necessary. Eluates were mixed for 24 hours and the negative and the positive ions were determined. Table 4 shows the results of the ion exclusion.

Table 4. Results of the ion exclusion

<table>
<thead>
<tr>
<th>Kations</th>
<th>mg/Kg</th>
<th>Anions</th>
<th>mg/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>1391</td>
<td>Cl</td>
<td>407</td>
</tr>
<tr>
<td>Mg</td>
<td>195</td>
<td>F</td>
<td>13</td>
</tr>
<tr>
<td>Na</td>
<td>644</td>
<td>NO$_2$</td>
<td>27</td>
</tr>
<tr>
<td>Al</td>
<td>6</td>
<td>SO$_4^{2-}$</td>
<td>3778</td>
</tr>
<tr>
<td>Fe</td>
<td>3</td>
<td>PO$_4^{3-}$</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td>51</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from the results, calcium (Ca) is the dominating kation. Because of the method, it was not possible to measure carbonate. Consequently sulfate (SO$_4^{2-}$) is the dominating anion but its content does not exceed the carbonate content. The result shows, that the salt content is not insignificant.
If the contained salt is easily water soluble, it would make a  
contribution to the collapse settlement, as it is common  
accepted. But to find out, how big the fraction of easily water  
soluble salt, minerals and other compounds is more research  
was necessary.

X-ray diffractometrical analysis was selected to get a  
detailed mineral disintegration of the loess soil. Afterwards the  
soil was dissolved in water (eluate) and X-ray diffractometrical  
analysis was made again. So it was possible to compare the  
results from the solid matter analysis with the eluate analysis to  
find out, if the salt fraction is easily soluble.

![X-ray diffractometrical analysis of loess](8110)

As can be seen in Figure 5, quartz crystal (Q) and calcite (C)  
are the dominating fractions. The sum of carbonate  
(predominantly calcite and dolomite) is about 37%. Other  
fractions are quartz crystal (16%), feldspar (16%). The sum of  
clay minerals, predominantly illite, muscovite, kaolinite and  
chlorite, is about 15%.

The result of solubility testing demonstrated, that just 2.1  
weight per cent of this kind of loess soil is easily water soluble  
minerals.

5 CONCLUSIONS

From the above test results the following mechanical properties  
of the loess soils have been deduced:

- The natural water content with the average value $w =  
 4.77\%$ of the loess soils is relatively low. The dry  
density with the average value $\rho_d = 1.46 \text{ g/cm}^3$ of the  
loess soils is relatively low. The void ratio with the  
average value $e = 0.87$ is relatively large. The salt and  
lime contents with the average value $V_{ca} = 24.3$ is very  
high.

- Most of the grains in the loess soils are silt grains with  
sizes between 0.002 and 0.06mm. In the natural state  
the consistency index $I_s$ is higher than 1. Thus, the loess  
soils with natural water content are in the semisolid  
state.

- The strength of the loess soils in their natural state with  
the friction angle $\phi = 29.5^\circ$, the cohesion $c = 100.6$  
kN/m$^2$ and the average blow count of 20 is very high.  
After watering but without consolidation (collapse)  
the blow count is very low, thus, the strength is very  
low. After watering and consolidation the strength of the  
loess soils with the friction angle $\phi' = 34.9^\circ$,  
although the cohesion $c' = 0$, is also relatively high  
for silts.

- After watering and under certain pressure (i.e.  
150kN/m$^2$) the deformations (collapse) of the loess  
soils were very large. According to the Chinese  
Standard GBJ 123-88 the loess soils belong to "highly  
collapsible loess soils" and they can be considered as  
"collapsible loess under overburden pressure".

- The deformation modulus $E_d$ of the loess soils with  
natural water content ranges between 20 and 42  
kN/m$^2$. The values of the modulus $E_d$ of  
compressibility average 7000kN/m$^2$ for the pressure  
interval between 25 and 200 kN/m$^2$. The values are  
not low for silts.

The unexpected result, that solely 2.1 weight per cent are easily  
water soluble, lead to the possibility that the collapse effect is based upon the dissolving of salt and lime bonding forces.

For further research, especially collapse under dynamic load,  
also mechanical and not chemical bonding forces will be  
considered.

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