VPLIV VROJENE SUKCIJE NA VOLUMENSKO OBNAŠANJE ZGOŠČENIH ZEMLJIN MED VLAŽENJEM

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o avtorjih

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izvleček

Vlaga zgoščenih zemljin se po vgradnji v zemeljske objekte uravnoteži z okolico. V pogojih vlažne in zmerne klime se glinene zemljine, ki so se kompaktirale na suhi strani Proctorjeve krivulje, dodatno navlažijo. Proces vlaženja spremlja zniževanje sukcije in dodatne deformacije, ki so lahko nabrekanje ali strukturni kolaps. Preiskave zemljin iz glinenih nasipov so pokazale, da se sukcija uravnoteži pri vrednostih pod ca. 300 kPa. V prispevku predstavljamo rezultate raziskav, opravljenih na zgoščenih zemljinah, v okviru katerih smo konvencionalne raziskave dopolnili z meritvami sukcije. Na izbranih vzorcih, ki smo jim določili retencijsko krivuljo, smo merili sukcijo pri različnih stopnjah zgoščenosti. Po preplavitvi smo v edometru opazovali deformacije, ki so se v odvisnosti od začetnega stanja odražale kot nabrekalni dvižki ali kolaps. S primerjavo podatkov smo ugotovili, da začetna sukcija nabitih vzorcev pomembno vpliva na značaj deformacij ob vlaženju in bi v prihodnje lahko služila kot pomemben kazalnik uporabnosti glinenih zemljin za inženirske nasipe.

ključne besede

edometrski test, sukcija, nabrekanje, kolaps

INFLUENCE OF MOULD SUCTION ON THE VOLUME-CHANGE BEHAVIOUR OF COMPACTED SOILS DURING INUNDATION

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abstract

After construction, compacted clayey soils in different earth structures equilibrate their water content and suction with the local environment. In wet climatic conditions the compaction on the dry side of the Proctor curve, which enables a high layer stiffness during construction, may result in permanent deformation and softening during the lifetime of the structure. This paper presents the results of the tests, performed on a relatively large number of compacted test specimens, where the conventional index parameters, used to identify compacted soils, were supplemented with a suction–water-content curve and measurements of "mould" suction. Correlations were established between the optimum water content and the suction–water-content curve for representative samples, and the influence of the mould suction on the vertical deformation of the compacted samples during inundation in oedometers was studied.

keywords

oedometer tests, suction, swelling, collapse

1 INTRODUCTION

Compacted fine-grained soils have been used in the construction of roads, railroad embankments, earth embankment dams and other types of earth structures for centuries. Conventional compaction criteria have been developed empirically and are, in general, based on three parameters:

- the minimum relative compaction of the compacted layer, defined by a standard or modified Proctor test,
- the range of water content during compaction, defined by the allowable deviation from the optimum water content determined with a standard or modified Proctor test
- the required stiffness measured as the layer deformation modulus (E_{v1} , E_{v2} , E_{vd} , M_E).

The first two criteria prevent large settlements of the embankment and the last one prevents deformations by heavy vehicles. However, a large number of other factors that influence the behaviour of compacted soils are not measured or are difficult to control during compaction. Past experiences show that the highest layer stiffness is achieved when the maximum dry density is reached on the dry side of the Proctor curve. From the standpoint of a road engineer, the criteria of layer stiffness often prevail over the criteria of the required water content and many road embankments and clayey sub-grades have been compacted at water contents that are 3-10% lower than that required by the national technical recommendations [1], [2] to fulfil the criteria of the required stiffness. As a consequence, the maintenance of "dry of optimum" conditions during compaction was one of the key tasks when fine-grained soils were used as a construction material in the past. Due to wet climatic conditions (Fig. 1) the initially "dry of optimum" compacted soil wetted and the stiffness of the compacted soil was reduced.

Seasonal water-content changes in road sub-bases may seriously affect the bearing capacity, stiffness and the life time of pavements - especially on low-level roads

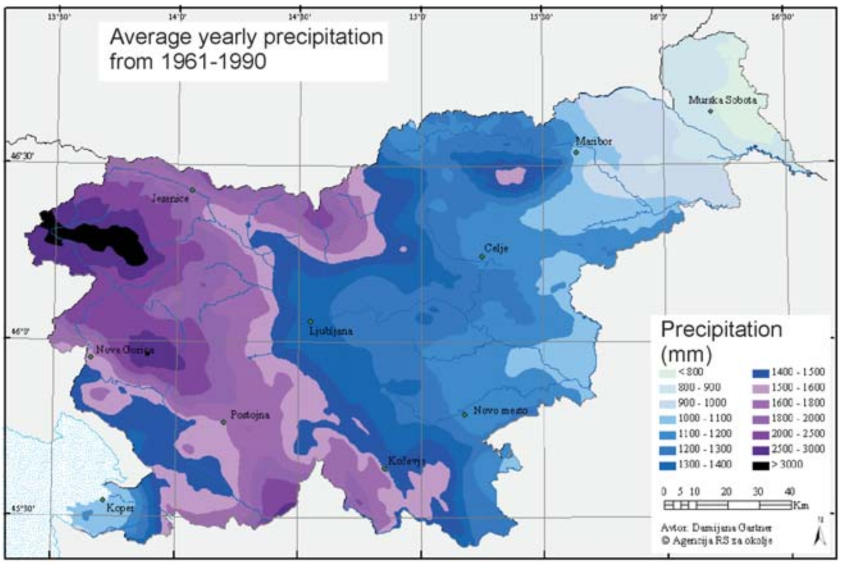


Figure 1. A map of average rainfall in Slovenia for the period 1961-1990 [3].

with thin bituminous layers. Post-construction damages recorded on pavements constructed on stiff, "too dry" sub-bases susceptible to moisture changes in poor drainage conditions are frequent [4], [5], [6]. Besides the seasonal soil-moisture changes that affect the behaviour of pavements, shallow foundations and sub-surface layers, the global environmental changes result in water content and volume changes inside the embankments and additional settlement or heave may seriously affect even very old earth structures.

Slovenia, like the whole of central Europe, has been facing significant climatic changes and extreme weather conditions in the past decade [7], [8]. The year 2003 was, for instance, exceptionally dry and hot (Fig. 2). After the autumn rain, unexpected deformations were observed on numerous Slovenian roads, embankments and slopes in deep cuttings. One of the newly constructed motorway

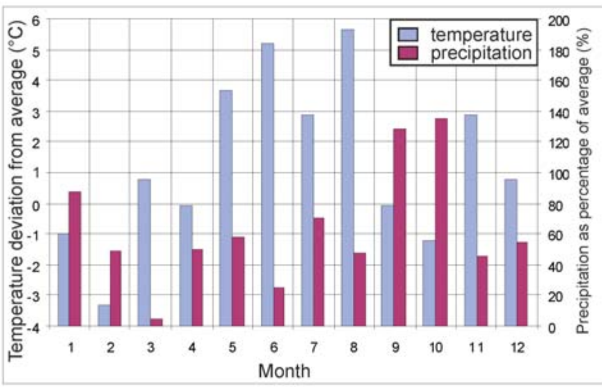


Figure 2. Temperature and precipitation conditions in Slovenia in 2003 compared with the 20-year average conditions [10].

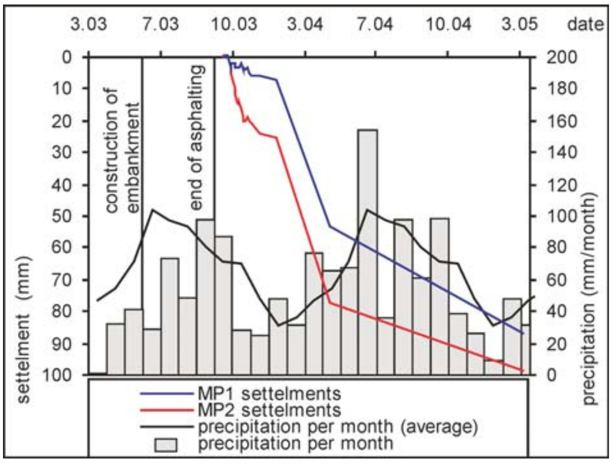


Figure 3. Deformation, measured on a motorway embankment (Eastern Slovenia), after a wet period, followed the extremely dry summer of 2003.

embankments in eastern Slovenia was so seriously damaged that in December 2003 the outermost driving lanes had to be closed to traffic (Fig. 3) [9].

A forensic investigation with deep boreholes and excavation pits, made through the pavement, showed that the soil-water content in the damaged motorway embankment increased from 2 to 12% within the 7-m-high and approximately 400-m-long embankment. The equilibration of the suction was recognized as a key driving parameter that caused the compacted soil to absorb additional water and deformation to appear. A few days after the beginning of the rain, a road heave and spreading of the slopes were observed by geodetic observation. Later on a collapse was observed. When the deformation of the embankment stopped in May 2004, the average additional settlements exceeded 7 cm and the soil suction in the embankment equilibrated at 80 to 300 kPa, as detected in the laboratory on intact samples. The layer modulus, measured with a light falling weight plate, was reduced from E_{vd} = 25 MPa to less than 10 MPa.

Several elastoplastic constitutive models presently available can predict the volumetric deformations of unsaturated soils subjected to soil suction and the mean stress changes [11], [12], [13]. Due to its complex nature the Barcelona expansive model [13], [14], [15] was mainly used to predict the behaviour of natural soils or artificial sand - bentonite mixtures designed for the barriers at nuclear waste storages [16], [17], [18]. Farulla and Ferrari [19] also applied the Barcelona expansive model in a study of volume deformations in compacted soils during cyclic suction changes between 10 and 800 kPa.

In conventional earth works in Slovenia, the application of unsaturated soil mechanics still lags behind the state-of-the-art knowledge, because the implementation of the unsaturated soil mechanics is time consuming and requires expensive laboratory tests and experienced laboratory staff [20]. For the purpose of the design of conventional earth structures the volumetric deformations of compacted soils are mainly studied between the initial ("mould") and zero suction, following one of the standard procedures, either in an oedometer cell according to the ASTM standard [21] or other standards using the CBR mould [22]. This simplified approach gives the engineer an estimation of the volume changes in the embankment, or due to different compactions in the laboratory and on the worksite, the sensitivity of the embankment to volume deformations. For countries with a wet climate this approach is also valid when clayey soils with a suction of over 300 kPa are built in the embankments. Such soils equilibrate at a suction of around 30-80 kPa and only the first or first two meters are prone to seasonal suction changes [9].

When the properties and applicability of the available fill material are studied for new earth structures, the intersection of the key requirements should be found. Daniel and Benson [23], for instance, proposed such an intersection for hydraulic fills (Fig. 4).

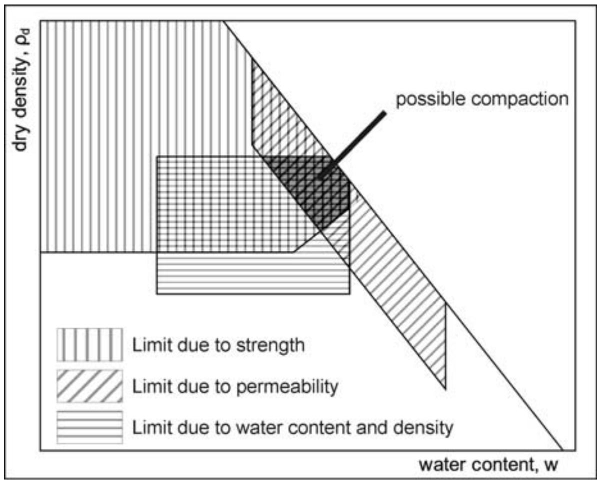


Figure 4. Intersection of acceptable shear strength, hydraulic conductivity and compaction [23].

2 THE OBJECTIVE OF THE RESEARCH

The objective of the research presented in this paper is focused on an investigation of the volume-change response of compacted clayey soils with a known mould suction, subjected to wetting in classical oedometers. The term "mould suction" used in this paper describes the suction, measured on the laboratory compacted soil. The volume-change response is discussed and interpreted in the context of the influence of the suction–water-content curve and the mould suction on the volumetric behaviour of the soil during wetting. The main goal of the research was to find out whether the data of the "single point" soil-suction measurement during compaction could be used as a tool for a better estimation of a potential risk of post-construction volumetric deformation due to seasonal or permanent wetting. The following points are examined and presented:

1. The index soil properties, used in the research program together with the initial state parameters (dry density, degree of compaction, degree of saturation)
2. The suction–water-content curve and the corresponding mould suction at different levels of compaction and water content
3. The influence of the initial mould suction on the volumetric deformation during wetting in the oedometer
4. The discussion about the acceptable range of the mould soil suction at which the compacted soils will not be prone to volumetric changes in future climatic conditions.

3 MATERIALS

Tests were carried out on three natural and two artificial soils. The artificial soils were pure calcite/stone flour (Calcivit CV, Stahovica, Slovenia) and calcium bentonite (Bentonak, Kriva Palanka, FYRM), both industrially produced and available on the market. Calcite flour represents the inert, non-plastic and non-swelling soil, while the bentonite represents the soil with a high swelling potential. The natural soils were obtained from sites at Ljubno, where stiff marine clays of the Oligocene era appear, and from the flysch formation in the Vipava valley. From both sites, difficulties with volumetric deformations on the embankments and slopes in deep cuts have already been reported [24], [25]. The last soil is a brick clay from Renče used in the construction of a protective cover layer at the Boršt landfill. No volumetric deformations were observed on site.

The main soil properties are given in Table 1 and the suction–water-content curve is given in Fig. 5. This figure also shows the suctions, defined at the optimum water content.

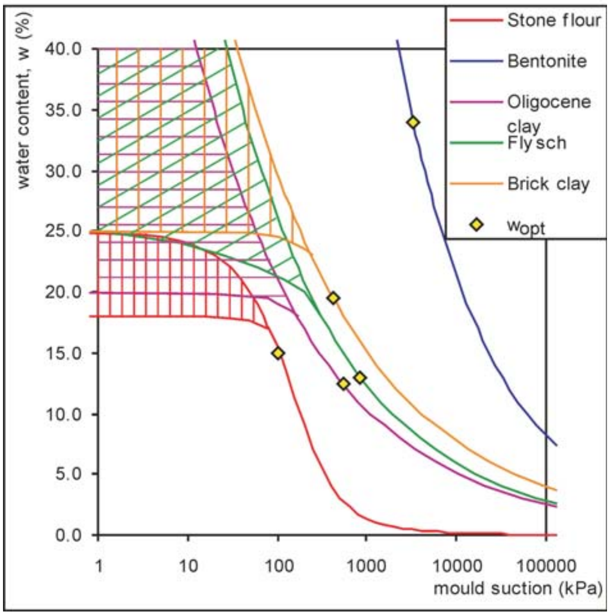


Figure 5. Suction - water content curve for tested materials and mould suction at optimum water content. Hatched areas presents suction variation due to different void ratio.

The suction–water-content curve was drawn from the suction measurements performed on various compacted specimens. It is important to emphasize the influence of the density, soil structure and the macro-pore distribution of each single specimen compacted with the standard Proctor effort on the measured soil suction [18], [26]. As a consequence of the structure, every single specimen lies on its own soil-water characteristic curve. However, the influence of the void ratio and the structure on the suction is much more significant at low suctions [27].

4 METHODS

The bentonite and calcite flour were industrially processed to fines passing a 63-μm sieve. The natural soils were pre-treated in the laboratory. They were firstly oven-dried at 105±5 °C to a constant mass, carefully crushed with a rubber mallet and then sieved through a 2-mm sieve to eliminate the biggest particles.

In the first step samples were prepared at different water contents by mixing dry soil with different quantities of water. Samples were carefully mixed by hand and then placed in plastic bags for 24 hours to achieve uniform water-content conditions and were later compacted using a standard Proctor effort in a mould with a diameter of 10 cm [28]. After compaction, the soil suction of each compacted specimen was measured using the filter paper method [29]. A specimen was put out of a mould and cut into two pieces. A dry Whatman No. 42 filter paper was placed on the lower piece and the upper piece was placed on top of the filter paper. The specimen was put in an air-tight jar and then into a thermo-isolated chest to reduce the temperature fluctuations. After two weeks the water content of the filter paper was measured. The suction was obtained through the suction-water content for wetting of the filter paper curve. The equation for the suction-water content for wetting of the filter paper curve was used from the ASTM standard D5298 [29] for Whatman No. 42 paper. The validity of the equation was checked on KCl solutions.

Table 1. Main properties of the soils used in the research.

material	w_L %	w_P %	I_P %	w_A %	MB_f g/kg	w_{opt} %	ρ_{dmax} t/m^3
Stone flour	23	/	/	32	2.0	14.9	1.76
Bentonite	210	35	175	297	125	33.9	1.22
Oligocene clay	40	14	26	62	38	12.5	1.83
Flysch	45	18	27	58	60	12.0	1.81
Brick clay	57	18	39	73	44	19.5	1.68

w_L is liquid limit, w_P is plastic limit, I_P is plasticity index all after CEN ISO/TS 17892-12, MB_f is methylene blue value on fines after EN 933-9, w_A is water absorption after DIN 18132, w_{opt} and ρ_{dmax} are optimal water content and maximum dry density after DIN 18127.

Table 2. Suction measured using filter paper method and dew point potentiometer on compacted specimens.

material	suction at w_{opt} -2% kPa	suction at w_{opt} kPa	suction at w_{opt} +2% kPa
Stone flour	130	105	80
Bentonite	3800	3300	2900
Oligocene clay	940	540	330
Flysch	1400	860	550
Brick clay	610	420	300

Later on the suction–water-content curves were completed with suction measurements performed in a dew-point potentiometer WP4-T (Decagon devices) on soil specimens compacted at different water contents. The specimens in the dew-point potentiometer were 38 mm in diameter and 6 mm high and were much smaller than the specimens compacted in the Proctor mould. As a result of the different specimen sizes the soil structure is different too. As the mould-suction measurements after the filter paper method and the dew-point potentiometer are within the expected error, there is no significant influence of sample size. The ranges of suction, measured on the compacted soils during compaction, are given in Table 2.

In the second step, each cylinder of compacted soil was divided into three to five specimens for the oedometer test. Altogether, 52 specimens were cut out from the compacted cylinders. The tests were performed in slightly different ways than suggested by ASTM D4546 [21]. To avoid difficulties when comparing the results, both methods are described as follows:

TEST METHOD A

The cut-out specimens of compacted samples were put in the oedometer with a dry filter paper, installed on dry porous stones. A moist paper towel was put around the oedometer cell and both the towel and the oedometer cell were wrapped in a plastic foil. The specimens were first loaded with vertical stresses of 50, 100, 200 and 400 kPa and then unloaded in a reverse stress path under dry conditions. Each loading and/or unloading step was ended in 5 minutes and the final displacements were measured.

After the last unloading stage the specimens were inundated and the plastic foil and paper towel were discarded. The deformations were measured continuously until the end of the primary swelling/settlement. After that, the specimens were loaded in steps of 50, 100, 200 and 400 kPa and the deformations were observed during each loading step. At the end of the test, the specimens were unloaded again.

The swelling deformation is calculated from the void ratios during the first loading and after inundation at the same vertical stress [21].

$$\frac{\Delta h}{h_0} = \frac{(e_{v0} - e_0)}{(1 + e_0)} \qquad (1)$$

where Δh is the change in the specimen height, h_0 is the specimen height before inundation, e_{v0} is the void ratio after the end of the swelling, and e_0 is void ratio before inundation.

TEST METHOD B

The specimens were prepared using the same procedure as for test method A. The main difference compared with method A was that each specimen was loaded with the selected vertical stress and the deformation under the load was measured after 5 minutes. After that the specimens were inundated and the plastic foil and paper towel were discarded. The deformations were measured continuously under a single selected load until the equilibration, and after that the specimens were unloaded.

The swelling deformation was calculated according to Equation 1.

Two major differences exist between methods A and B. In method A the free swell deformations were measured, and the swelling deformations at other vertical stresses were estimated on the same specimen during secondary loading. In method B each individual specimen was exposed to a selected vertical load and the deformations realized as swelling or collapse for the selected loads were measured.

5 TEST RESULTS AND INTERPRETATION OF THE RESULTS

The parameters determined during the tests are presented in Table 3 and Table 4.

Table 3. Results of oedometer tests, performed on compacted specimens, method A.

	w_i (%)	$\rho_{d,i}$ (t/m^3)	D_{pr} (%)	S_{ri} (%)	mould suction[1] (kPa)	σ_v (kPa)	$\Delta h/h_0$ (kPa)
Stone flour	12.4	1.58	91	47	140	50	-1.4
						100	-1.9
						200	-2.8
						400	-3.5
	13.0	1.60	92	51	130	50	-0.1
						100	-0.4
						200	-0.8
						400	-1.3
	15.5	1.64	94	64	100	50	-0.3
						100	-0.2
						200	-0.3
						400	-0.4
	21.7	1.66	95	92	0	50	n.p.[2]
						100	n.p.
						200	n.p.
						400	n.p.
Oligocene clay	13.4	1.74	95	63	430	50	3.0
						100	1.7
						200	0.1
						400	-2.2
	17.4	1.78	97	88	190	50	-0.2
						100	-0.5
						200	-0.6
						400	-0.5
	22.9	1.68	92	99	80	50	n.p.
						100	n.p.
						200	n.p.
						400	n.p.
Flysch	7.0	1.51	84	23	5700	50	2.1
						100	-1.3
						200	-4.8
						400	-8.7
	10.1	1.63	90	40	1900	50	5.2
						100	2.4
						200	-0.6
						400	-4.3
	14.3	1.68	93	62	640	50	5.5
						100	3.2
						200	0.9
						400	-1.9
	18.8	1.69	93	82	270	50	3.3
						100	1.9
						200	0.6
						400	-1.0
Brick clay	17.5	1.70	101	79	600	50	7.3
						100	5.2
						200	2.6
						400	0.1
	17.7	1.61	96	69	590	50	4.3
						100	1.4
						200	-1.5
						400	-3.8
	21.1	1.67	99	90	320	50	2.3
						100	2.4
						200	0.9
						400	-0.3
	21.6	1.65	98	90	300	50	5.2
						100	4.9
						200	2.8
						400	1.1
	29.9	1.45	87	93	140	50	n.p.
						100	n.p.
						200	n.p.
						400	n.p.

[1] the values of mould suction are obtained from suction – water content curve
[2] n.p. – not possible to determined, deformations are to small or influence of primary loading is too big

Table 4. Results of oedometer tests, performed on compacted specimens, method B.

	specimen	w_i (%)	$\rho_{d,i}$ (t/m^3)	D_{pr} (%)	S_{ri} (%)	mould suction[1] (kPa)	σ_v (kPa)	$\Delta h/h_0$ (%)
Stone flour	A	11.4	1.62	92	45	160	50	-0.5
	A	10.4	1.56	89	38	160	100	-2.8
	A	11.7	1.57	90	44	160	200	-2.7
	B	13.6	1.62	92	54	120	50	-0.2
	B	13.0	1.61	92	51	130	100	-0.3
	B	13.1	1.60	92	51	130	200	-0.4
	C	15.9	1.66	95	67	94	50	-0.2
	C	16.0	1.67	96	69	94	100	-0.3
	C	15.8	1.68	96	69	94	200	-0.2
	D	18.0	1.69	97	80	0.1	50	0.0
	D	19.1	1.68	96	83	0.1	100	0.0
	D	22.2	1.62	93	89	0.1	200	0.0
Bentonite	A	39.4	1.28	105	99	2300	200	16.1
	A	38.6	1.25	103	93	2400	400	7.2
	A	38.0	1.27	104	95	2500	800	2.6
	A	42.0	1.19	97	92	2000	1200	1.0
Oligocene clay	A	11.5	1.83	100	62	710	50	1.7
	A	11.4	1.82	99	62	710	200	0.4
	A	11.4	1.73	94	53	710	500	-3.0
	B	16.2	1.82	99	87	230	50	0.2
	B	15.9	1.86	102	91	250	200	0.0
	B	16.2	1.87	102	94	230	500	-0.1
	C	20.8	1.71	93	94	110	50	0.0
	C	20.7	1.71	94	94	110	100	0.0
	C	20.7	1.69	92	90	110	200	-0.1
Flysch	A	4.7	1.66	92	20	19000	50	-0.1
	A	4.1	1.70	94	18	30000	200	-4.3
	A	4.5	1.67	92	19	22000	256	-8.3
	B	7.0	1.79	99	36	5700	50	2.4
	B	7.2	1.76	97	35	5200	200	-2.5
	B	7.2	1.78	98	36	5300	500	-4.3
	C	11.8	1.86	103	68	1200	50	1.9
	C	11.9	1.86	103	69	1100	200	0.1
	C	11.6	1.89	104	70	1200	500	-0.1
	D	17.0	1.80	100	89	380	100	0.9
	D	16.2	1.76	97	79	440	200	-2.5
	D	17.0	1.81	100	90	380	500	-0.2
	E	21.0	1.71	94	95	200	50	0.8
	E	21.6	1.70	94	96	180	100	0.3
	E	21.0	1.70	94	94	200	200	0.0

[1] the values of mould suction are obtained from suction – water content curve

5.1 VERTICAL HETEROGENEITY OF THE COMPACTED SPECIMEN

One very important finding derived from the results, presented in Table 4, is that the scatter of the mould-water content (±1.5%) and the mould dry density (±0.06 t/m^3) inside a single Proctor compacted specimen were immense. Fleureau et al. [30] also reported the vertical heterogeneity of a compacted soil. However, the scatter in their results was much lower than registered in this paper.

5.2 MOULD WATER CONTENT (SUCTION) AND ITS IMPORTANCE FOR VOLUMETRIC BEHAVIOUR

Fig. 6 shows the results of the deformation behaviour recorded in the oedometer tests on Flysch specimens performed after method B. The first graph (Fig. 6a) presents the relationship between the void ratio and the vertical stress at a mould-water content of 7.2% (specimen B), while the second graph (Fig. 6b) corresponds

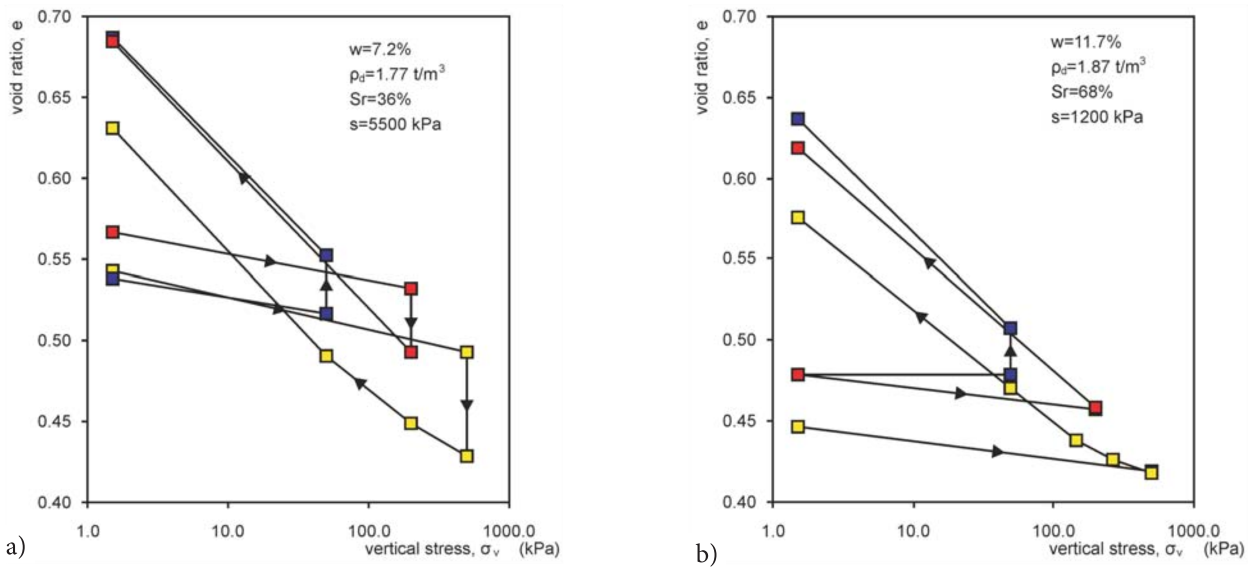


Figure 6. Deformation of compacted flysch. Loading path is marked by arrows.

to the specimen with a 11.8% water content (specimen C). Swelling deformations were observed for both specimens inundated at 50 kPa. However, a significant collapse was detected at a vertical load of 200 and 500 kPa only for the dryer specimen (Fig. 6a). Fig. 7 shows the influence of the mould-water content on the deformation behaviour at different vertical loads. From the measured values it could be concluded that specimens compacted on the dry side of the Proctor curve are much more sensitive to volumetric changes during wetting.

5.3 INTERSECTION OF MOULD-WATER CONTENT, DRY DENSITY, SUCTION AND DEFORMATION

Following the idea of Daniel and Benson [23], the Proctor curve, the suction–water-content curve and the deformation measured for different vertical loads in the oedometer, are presented in the same diagrams (Fig. 8). The black rectangles represent the area of the common requirements for the compaction given in the Slovenian specifications for earth works on roads [2].

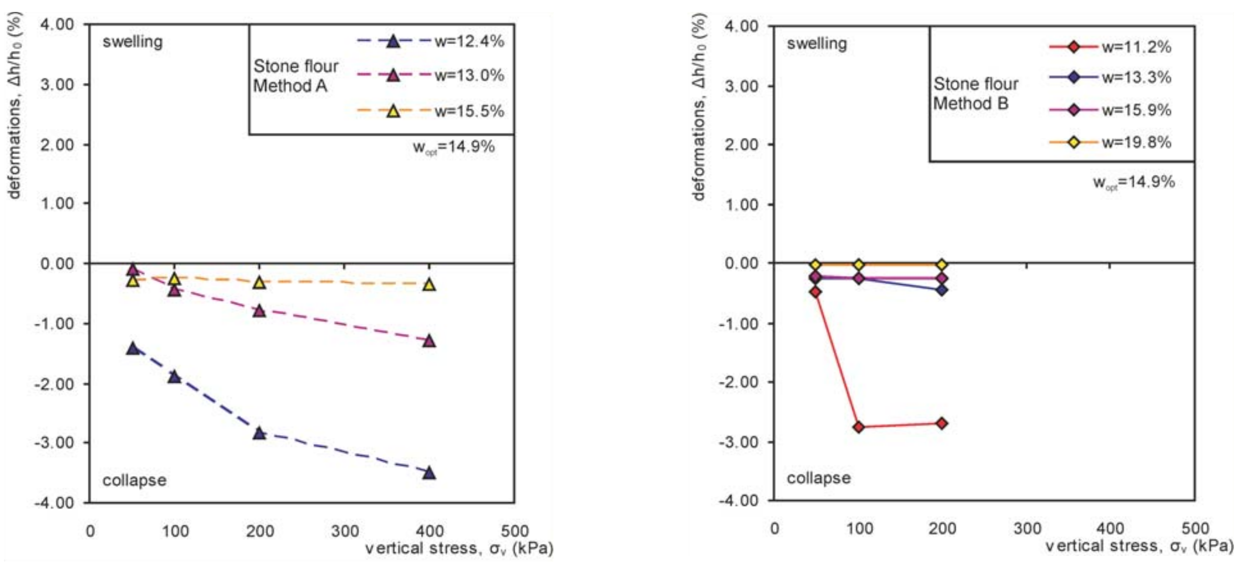
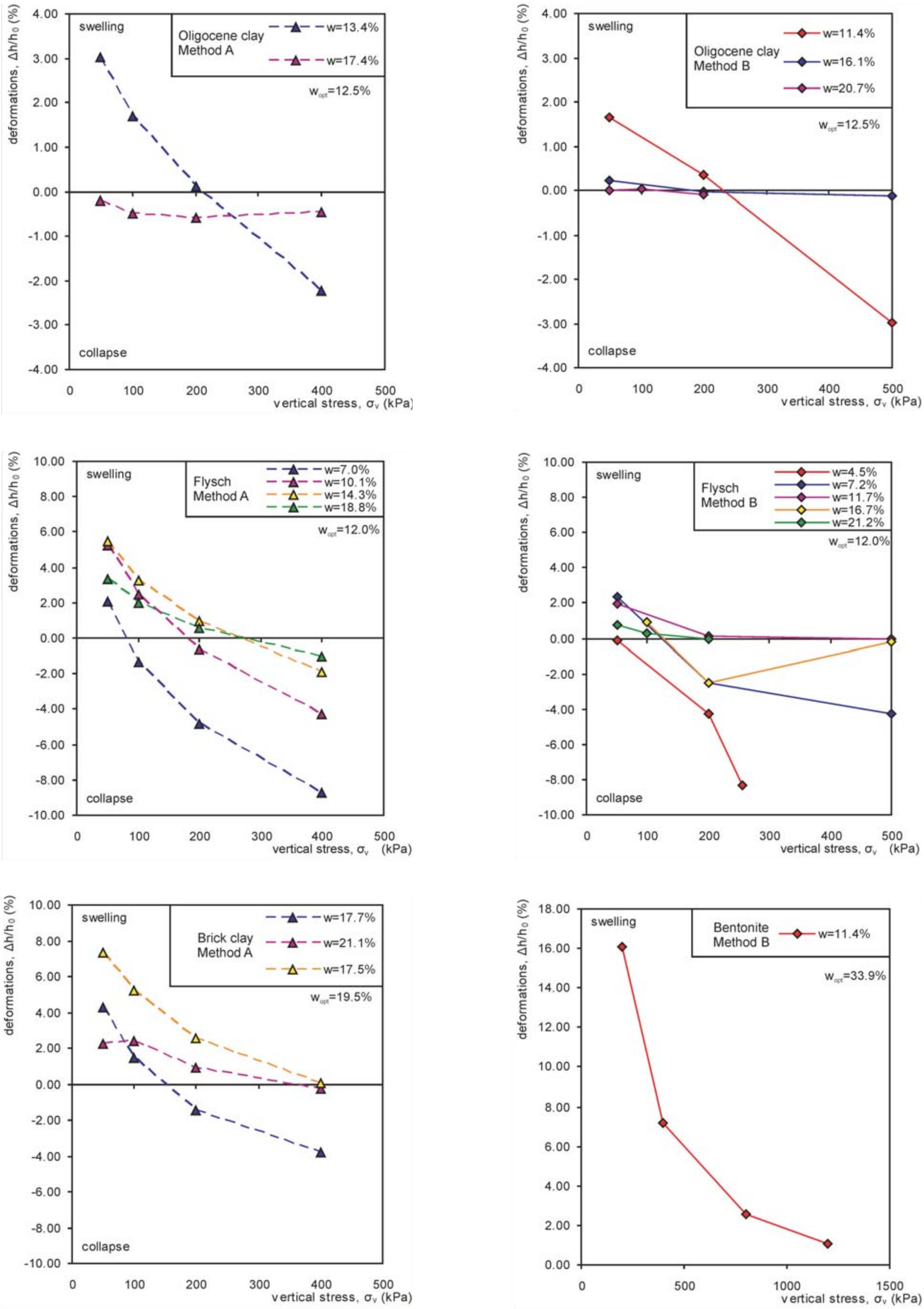
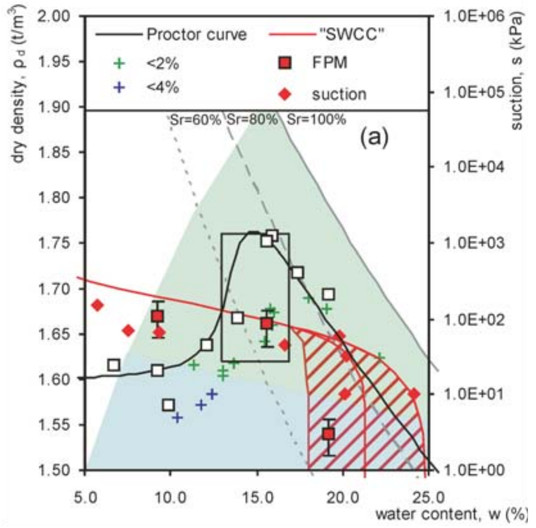


Figure 7. Influence of mould water content on the deformation behaviour of compacted specimens (continued on opposite page).


swelling
Oligocene clay
Method A
w=13.4%
w=17.4%
w_{opt}=12.5%
collapse
deformations, Δh/h₀ (%)
vertical stress, σ_v (kPa)
swelling
Oligocene clay
Method B
w=11.4%
w=16.1%
w=20.7%
w_{opt}=12.5%
collapse
swelling
Flysch
Method A
w=7.0%
w=10.1%
w=14.3%
w=18.8%
w_{opt}=12.0%
collapse
swelling
Flysch
Method B
w=4.5%
w=7.2%
w=11.7%
w=16.7%
w=21.2%
w_{opt}=12.0%
collapse
swelling
Brick clay
Method A
w=17.7%
w=21.1%
w=17.5%
w_{opt}=19.5%
collapse
swelling
Bentonite
Method B
w=11.4%
w_{opt}=33.9%

The coloured areas indicate three classes divided on the basis of absolute deformations measured after inundation in the oedometers. The first class (green) belongs to the specimens that exhibited deformations lower than 2%, the second class (blue) belongs to the specimens with deformations between 2 and 4% and the third class (red) indicates specimens with deformations higher than 4%. The hatched red area also represents the area of suction where the suction-water content relationship is significantly influenced by the specimen structure. Even more interesting is the graph given in Fig. 9. For a mould suction lower than 250 kPa the compacted specimens exhibited negligible heave or collapse after inundation. For the mould suction of 250–600 kPa, deformation due to heave or collapse can reach up to 4%. For mould suctions higher than 1500 kPa, the compacted specimens did not fulfill the required minimum degree of compaction and the expected deformations were higher than 6%.



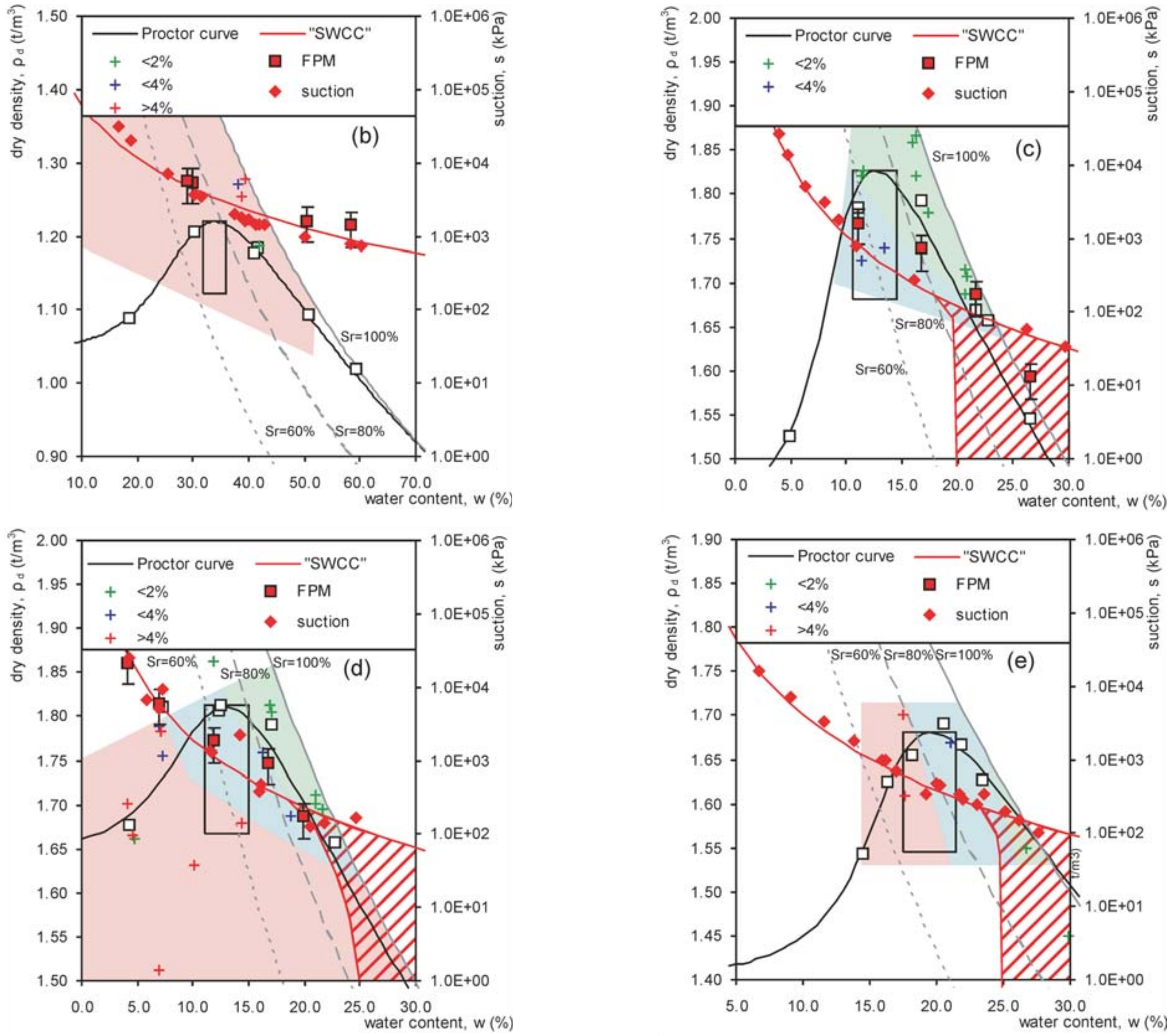


Figure 8. Comparison of Proctor curve and the suction - water content curve for tested soils with the information about the range of deformations, measured in oedometers (a) stone flour, (b) bentonite, (c) Oligocene clay, (d) flysch and (e) brick clay; FPM – suction measured by filter paper method, suction – suction measured by dew point potentiometer.

As was expected, the properly compacted stone flour exhibited negligible deformation after inundation. The mould soil suction was lower than 120 kPa. However, specimens compacted at too low a degree of compaction (less than 92% of the relative compaction) exhibited some settlements, which is a well-known phenomenon. The mould suction of bentonite at the optimum water content was between 2900 and 3800 kPa. Due to the high suction the compacted specimens of bentonite exhibited very large swelling deformations, even under a high vertical load. In Fig. 8 we already marked the range of the optimum water content for different soils. We can conclude that the "mould" suction at the optimum water content increases with the increasing plasticity of the soil and can be used as an important parameter when the volumetric behaviour of compacted soils is considered.

When studying the results of real soils, special attention should be paid to the behaviour of flysch material. Highly over-consolidated stiff clay from Flysch formation can also be treated as a soft, clay bearing bedrock. Although the index parameters given in Table 1 did not indicate any significant differences between the Oligocene clay and the flysch, the deformation behaviour of the flysch is much more unfavourable from the engineering point of view. One of the possible and reasonable explanations is that the time of 24 hours was not long enough to ensure a homogenous water-content distribution throughout the sample and that the single grains of flysch remained drier than the average soil mixture during compaction.

6 DISCUSSION

The relationship between the optimum water content, the liquid limit and the mould suction at the optimum water content is given in Fig.10 for the investigated soils and compiled with the data from Fleureau et al. [30]. From Fig. 10 it could be observed that the samples with a higher optimum water content tend to have a higher liquid limit and a higher mould suction. These results complement the results presented in Figures 8 and 9.

The swelling behaviour of the compacted soils could be evaluated using different methods, following local experiences and national guidelines. The fines content, the liquid limit, the plasticity index and the methylene blue value are some of the most indicative parameters that offer a first insight into the soil's volumetric characteristics for engineers in practice [31], [32]. The liquid limit, the plasticity index, the methylene blue value only evaluate the tendency of the soil to undergo large swelling deformations. Mould suction, on the other hand, evaluates the tendency of the soil to undergo large volume deformations for a given test specimen and range of water content with a low tendency to large volume deformations could be observed. From the results presented in this study it can be concluded that with measurements of mould suction (Fig. 9), the index properties could be excellently complemented for the evaluation of the behaviour of compacted soils.

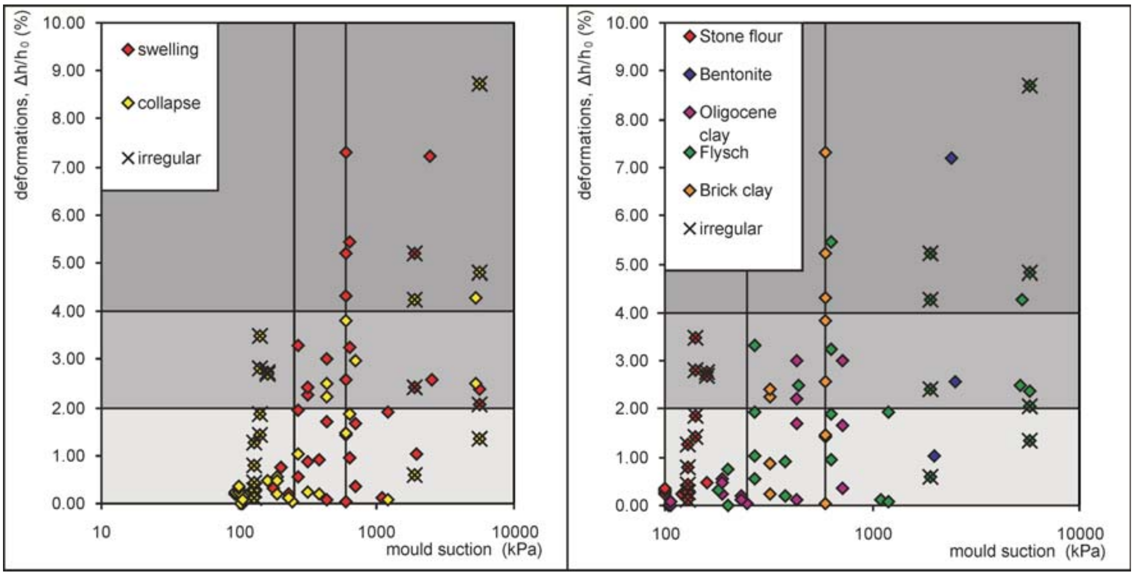


Figure 9. Evolution of vertical deformations (heave and collapse) after inundation at different suctions (left) and the evolution of absolute vertical deformations for different compacted samples (right). "Irregular" specimens have a degree of compaction less than 92% of the maximum Proctor dry density.

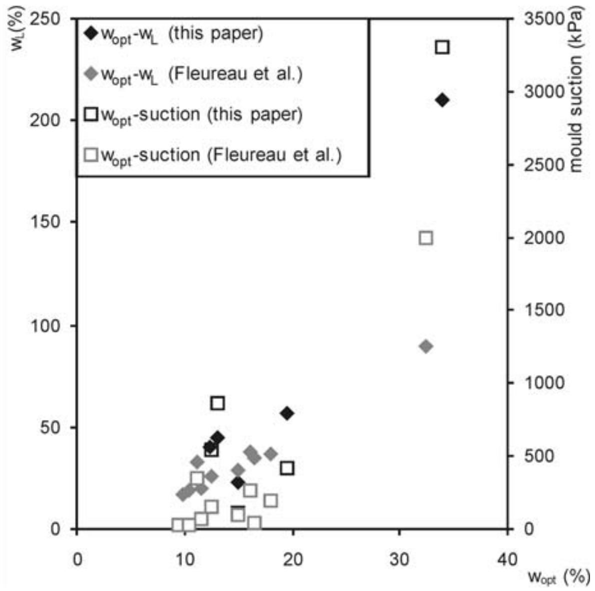


Figure 10. Relationship between the optimum water content, the liquid limit and the mould suction at optimum water content for the investigated material and compiled with the data from Fleureau et al. [30].

7 CONCLUSIONS

The aim of this paper was to give a simplified overview of the volumetric behaviour of compacted clayey soils during wetting. Soil wetting is common in countries with wet climates, like Slovenia, when soil with high suction is used for embankment construction and exposed to weather. For a study of the volumetric behaviour, conventional geotechnical laboratory tests were combined with soil-suction measurements, using the simplest and very basic laboratory tests, which could be used in a commercial laboratory.

The mould-soil suction was recognized as an important factor that can indicate the volumetric behaviour of a compacted soil at very early stages of a preliminary investigation. It was found that the most simple and low-cost soil-suction measuring devices, like the filter paper method and the dew-point potentiometer, offer a new alternative to conventional practice in the field of earthworks. The main finding was that the soil that exhibits high mould suction after compaction will exhibit higher deformation during wetting. High mould suctions can also indicate compaction or a non-uniform arrangement of water and density in the soil. The field measurements of suction in three old Slovenian motorway embankments, which suffered from unpredicted deformation, proved that the soil suction in the real clay embankment equilibrated at values lower than 300 kPa, regardless of the suction at which the soil was compacted during construction [9].

The authors of this paper are aware that the described simple approach cannot compete with fundamental researches, performed using the most advanced laboratory equipment. The scatter of the results presented in the study is significant. However, it is important to stress that compacted soils are the most widely used construction material and the Proctor compaction test is still the most widely used reference test to control the quality of compaction. The deficiencies of the Proctor test are well known, but at the moment there is no better test. The heterogeneity of the densities and the water contents, the differences in microstructure and macrostructure of the compaction layers do exist in the field and the earth structure will deform or fail when the most vulnerable part of the structure fails.

The results, gathered from five different soil samples and 52 specimens, compacted at different dry densities and water contents, show that the mould soil suction measurement can complement the conventional geotechnical tests and they can be used as a good tool during the preliminary as well as the quality-assurance and quality-control tests. A lot of additional investigations will have to be made before the recommendations about the allowable value of the mould suction are prepared for use in different local geo-environments. However, the results indicate that for conventional earth structures, the mould suction of the compacted soil should not exceed 600 kPa in wet climate conditions.

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