THE INFLUENCE OF POROSITY ON GEOMECHANICAL CHARACTERISTICS OF SNAIL SOIL IN THE LJUBLJANA MARSH

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Abstract

This article focuses on mineralogical and physical characteristics of snail soil and their influence on parameter values of geomechanical characteristics. Snail soil, which got its name from fossil remains, is a typical layer observed in the Ljubljana marsh. It is distinctly porous, saturated and in a liquid consistency state.
Snail soil was investigated for mineralogical and physical characteristics in the Laboratory of Soil Mechanics, Faculty of Civil Engineering of the University of Maribor. Mineral and chemical composition, visual appearance, specific surface and grain property were determined. Physical characteristics show that snail soil is saturated in nature, highly porous and almost liquid.
Geomechanical characteristics were investigated for their interdependency on physical characteristics. A series of triaxial tests were performed on snail soil samples of different porosity, density and water content. Cylindrical samples of the height of 100 mm and the diameter of 50 mm were tested using three-axial testing apparatuses.
The results of the tests show that interdependency exists between geomechanical characteristics and porosity. These relationships can be expressed as functions of density, porosity or water content. It is evident from the results that changes of the coefficient of permeability, the coefficient of consolidation, and the coefficient of volume compressibility are non-linear with respect to changes of porosity. Changes of mechanical parameters, such as Young's modulus, Poisson's ratio, and friction angle are indistinct and almost linear at lower changes of porosity.

Keywords

Snail soil, triaxial test, porosity, permeability, consolidation, Young's modulus, Poisson's ratio, friction angle

1 INTRODUCTION

This article focuses on mineralogical and physical characteristics of snail soil and their influence on parameter values of geomechanical characteristics. Snail soil, which got its name from fossil remains, is a typical layer observed in the Ljubljana marsh. It is distinctly porous, saturated and in a liquid consistency state.

The Ljubljana marsh is a wide tectonic sink which was formed two million years ago by a gradual depression of the area. The marsh is located in the south of Ljubljana, at the elevation of 287–290 m above the sea level, and covers the surface of 163 km^2.

The Ljubljana marsh was inhabited already thousands of years ago. Archeological findings (fascine dwellings) date from the iron, copper, and bronze periods. Later, this marshy area was invaded by the Romans who were the first to start draining the land. The contribution of fascine dwellers from the Ljubljana marsh to a wider cultural space is also proven by the recent archeological finding, i.e. a wheel and the ax of a two-wheel vehicle, which dates from about 3200 A. D. For the present, this archeological finding is known to be the oldest of its type in the world.

Today, this area is almost completely drained and urbanized. Yet, the construction of traffic ways and tall buildings presents a great challenge to construction engineers due to the softness of layers below the surface.

Geological structure of the marsh is very interesting. Ground water is located immediately below the surface. The surface layer is composed of peat of the thickness of 1 m to 8 m. The dept of the peat is nowadays essentially smaller than in a past, due to the intensive excavations in a first half of the 20th century. Below the peat layer, there is a layer of snail soil of the thickness of a few meters at the borders to more than 10 m in the center of the marsh. The snail soil layer is distinctly porous, saturated with water and of a low-bearing capacity. There are clay and sandy-gravel layers below the snail soil layer. A layer of rocks starts at the depth of some ten meters.

Geological structure of the Ljubljana marsh has been studied by numerous experts. The oldest geological documents go back to the middle of the 19th century, when the first geological map was drawn of this region. Later, several other studies were performed. In the second half of the 20th century the researches were focused on geomechanical characteristics of the soil and detailed investigations of physical and mechanical characteristics of snail soil were performed. Strength parameters showing possible static loadings were also determined. To understand geomechanical characteristics of this marshy area it is essential to know rheological characteristics of snail soil. In 1979, in the framework of Trauner's doctoral thesis [1], slow triaxial tests were performed in the Laboratory of Soil Mechanics at the Faculty of Architecture, Geodesy and Civil Engineering of the University of Ljubljana. A similar investigation was later repeated in the Laboratory of Soil Mechanics (LSM), Faculty of Civil Engineering of the University of Maribor. A rheological model of snail soil was set which shows relationships between stresses, deformations and time [2]. The results of investigation were expressed with rheological dependencies, i.e. function relationships between rheological parameters and stress state and deformation, at void ratio e = 2.1.

An example of dependencies (Figure 1a) showing the relationship between shear stress τ and effective normal stress σ', with low value of friction angle $\varphi = 21^\circ$ and no cohesion c = 0.

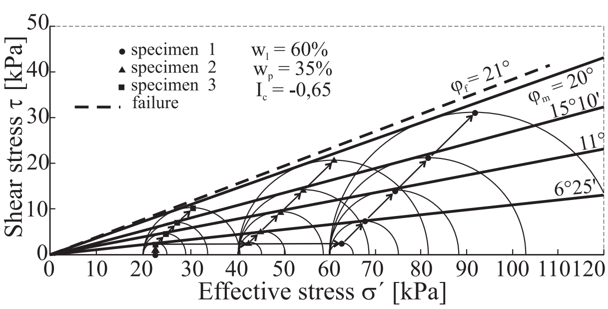

Figure 1a. Relationship between shear stress τ and effective normal stress σ'.

Fig. 1b shows a typical result obtained for the octahedral strain ε_0 depending on the octahedral shear stress τ_0 and effective octahedral stress state σ_0' of snail soil.

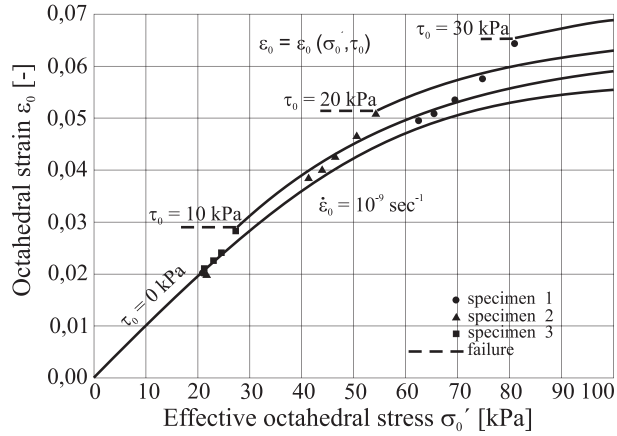

Figure 1b. Octahedral strain ε_0 vs. shear stress τ_0 for effective octahedral stress state σ_0'.

Fig. 1c shows a typical result obtained for the octahedral shear strain γ_0 depending on the octahedral shear stress τ_0 and effective octahedral stress state σ_0' of snail soil.

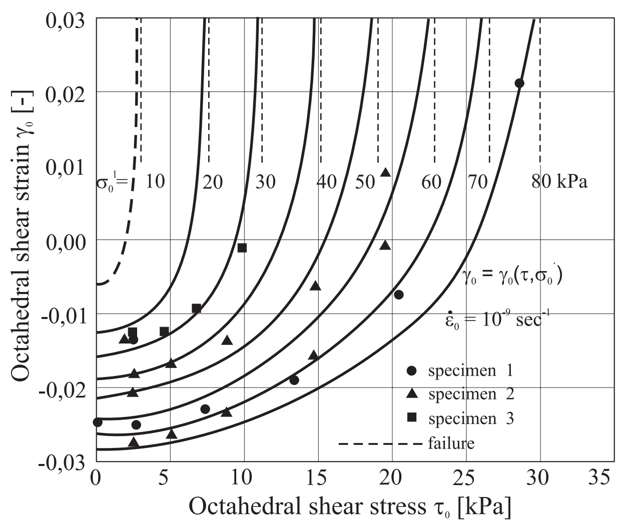

Figure 1c. Octahedral shear strain γ_0 vs. octahedral shear stress τ_0 for different effective octahedral stress state σ_0'.

Three years ago, the testing of snail soil was repeated and upgraded with the investigation of mineralogical and physical characteristics, as well as of geomechanical characteristics depending on physical characteristics. This article briefly presents researches performed and the influence of snail soil porosity on geomechanical characteristics.

2 CHARACTERISTICS OF SNAIL SOIL

A set of samples were taken on the southwest region of the Ljubljana marsh to conduct this research. Sampling was performed in the region of 3 m x 3 m at the depth of 3 m, so the ground was excavated to the depth of 2,5 m and a thin wall tube sampler (of the internal diameter of 100 mm) was forced into the ground. Samples of the diameter of 100 mm and the height of 300 mm were immediately packed after sampling. The ground water level was 1m under the surface in the region of sampling.

2.1 MINERAL COMPOSITION

The mineral composition (Table 1) was determined in the Laboratory of Geological Survey of Slovenia. The samples were scanned by X-ray diffraction technique (XRD) using a Philips PW 3710 diffractometer, a goniometer 1820, with an automatic divergence slit and a curved graphite monochromator, operating at 40 kV, 30 mA with CuK_α radiation and an Ni filter.

Table 1. Mineral composition of snail soil samples.

Mineral composition	Weight portion (%)
Calcite	87
Kaolinite	7
Muscovite	4
Quartz	3

2.2 CHEMICAL COMPOSITION

Chemical composition of the snail soil (Table 2) was determined at Centrum for electronic microscopy in University of Maribor. The scanning electron microscope SIRION which is equipped with the energy dispersive spectrometer EDS Oxford INCA 350, was used. The latter allows qualitative and quantitative micro chemical point and plane analyses, as well as qualitative linear analysis and determination of surface element distribution. Elements from beryllium to uranium can be analyzed.

Table 2. Chemical composition of snail soil.

Element	Average value (%)	Standard deviation (%)
C	12.15	1.49
O	48.78	1.95
Mg	0.52	0.09
Al	2.90	1.14
Si	5.34	2.25
K	0.80	0.25
Ca	29.51	5.17

2.3 VISUAL APPEARANCE

Visual appearance of snail soil samples was tested with the environmental scanning electron microscope QUANTA 200 3D, at Centrum for electronic microscopy in University of Maribor. The electron microscope is equipped with a system of double jets, i.e. electronic and ionic. The microscope is denoted with the word "environmental" or with the marking "ESEM" because it can be used at different pressures and at 100 % humidity.

The pressure in the chamber determines the types of samples to be observed.

Three operating principles are possible:

- High vacuum – It allows to observe conductive and non-conductive samples covered with a conductive coating (Au, C, Ag).
- Low vacuum – It allows to observe conductive and non-conductive samples without prior preparation.
- ESEM tape – It allows to observe all samples, also wet and greasy ones, and in-situ processes (hydration, dissolution …).

In observing the samples of snail soil, all three principles were used. Photographs were taken of damp samples and different blow ups were made; photographs of dry samples (Figure 2a), minerals in crystallized form, and remains of micro-organisms in the snail soil (Figure 2b) were also developed.

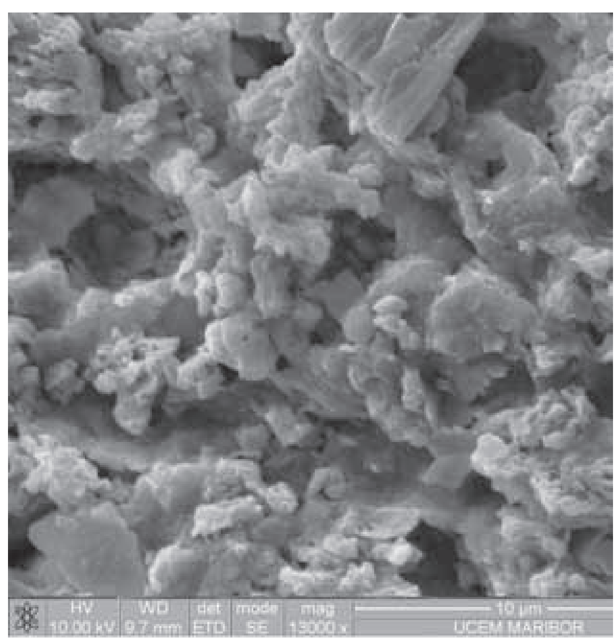

Figure 2a. A dry sample of snail soil (ESEM).

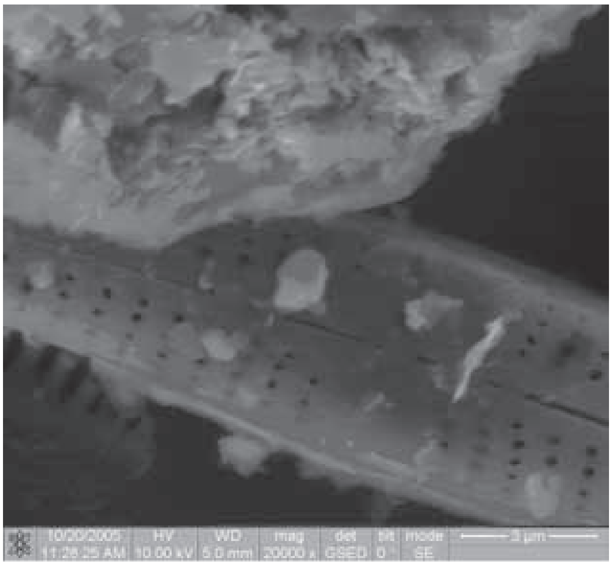

Figure 2b. Remain of micro-organism in snail soil, a dry sample (ESEM).

2.4 SPECIFIC SURFACE

Specific surface of grains is the surface of grains per unit mass. It is expressed in square meters per gram of dry substance (m^2/g). Specific surface of snail soil was determined at Chemical Institute Ljubljana, with the five-point BET method with adsorption of liquid nitrogen of 99.9% cleanliness and the temperature of 77^0 K.

The measurements were performed using the automatic TriStar 3000 gas adsorption analyzer, produced by Micromeritics Instrument Corporation, Norcross, U.S.A. The results of the test showed that snail soil has the specific surface of 5.03 ± 0.03 m^2/g.

2.5 PARTICLE SIZE DISTRIBUTION

Grain property of the snail soil sample was determined using the Fritsch Laser Particle Sizer Analysette 22 at the laboratory of Geological Survey of Slovenia. The results of the grain property analysis show (Fig. 3) that this snail soil falls within the range of silt (MH) with respect to granulometrical structure.

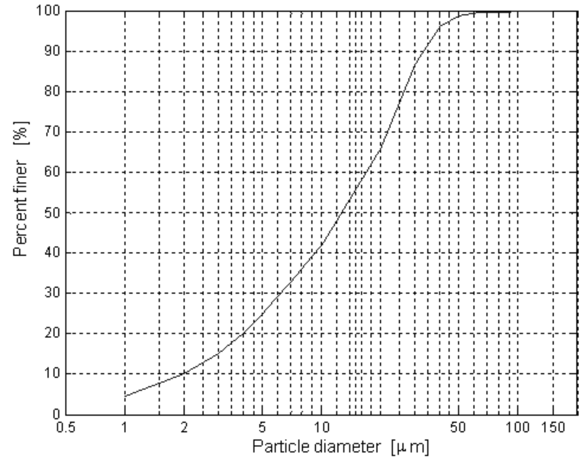

Figure 3. Particle size distribution of snail soil.

2.6 PHYSICAL CHARACTERISTICS

Physical characteristics (Table 3) show that snail soil is saturated in nature, highly porous and almost liquid.

Table 3. Physical characteristics of snail soil.

Soil property	Symbol	Unit	Value
Water content	w	%	75
Plastic limit	w_P	%	37
Liquid limit	w_L	%	60
Plasticity index	I_p	%	23
Consistency index	I_c	-	-0.65
Liquidity index	I_L	-	1.65
Density of solid	ρ_s	g/cm^3	2.62
Unit weight	γ	kN/m^3	15.5
Dry unit weight	γ_d	kN/m^3	8.8
Degree of saturation	S_r	%	100
Void ratio	e	-	2.1

2.7 COMPRESSIBILITY AND CONSOLIDATION

The investigation of compressibility was performed in LSM. Snail soil is markedly compressible; its volume undergoes great changes already when loaded with small changes of stress. Triaxial consolidation tests were performed at the effective stress changes σ'_0.

Consolidation parameters of snail soil in nature are given in Table 4. The values of consolidation parameters change with lower porosity, the parameters can be expressed as functions of porosity.

Table 4. Consolidation parameters (void ratio e = 2.1).

Soil property	Symbol	Unit	Value
Consolidation coefficient	c_v	m²/year	2,8 ÷ 3,2
Coefficient of volume compressibility	m_v	kPa^{-1}	$1 \div 1,2 \cdot 10^{-3}$
Coefficient of soil permeability	k	m/s	$2 \div 5 \cdot 10^{-9}$
Secondary compression ratio	$C_{\alpha\varepsilon}$ $C_{\alpha e}$	-	0.002 0.006

2.8 STRENGTH AND DEFORMABILITY

Strength parameters were determined in a series of triaxial tests. Strength parameters of snail soil in nature are given in Table 5. Values of parameters can also change with lower porosity; they can be expressed as functions of porosity.

Table 5. Consolidation parameters (void ratio e = 2.1).

Soil property	Symbol	Unit	Value
Consolidation coefficient	c	kPa	0
Friction angle	φ	°	21
Constrained modulus	M_c	kPa	800 ÷ 1000
Poisson's ratio	ν	-	0.4

3 POROSITY – GEOMECHANICAL PARAMETERS RELATIONSHIPS

The investigation of the influence of porosity on geomechanical characteristics was performed. Tests for determining mechanical properties were performed using triaxial apparatuses. The following steps were observed in testing: preparation of the sample, procedure on the apparatus, performance of the test, and interpretation of the obtained results. The investigation included drained and undrained stress oriented triaxial tests according to the following phases:

- Saturation,
- Consolidation,
- Static loading.

In the first phase, saturation was tested by determining the coefficient $B = du/d\sigma > 0.96$. This was a relatively short-term phase because of saturation in the nature.

The saturated sample was then consolidated at the selected effective isotropic consolidation stress σ'_{3c} and selected compression stress change $\Delta\sigma_{3c}$. The effective isotropic consolidation stress is expressed as a difference between the cell pressure σ_{3c} and the back pressure u_b.

Static loading was performed so that the sample was loaded with the selected compression stress $d\sigma_{3c}$ or the axial stress $\Delta\sigma_a = \Delta\sigma_z$.

Sixty-two triaxial tests were performed. The investigation was based on a series of tests in which the below conditions varied:

- Void ratio e = 2.1 ÷ 1.2 (Δe is calculated),
- Initial effective pressures $\sigma_0' = \sigma'_{3c}$ = 0, 50, 100, 150 kPa,
- Variations of effective pressures $\Delta\sigma'$ = 50, 100, 150 kPa,
- Variations of axial pressures $d\sigma_z$ (depending on axial deformation).

The below pressures were measured during the test:

- Cell pressure σ_{3c} (kPa),
- Back pressure u_b (kPa),
- Pore water pressure u_w (kPa),
- Axial vertical stress in compression σ_z (kPa),
- Axial vertical and radial strain ε_z (-), ε_r (-),
- Volume deformation ε_v (-).

For undrained test ε_v (-)=0.

Constants in the research are:

- Specific surface,
- Chemical composition,
- Mineral composition,
- Grain property,
- Natural humidity, density and coefficient of porosity,
- Liquid limit, plasticity index, consistency index,
- Density of a solid mass,
- Dry volume weight,
- Saturation.

The following strength parameters were calculated: coefficients of permeability k (m/s), consolidation c_v (m²/s) and volume compressibility m_v (kPa^{-1}), constrained modulus M_c (kPa), Young's modulus E (kPa) and Poisson's ratio ν (-), or compression modulus K (kPa), and shear modulus G (kPa).

Standard oedometer tests and direct shear tests of snail soil were also performed.

Snail soil has the void ratio e = 2.1 in nature, which is an extremely high value. Values of mechanical parameters change with lowering the void ratio.

Porosity (void ratio *e*) is in linear correlation with water content *w*. Density (ρ) or unit weight (γ) is in nonlinear correlation with void ratio *e*.

$$w = \frac{1}{D_r} \cdot e = \frac{\gamma_w}{\gamma_s} \cdot e \qquad \gamma = \frac{D_r + (S_r \cdot e / 100)}{1+e} \cdot \gamma_w \quad (1)$$

where:

γ_w, γ_s unit weight of water and solids,
D_r relative density of soil,
S_r=1 degree of saturation.

Figures 4 show the correlation between void ratio *e* and water content *w*, and the correlation between void ratio *e* and density ρ. Therefore, the snail soil was in liquid or plastic consistency, for different tests.

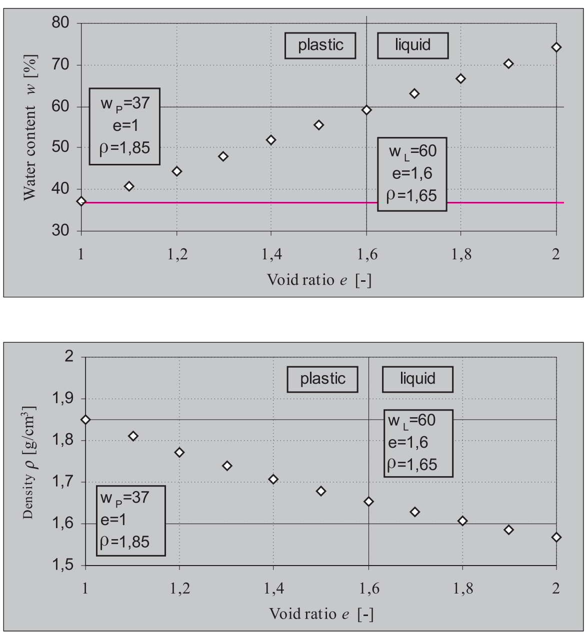

Figure 4. The correlation between void ratio *e* and water content *w*, and correlation between void ratio *e* and density ρ.

3.1 COEFFICIENT OF PERMEABILITY

The coefficient of permeability is expressed with equation

$$k = c_v \cdot m_v \cdot \gamma_w \qquad (2)$$

The coefficient of permeability of snail soil in nature is $k = 2 \cdot 10^{-9}$ m/s. The value of the coefficient of permeability decreases with decreasing void ratio *e* as shown in Fig. 5. The permeability can be expressed similar to a known expression of Ahuja et al. [3].

$$K_s = B \cdot \phi_e^n \qquad (3)$$

where:

K_s hydraulic conductivity,
ϕ_e effective porosity,
B, n are constants.

The relationship of the coefficient of permeability *k* vs. void ratio *e* for all tests is:

$$k(e) = B_1 \cdot e^n \qquad (4)$$

where

e void ratio
B_1, n_1 are coefficients.

We obtained the expression $k = 4 \cdot 10^{-11} \cdot e^{5,5019}$ for a series of all tests (where *e* is void ratio). Fig. 5 shows the relationship of the coefficient of permeability vs. void ratio for all tests. Deviation of the results (R = 0.3) from the above function is high because the function does not include stress conditions or pore pressure gradients, respectively. However, a more detailed description of the coefficient of permeability can be made with the functions of void ratio and stress states σ_0' = 50, 100, 150 kPa or with pertaining pore pressure gradients.

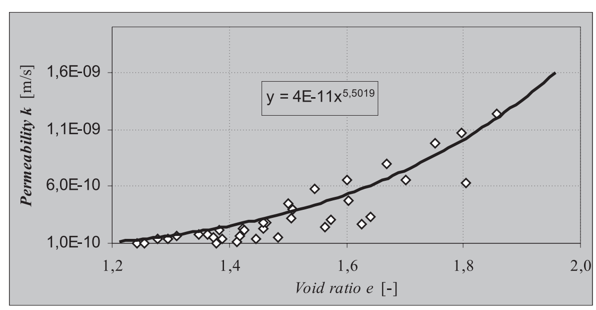

Figure 5. The coefficient of permeability *k* vs. void ratio *e*.

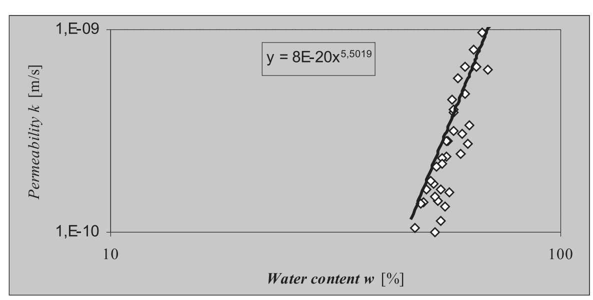

Figure 6. The coefficient of permeability *k* vs. water content *w*.

If the relationship of the coefficient of permeability *k* vs. void ratio *e* (or density ρ, or water content *w*) is expressed in the logarithmic form, we can see that it is almost linear. Figure 6 shows this relationship as the coefficient of permeability *k* vs. water content *w*.

3.2 COEFFICIENT OF CONSOLIDATION

The coefficient of consolidation c_v is expressed using equation from BS 1377 [4]

$$c_v = \frac{1{,}65 \cdot D^2}{\lambda \cdot t_{100}} \qquad (5)$$

where:

D diameter of the specimen (mm),
λ coefficient which depends on the drainage,
t_{100} time of primary consolidation.

The relationship of the coefficient of consolidation c_v vs. void ratio *e* could be expressed similarly to the coefficient of permeability *k*. Fig. 7 shows the relationship of coefficient of consolidation c_v vs. void ratio e_c for all tests. We obtained the expression $c_v = 3 \cdot 10^{-8} \cdot e^{1{,}464}$ (*e* is void ratio).

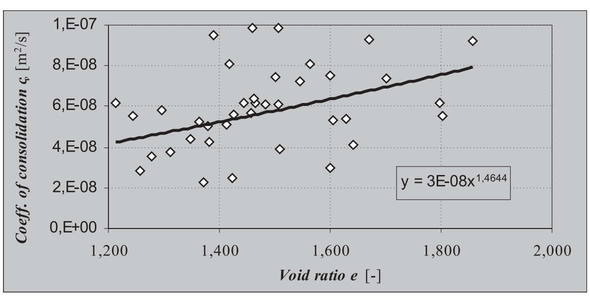

Figure 7. The coefficient of consolidation c_v vs. void ratio *e*.

3.3 COEFFICIENT OF VOLUME COMPRESSIBILITY

The coefficient of volume compressibility m_v is expressed with equation

$$m_v = \frac{\Delta e}{(1+e)\cdot \Delta\sigma}, = \frac{\Delta \varepsilon_v}{\Delta \sigma}, \qquad (6)$$

Fig. 8 shows the relationship of the coefficient of volume compressibility m_v vs. void ratio *e* for all tests. We obtained the expression $m_v = 9 \cdot 10^{-5} \cdot e^{3{,}5005}$.

The logarithmic form of relationship of volume compressibility m_v vs. water content *w* shows linear correlation log. $m_v = 3 \cdot 10^{-10} \cdot w^{3{,}5005}$.

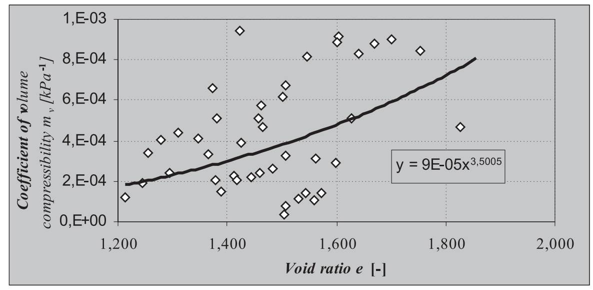

Figure 8. The coefficient of volume compressibility m_v vs. void ratio *e*.

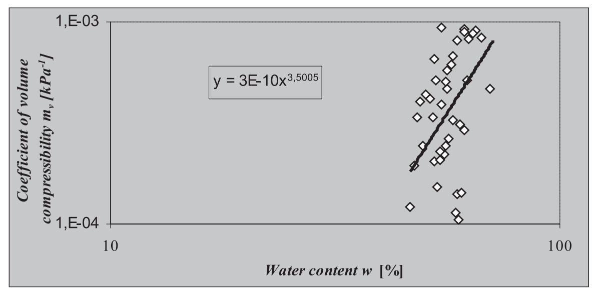

Figure 9. The coefficient of volume compressibility m_v vs. water content *w*.

3.4 STRENGTH PARAMETERS

To determine the relationship of strength parameters vs. void ratio an insufficient number of tests were performed therefore the results are unreliable. Fig. 8 shows Young's modulus *E* vs. void ratio e_c. We can see that strength does not substantially increase with increasing density or decreasing porosity; a greater difference can be only seen at higher changes of density or porosity. Poisson's ratio is ν = 0.4 at void ratio *e* = 2.0 and decreases for 0.03 at void ratio *e* = 1.4.

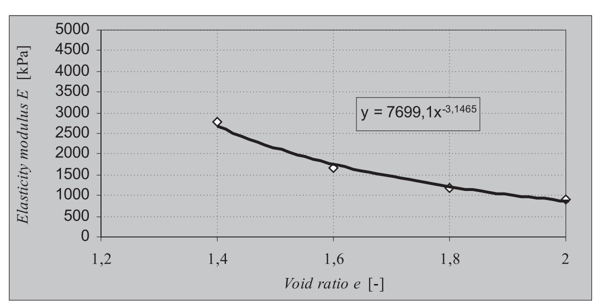

Figure 10. Young's modulus *E* vs. void ratio *e*.

If the relationship of the Young's modulus *E* vs. water content *w* is expressed in the logarithmic form, we can see that it is almost linear (Fig. 10).

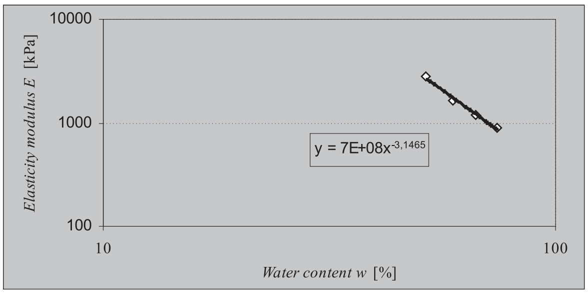

Figure 11. Young's modulus *E* vs. water content *w*.

The same is true for shear properties. Fig. 12 shows the relationship of friction angle φ vs. unit weight γ. We can see that it increases almost linearly at lower changes of density or void ratio, respectively.

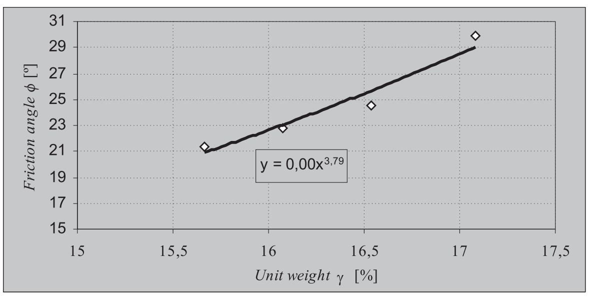

Figure 12. The friction angle φ vs. unit weight γ.

4 CONCLUSIONS

This article focuses on the investigation of snail soil and the research of its mineralogical and physical characteristics. Geomechanical characteristics were investigated for their dependence on physical characteristics. A series of triaxial tests of snail soil of different density, porosity and water content was performed. The results of the tests show that geomechanical characteristics depend on porosity.

The relationships were expressed as functions of porosity. It is evident from the results that changes of the coefficient of permeability, the coefficient of consolidation, and the coefficient of volume compressibility are nonlinear with respect to void ratio. Changes of mechanical parameters such as Young's modulus, Poisson's ratio and friction angle are indistinct and almost linear at lower changes of porosity.

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