AGH Journal of Mining and Geoengineering • Vol. 36 • No. 2 • 2012

*Dariusz Łydżba *, Matylda Tankiewicz **

# PRELIMINARY STUDY OF FAILURE ANISOTROPY CHARACTERIZATION OF VARVED CLAY

## 1. Introduction

Sedimentary soils and rocks are very often characterized as materials with a so-called layered microstructure, i.e. two or more constituents form a fabric of periodically repeating layers. This specific pattern is an effect of the decomposition and sedimentation in different, but periodically repeating conditions during diagenesis process. Soil called varved clay is a special class of such materials. This soil was formed in glacial lakes and is composed of two layers arranged in a periodic manner. The macroscopic effect of the layered microstructure is a strong anisotropy in both an elastic and inelastic range. Particularly, the two main mechanisms of the failure of the laminated microstructure can be distinguished, i.e.: a localized shearing on the “weakness plane” or the destruction of the entire structure by a failure of all constituents. From an engineering point of view, identification of an adequate anisotropic strength criterion for sedimentary rocks is an especially important problem [2, 5].

This work presents the preliminary results of the strength anisotropy of varved clay. The paper is organized as follows. In Section 2 the physical properties of the soil investigated are discussed. Next, the results of the directional failure characteristics of the varved clay considered are presented. These results have been obtained at three different values of confinement, i.e. at 0 kPa, 50 kPa and 200 kPa. The failure pattern corresponding to different angles of bedding planes orientation with respect to loading direction are discussed in the Section 4. Final remarks end the paper.

## 2. Physical properties of varved clay

Varved clay is a soil, formed in glacial lakes and composed from two layers — dark and light — sedimented alternately. Light varves consist mainly of coarser particles (sand

* Wrocław University of Technology, Faculty of Civil Engineering, Wrocław

and silt) deposited in warmer periods of time, when the glacier was melting, and dark layers consist of fine particles (silt and clay) deposited in colder periods when the lake surface was frozen. The thickness and the texture of varves depend on various sedimentary conditions such as temperature variation or location of the glacial lake relative to the glacier head.

The results of the laboratory tests presented in this paper have been conducted on the varved clay deposited near the city of Bełchatów in Poland. The samples have been taken from an open-cast mine named KWB Bełchatów, in the Szczerców field. The distribution of ice-marginal deposits and its texture are very irregular in this area and they are located mainly in the southwestern and northeastern part of the outcrop. The maximum thickness of the sediments are around 30 m and they are located horizontally or at a slight angle up to 20º. A major part of the sediments are silts and the deposits of varved clay which have a lower thickness. The investigated material (Fig. 1) is composed of dark varves with thickness up to 1cm and very thin light layers. All of the samples of varved clay have been taken from one spot located in southwestern corner of the open cast.

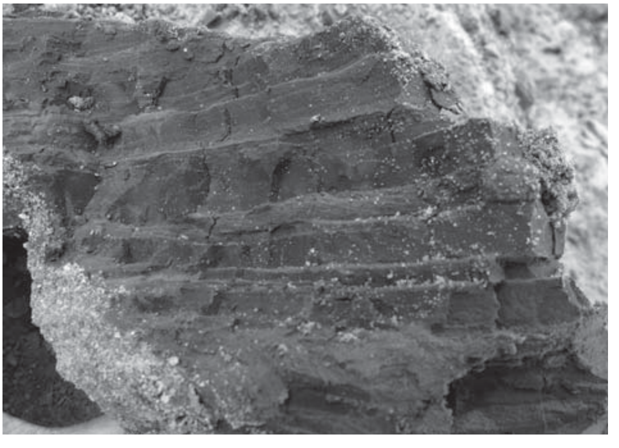

**Fig. 1.** Lamination in the varved clay

The physical properties such as: particle size distribution, particle density, bulk density, moisture content, liquid limit, plastic limit, plasticity index and organic matter content were first estimated for representative samples of varved clay. Next, the properties of constituents have been examined in additions. Because of the very low thickness of the layers the particle size distribution and particle density have been measured only. The whole investigation has been conducted according to the polish standard PN-B-04481:1988 [6] and PN-EN ISO 14688-1,2:2006 [7].

The soil texture and its variation have been estimated by conducting 3 tests for each varve and the composed soil as well. The particle density, particle size distributions and the type of soil for each component are presented in table 1. The dark varve consists of clay and silt particles, but the proportion of the constituents are variable. The light varve consists mainly of coarser particles, but it could be more sandy or more silty. A high amount of clay is probably caused by small thicknesses of layers and difficulties with sample preparation.

The particle size distribution of the varved clay depends, in general, on the composition of each varve and contents of it in the soil.

TABLE 1
**The texture of varved clay**

| **Type** | **Specific density [Mg/m$^3$]** | **Sand 2–0,063 mm [%]** | **Silt 0,063–0,002 mm [%]** | **Clay < 0,002 mm [%]** | **Type of soil** |
|---|---|---|---|---|---|
| Varved clay | 2,72 | 2,4–3,6 | 53,2–67,7 | 28,7–44,4 | Cl/siCl |
| Light varve | 2,67 | 5,7–22,9 | 52,5–71,8 | 18,7–24,6 | siCl/sasiCl |
| Dark varve | 2,70 | 0,2–0,4 | 36,5–51,2 | 48,6–63,1 | Cl |

The other examined the physical properties are presented in table 2. The liquid limit, plastic limit and organic matter content have been estimated in a few tests and the bulk density, moisture content and consistency index have been examined in each triaxial and unconfined compression test. As it is presented in table 2 these properties are almost constant, their small variations are probably caused by the variable texture of soil.

TABLE 2
**Physical properties of the varved clay**

| **Property** | **Bulk density [Mg/m$^3$]** | **Moisture content [%]** | **Liquid limit [%]** | **Plastic limit [%]** | **Plasticity index [%]** | **Consistency index [-]** | **Organic matter content [%]** |
|---|---|---|---|---|---|---|---|
| Range | 1,95–2,04 | 21,0–26,6 | 44,7–48,8 | 17,7–19,8 | 24,9–31,1 | 0,73–0,93 | 2,34–6,01 |
| Mean value | 1,99 | 23,7 | 46,5 | 19,1 | 27,4 | 0,83 | 4,35 |

## 3. Directional failure characteristics

The mechanical behavior of the varved clay has been investigated by conducting a series of unconfined compression and triaxial tests. All of the examinations have been carried out using the triaxial system of ELE International Company, which have been also adapted for the unconfined compression test. The cylindrical samples used in the test have been prepared by cutting cores at various orientations of the bedding plane, namely: $\alpha$ = 0°, 15°, 30°, 45°, 60°, 75°, 90°. Their dimensions were 38 mm in diameter and 76 mm in length of the specimens. Figure 2 presents the cross-section of a typical sample and illustrates the definition of orientation angle $\alpha$, $\sigma_2 = \sigma_3$ is the confining pressure and $(\sigma_1 – \sigma_3)$ is the applied deviatoric load.

The unconfined compression tests have been conducted on over 15 samples with different orientations of bedding planes. The results obtained are presented in figure 3 in which the unconfined compressive strength is plotted versus the angle of bedding planes orientation. The results clearly show that the strength of the varved clay is very variable, the maximum strength is about 73,2 kPa when the minimum is about 5,4 kPa, which is almost 14 times

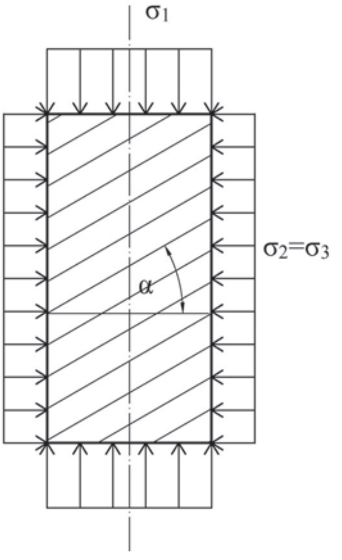


**Fig. 2.** Cross-section of a sample during testing

lower. Furthermore, any trend function can’t be established for the dependence between the strength of soil and the orientation angle.

The triaxial tests have been conducted in 2 different series for confining pressure at 50 kPa and 200 kPa. The procedure which has been used is called the consolidated undrained test and it has been conducted on samples with natural moisture content. The results of the tests are presented in figure 4 as a dependence of the failure stress on the angle of bedding planes orientation. For the confining pressure at 50 kPa maximum failure stress is about

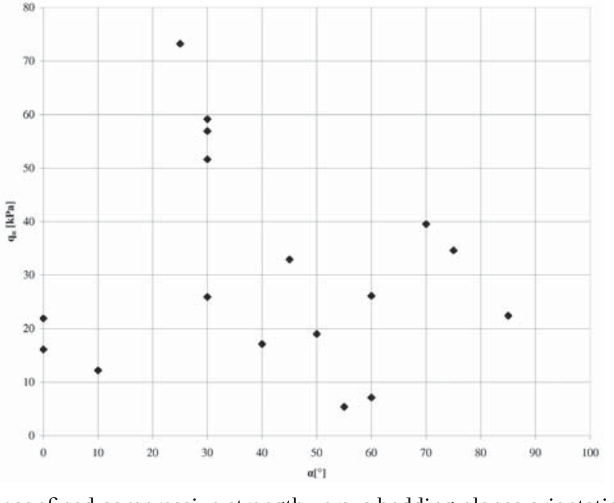


**Fig. 3.** Unconfined compressive strength versus bedding planes orientation angle

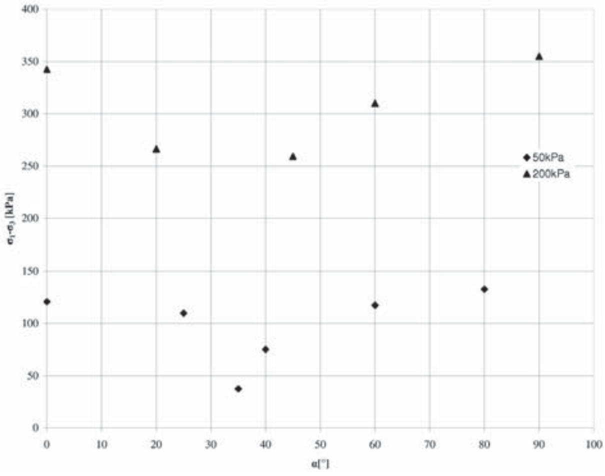


**Fig. 4.** Failure stress versus bedding planes orientation angle for confining pressure at 50 kPa and 200 kPa

132.7 kPa and corresponds to $\alpha$ = 80° whereas the minimum value of 37.4 kPa is associated with $\alpha$ = 35°. For the confining pressure at 200 kPa the failure stress is much higher and the maximum value is 355 kPa whereas the minimum is about 259.3 kPa.

## 4. Failure mechanism

The laboratory examinations were carried out with special attention to failure mechanism identification. Each sample of the varved clay has been described and photographed after besting. A strong dependence between the failure mechanism and the bedding planes orientation has been observed. For different orientation of lamination the different failure mechanism occurs, which is mainly the cause of variable strength of soil.

Figure 5 presents the typical failure mechanisms observed in tested samples for specific values of bedding planes orientations. For the orientation $\alpha$ = 0° (first from the left), which means that the layers are situated horizontally, the whole sample is cracked and the failure takes place across the lamination. For the orientation $\alpha$ = 45° the failure mechanism is associated with a localized failure in the bedding planes — slip on the light varve occurs, which is strongly visible in the middle sample. For the orientation $\alpha$ = 90° the sample is split out by one failure surface, which is nearly vertical. For all other orientations the failure mechanism is a combination of these simple failure modes. Such failure modes are also typical for any other sedimentary soils and rocks with layered microstructure [1, 3, 4].

## 5. Summary

In this paper the directional strength characteristic of the varved clay from the Bełchatów region has been presented. These characteristics have been estimated based on the

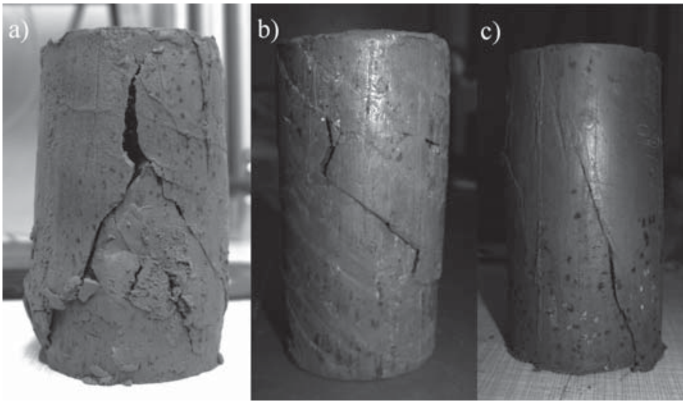

**Fig. 5.** Typically failures modes in samples tested at
a) $\alpha = 0°$, b) $\alpha = 45°$ and c) $\alpha = 90°$

results of laboratory tests conducted on samples with different bedding plane orientations. The results obtained, particularly for the uniaxial strength characteristic, are characterized by a quite large scatter, which is brought about mainly by difficulties with the sample preparation process. It has to be noted that one-third of all prepared samples were useless due to the destruction of their original microstructure. Because of this the results have to be interpreted as the preliminary ones.

The examinations will be continued in order to estimate, with greater confidence the dependence between the strength of varved clay and the orientation of microstructure. The results will be used for identifying a number of anisotropic failure criterion and finally evaluating its utility in this type of soil.

REFERENCES


[1] Duveau G., Shao J.F., Henry J.P.: *Assessment of Some Failure Criteria for Strongly Anisotropic Geomaterials.* Mech. of Cohes.-Frict. Mater., Vol. 3, 1998, p. 1–26.

[2] Duveau G., Shao J.F., Henry J.P.: *Assessment of Some Failure Criteria for Strongly Anisotropic Rocks.* Int. J. Numer. Anal. Meth. Geomech., Vol. 1, 1997, p. 1–26.

[3] Jaeger J.C.: *Shear Failure of Anisotropic Rocks.* Geol. Mag., Vol. 27, 1960, p. 65–72.

[4] Lydzba D., Pietruszak S., Shao J.F.: *On Anisotropy of Stratified Rocks: Homogenization and Fabric Tensor Approach*. Comput. Geotech., Vol. 30, 2003, p. 289–302.

[5] Pietruszczak S., Lydzba D., Shao J.F.: *Modelling of Inherent Anisotropy in Sedimentary Rocks*. Int. J. Solids Struct., Vol. 39, 2002, p. 637–648.

[6] PN-B-04481:1988: *Building Soils. Laboratory Testing.*

[7] PN-EN ISO 14688-1,2:2006: *Geotechnical Investigation and Testing. Identification and Classification of Soil.*