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EXAMINING THE SHORT PERIOD SETTLEMENT OF MUNICIPAL SOLID WASTE SAMPLES

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Abstract: *It is necessary to know the deformation behavior of the waste deposits during operation and utilization of the area after closure, too. The waste body was examined, the samples were taken from different depths (samples of varying degrees of degradation). We determined consolidation and compression curves, Poisson - ratio and oedometric modulus to the given waste body taking into consideration the degradation degree, too. The prerequisite of modeling and calculating the settlement is to know the load – deformation – time relation and to describe this complicated physical – chemical and biological process in a mathematical way. After deposition and loading the main part of deformation is the so-called strain dependent one of short period, which is completed by deformation due to biodegradation later. To describe the deformation of short period we tried to apply the consolidation models, which had to be modified by applying immediate compression, and rheological models.*

Keywords: *MSW landfill; deformation; oedometric test.*

1. INTRODUCTION

Environmental protection is one of the key issues of the waste management. In Hungary and in the bigger part of the world, most of the communal waste is placed in landfills. It is not the best solution to keep waste in deposits (BAT - best available technology), but it is important to expand knowledge in connection with landfills, because they will operate for a long time. New knowledge is needed for their recultivation and also the utilization of the recultivated land. One of the motivations of the land use can be the fact, that due to the expansion of the city, the previous outskirts become inner-city areas. The other possibility is that the territory of the landfill remains permanently in the outer areas, in this case their energetic use is justified (Energy Hill Concept). In both cases mechanical characteristics of waste hills are needed since the foundation of engineering structures can be planned economically only with the full knowledge of them, and in this case the substratum is the deposited waste.

2. EXPERIMENTS

After the review of the literature, it can be concluded that mechanical, rheological, biodegradational, and empirical models can be classified [1] [2]. The different models show high deviation [3], the deformation behavior depends on the applied model [4] [5]. More exact prognosis can be made when surface subsidence is measured on the landfill and the expectable subsidence is given based on the data of the initial measurement. The longer measurement time series are available, the more accurate the estimate will be [6] [7]. We opted for the soil mechanics-based modeling since the waste can be considered as grainy material [8] [9], and rheological models, which are well known in classical physics and describe the time dependent behavior of deformation. We were looking for the simplest tests, theories and models, which provide acceptable accuracy, because that is the most favorable from the practical point of view. So, we investigated only the mechanical properties of short period, not the gas extraction, hydraulically-, biological- etc. aspects.

Due to the changes in municipal waste (physical-chemical transformation, biodegradation), it was found advisable to examine the samples of different ages separately. The degree of degradation of the sample expresses the age of the sample (the time elapsed). The degradation degree of the sample, where the degree of degradation 1st is the degree of degradation of fresh waste and degradation 5th is degree of completely transformed, degraded waste. The categorization of the samples we examined was based on published literature methods [10].

1.1. *Spot of the test*

The landfill site under investigation was a regional waste management center in Pusztazámor, which is the "landfill of Budapest", thus it is one of the largest ones in Hungary, which can be found 23 km-s from Budapest to the South-West. The landfill is built with technical protection in accordance with domestic regulations and guidelines of the EU. The landfill operates in 5 phases and with nominal capacity of 19 million m^3 (91 ha = 0,91 km^2). The first phase (18,3 ha, 4 million m^3) became full by the end of 2012 and its height reached 50 meters. (Figure 1).

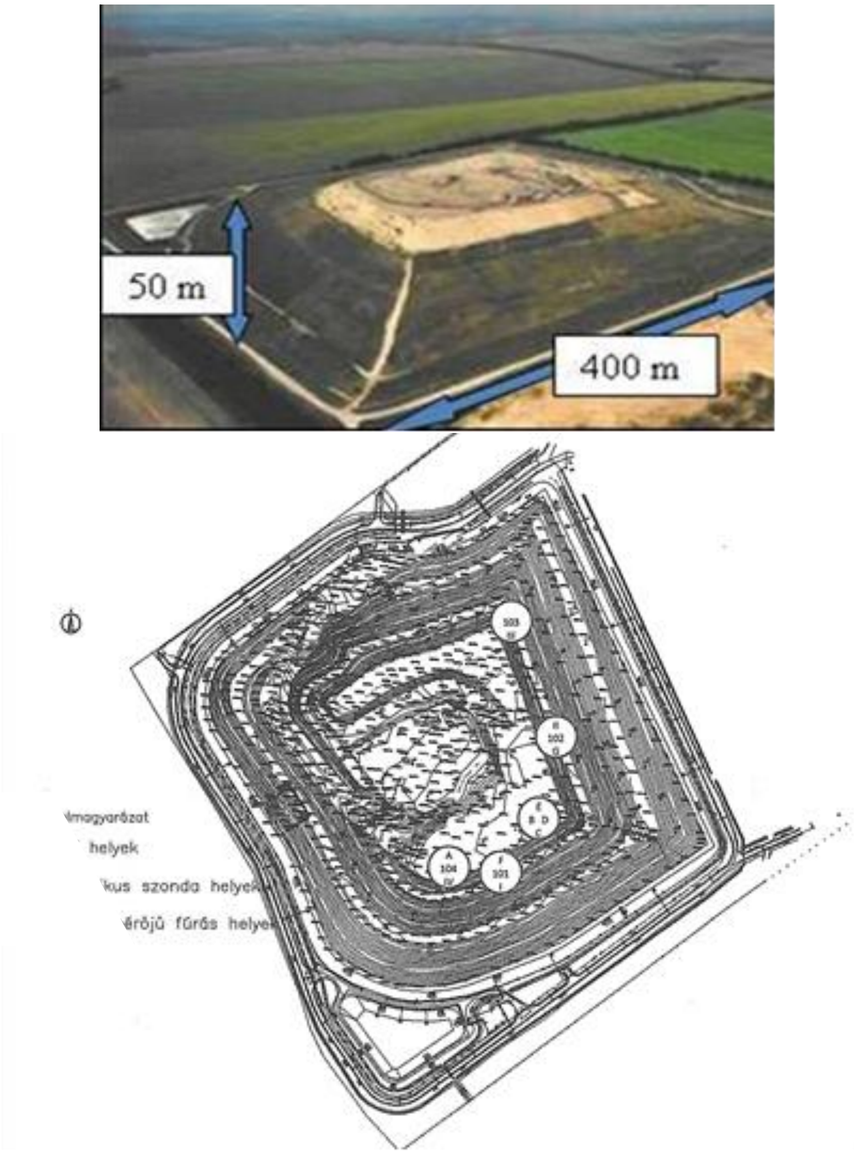


Figure 1 Photo of the landfill (phase I.) and the spots of excavations (FKF Zrt.)

1.2. *Measuring in laboratory*

For our tests, the 22 semi-confusion samples were preserved by freezing. From these samples we formed average samples, considering their degree of degradation, in the following way (Table 1).

Name	Degradation phase	Boreholes	Depths (m)
S-1	2	103F	0,50, 1,00, 1,50, 2,00
		104 F	0,50, 1,00, 1,50, 2,00

S-2	3	103F	2,50, 3,50, 4,50, 5,50
		104 F	2,50, 3,00, 4,50, 5,50
S-3	4	103F	6,50, 7,50, 8,50, 9,50, 10,50, 11,50

Table 1. Samples

We built a special oedometer [11], since the waste contains bigger "grains" than usually soil of different types (Figure 2). We built two steel diaphragm pressure sensors in the sidewall of the box, so it was possible to measure side pressure. We loaded it vertically (5-10-20-40-80-160-320-640 kN/m^2), and we read the compression in time (1-2-5-10-15-30-60-120-180-240-300-1440-2880 min. etc.). We operated each load step for a reasonable period of time until the physical compression was probably played out. We applied load & reload cycles at planned and necessary times.

As shown by the laboratory tests, the waste samples examined were in the quasi saturated state. This is due to the lack of the upper closure, the uncertainty of the drainage conditions, the high moisture content of waste deposited and the degradation processes. Of course, it is not saturated, it is almost saturated, just because of the formation of the landfill gas site. The leachate generated during the test was taken care of.

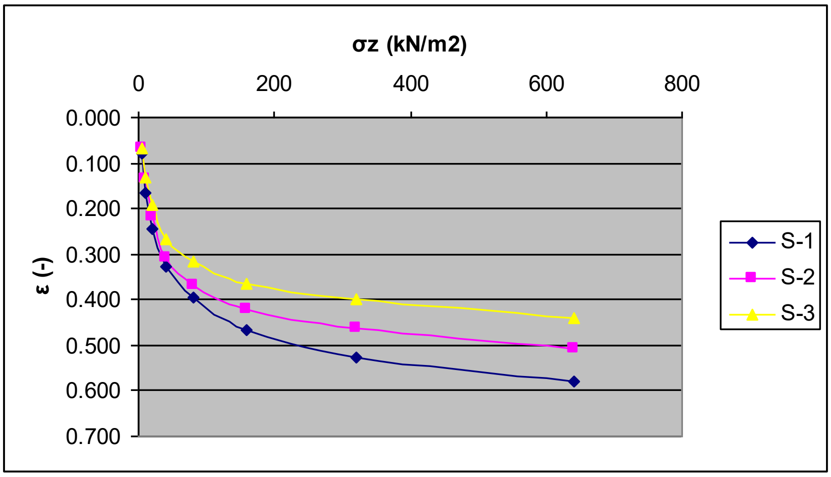
Figure 2 The new oedometric investigation

3. RESULTS AND DISCUSSION

In soil mechanics, solving of deformational problems an examination of deformation, for practical reasons, is generally divided into two parts: compression and consolidation. This method has been applied to soil mechanics based modeling, the rheology examination always contains the time variable, due to its nature.

3.1. *Compression*

Suspension of compression according to the degradation degree is well illustrated by the compression curves in the common figure (Figure 3). Due to the characteristics of the curves, it is a practical approach to use logarithmic or exponential function as it is applied in soil mechanics (Eq. (1-3)). However, parts under preload stress have to be left out of consideration and extrapolated, because compression of solid parts (e.g. cans etc.) cannot be ceased loosening during sampling.



where: σ_z – Normal stress
ε – Vertical normalized compress

Figure 3 The compression curves of the tested samples

S-1: $\varepsilon = 0{,}096\,\mathrm{Ln}(\sigma_z) - 0{,}0311$ ($R^2 = 0{,}9949$) or

$\varepsilon = 0{,}129\,\sigma_z^{0.242}$ ($R^2 = 0{,}9623$) (1)

S-2: $\varepsilon = 0{,}071\,\mathrm{Ln}(\sigma_z) + 0{,}0547$ ($R^2 = 0.{,}9936$) or

$\varepsilon = 0{,}167\,\sigma_z^{0.176}$ ($R^2 = 0{,}9764$) (2)

S-3: $\varepsilon = 0{,}059\,\mathrm{Ln}(\sigma_z) + 0{,}0619$ ($R^2 = 0{,}9943$) or

$\varepsilon = 0{,}161\,\sigma_z^{0.157}$ ($R^2 = 0{,}9851$) (3)

It is also useful to determine the compression modulus (E_{oed} – oedometer modulus: $\Delta\sigma/\Delta\varepsilon$; [kN/m^2]) of waste samples of different degradation degree, which can be generated by linearizing the compression function piecewise by load-sections, that is, the functions are in y=ax+b form (Eq. (4-6)).

The function of oedometric modulus (E_{oed}) by linearization of the load section:

S-1: $E_{oed} = 9{,}73\,\sigma_{zi} - 323$ [kN/m^2], ($R^2 = 0{,}9977$) (4)

S-2: $E_{oed} = 12{,}08\,\sigma_{zi} - 270$ [kN/m^2], ($R^2 = 0{,}9981$) (5)

S-3 $E_{oed} = 13{,}10\,\sigma_{zi} - 29$ [kN/m^2], ($R^2 = 0{,}9880$) (6)

It shows a good agreement with König's results of in situ tests [4].

Simplifying in y = ax form (Eq. (7-9)):

S-1: $E_{oed} = 9{,}022\,\sigma_{zi}$ [kN / m^2], ($R^2 = 0{,}9897$) (7)

S-2: $E_{oed} = 11{,}523\,\sigma_{zi}$, [kN / m^2], ($R^2 = 0{,}9953$) (8)

S-3 $E_{oed} = 13{,}127\,\sigma_{zi}$ [kN / m^2], ($R^2 = 0{,}9757$) (9)

During the compression test, the side pressure was also measured, so it is possible to calculate the Poisson factor, which is possible at degradation and due to nonlinear behaviour it is necessary in vertical load intervals. It can be deduced from the general Hook law that in the linear deformation and axial symmetric stress state (oedometric test):

$$\sigma_x = \sigma_y = \frac{\nu}{1-\nu}\cdot\sigma_z \qquad (10)$$

Because, in this case:

$$\varepsilon_x = \varepsilon_y = 0$$
$$\sigma_x \neq 0; \sigma_y \neq 0$$

The values of the Poisson factor are presented in Table 2.

load (kN/m^2) \ sample	S-1	S-2	S-3
Poisson factor [-]			
20 >	nm.	nm.	nm.
40	0.48	0.47	0.45
80	0.41	0.39	0.38
160	0.36	0.35	0.34
>320	ni.	ni.	ni.
Ratio of deformities			
elastic / residual deformations [%] (as a percentage of total deformation)	9 / 91	6 / 94	6 / 94

nm.: not measurable, ni.: can not be interpreted due to the geometric condition

Table 2 Changes of the Poisson factor [-], and ratio of deformities [%]

From the examination of the load-reload, the ratio of elastic and residual deformities can be determined (Table 2). Hysteresis effect was not measurable.

3.2. *Consolidation*

Terzaghi's theory of consolidation can be derived from the following assumptions. Solid particles and water are uncompressible, the Law of Darcy applies, the sinking occurs only from the disappearance of the water. The compressible layer is laterally delimited in any horizontal section, at a given time the neutral, the effective and the full strains are constant, the soil is homogeneous, isotropic, soil compression modulus (E_{oed}) is constant. Not all the assumptions mentioned above are valid for waste (not for soils in every case). Basically, the waste is inhomogeneous, anisotropic, and the sinking of the pore water is the result of instant compression, grain rearrangement is the result of degradation processes. Due to the inadequate drainage and until the top closure is completed, the quasi-saturated state can be assumed if sampling and on-the-spot tests justify this. Other initial assumptions can be considered approximately true for waste as well.

The known consolidation models (Terzaghi, Bjerrum) describe the process of consolidation in terms of some parameters and applying immediate compression.

The modified Terzaghi model is:

$$v(t) = v_0 + v_1(t) \tag{11}$$

where:

v(t): the time depended vertical deformation of the top of the sample

v_0: the immediate compression

$v_1(t)$: the primary consolidation settlement:

$$v_1(c_v, t) = v_{1,\infty}\left[1 - \int_0^{2H} \frac{u(c_v, t, z)}{2H\Delta\sigma} dz\right] \tag{12}$$

where:

c_v: consolidation ratio

t: time

H: half-height of the sample

$\Delta\sigma$: added pressure

u: the neutral stress can be described by the initial boundary value problem of the partial differential equation (Terzaghi):

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t}, u(t,0) = 0, u(t,2H) = 0, t \in [0,T], z \in [0,2H], u(0,z)|_{(0,2H)} = u_0 \tag{13}$$

The solution can be given in form of a function series (Terzaghi),

$$u(t,z) = \frac{4}{\pi} u_0 \sum_{n=0}^{\infty} \frac{\sin\left(\frac{(2n+1)\pi z}{2H}\right)}{2n+1} e^{-(2n+1)^2 \pi^2 \frac{c_v t}{4H^2}} \tag{14}$$

Which is uniformly convergent for every $t>0$ and equals to u_0 at $t=0$. Thus, it is integrable with respect to z for every t >=0. The terms in the sum decrease rapidly with n, taking the sum of the first N term provides a good approximation of the series. By integrating this finite sum term by term with respect to z one gets

$$v_1(t) \cong \tilde{v}_1(c_v, t) = u_0 2H \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{N} \frac{e^{-(2n+1)^2 \pi^2 \frac{c_v t}{4H^2}}}{(2n+1)^2} \right] \tag{15}$$

The argument indicates the dependence of $\tilde{v}_1$ on this parameter.
The modified Bjerrum model,

$$v(t) = v_0 + v_1(t) + v_2(t) \tag{16}$$

extends the above one with

$$v_2(t) = C_\alpha \frac{2H}{1+e_0} \log \frac{t+t_0}{t_0} \tag{17}$$

where: C_α: creep modulus, the creep settlement.

Degrees of degradation and load parameters are presented in Table 3.

	Modified Terzaghi model			Modified Bjerrum model				
S-1								
load kN/m²	v_0 / v (%)	v_1 / v (%)	c_v (m²/s)	v_0 / v (%)	v_1 / v (%)	v_2 / v (%)	c_v (m²/s)	C_α (-)
5	31.4	68.6	2.52E-08	25.6	65.7	8.7	E-3	0.00297
10	37.1	62.9	3.70E-08	32.7	56.6	10.7	3E-3	0.00368
40	47.1	52.9	3.01E-08	45.4	50.2	4.3	5E-13	0.00287
80	47.4	52.6	2.05E-08	45.8	42.6	11.6	5E-13	0.00332
160	47.4	52.6	2.78E-08	46.1	36.4	17.5	5E-13	0.00340
320	48.3	51.7	2.04E-08	47.4	41.6	11.0	5E-13	0.00278
640	48.7	51.3	4.17E-09	48.3	43.8	7.9	5E-13	0.00181
mean*	47.8	52.2	2.1E-08	46.6	42.9	10.5	n.r.	0.00283
S-2								
load kN/m²	v_0 / v (%)	v_1 / v (%)	c_v (m²/s)	v_0 / v (%)	v_1 / v (%)	v_2 / v (%)	c_v (m²/s)	C_α (-)
5	32.9	67.1	3.82E-08	19.8	68.4	11.8	7E-12	0.00375
10	34.3	65.7	9.75E-08	32.7	64.3	3.0	6E-2	0.00098

20	42.6	57.4	1.25E-08	39.1	57.5	3.4	3E-4	0.00400
40	48.1	51.9	1.30E-08	46.1	46.4	7.5	5E-4	0.00277
80	48.9	51.1	2.04E-08	46.7	48.0	5.2	6E-13	0.00380
160	50.1	49.9	3.46E-08	48.7	40.3	11.0	3E-4	0.00264
320	51.2	48.8	3.25E-08	50.0	37.8	12.2	6E-13	0.00244
640	51.1	48.9	1.30E-08	50.0	39.1	10.9	2E-4	0.00198
mean*	49.9	50.1	2.3E-08	48.3	42.3	9.4	n.r.	0.00273
S-3								
load kN/m^2	v_0 / v (%)	v_1 / v (%)	c_v (m^2/s)	v_0 / v (%)	v_1 / v (%)	v_2 / v (%)	c_v (m^2/s)	C_α (-)
5	40.6	59.4	3.50E-09	30.7	60.1	9.2	6E-13	0.00165
10	37.7	62.3	2.32E-08	33.2	51.2	15.6	6E-13	0.00439
20	41.8	58.2	2.09E-08	39.8	49.3	10.9	E-3	0.00266
40	45.0	55.0	1.16E-08	42.0	45.4	12.6	6E-13	0.00339
80	46.0	54.0	1.18E-08	44.4	45.6	10.0	8E-4	0.00182
160	46.8	53.2	9.81E-09	45.5	43.4	11.1	9E-4	0.00169
320	48.5	51.5	1.05E-08	47.5	39.7	12.9	6E-13	0.00140
640	48.6	51.4	9.27E-09	47.6	40.2	12.2	6E-13	0.00156
mean*	47.5	52.5	1.02E-08	46.2	42.2	11.6	n.r.	0.00161

* only after the preload

Table 3 Significant consolidation characteristics of S-1-S-3 samples according to the modified Terzaghi and modified Bjerrum model

3.3. *Rheological models*

There are more two rheological models were examined. The rheological models were also tested and fit to the data. The Poyting –Thomson model (that coincides with the Lo model known in the literature).

$$\varepsilon(t) = \sigma_1 \left(\frac{1}{E_1} + \frac{1}{E_3} - \frac{1}{E_3} e^{-E_3 t / \eta} \right) \tag{18}$$

where: ε: normalized deformation (-),
t: time (s),
σ: stress (kN/m^2),
E: Young - modulus (kN/m^2),
η: viscosity ratio (Ns/m^2).

and the Burger-model

$$\varepsilon(t) = \sigma_1 \left(\frac{t}{\eta_1} + \frac{1}{E_1} + \frac{1}{E_3} - \frac{1}{E_3} \cdot e^{-E_3 t / \eta_2} \right) \tag{19}$$

These four models were fit to the measured data (Figure 4), that is, the parameters v_0, c_v, C_α, t_0 and E_1, E_3, η_3 were determined with Wolfram Mathematica that provides the function closest to the measured data.

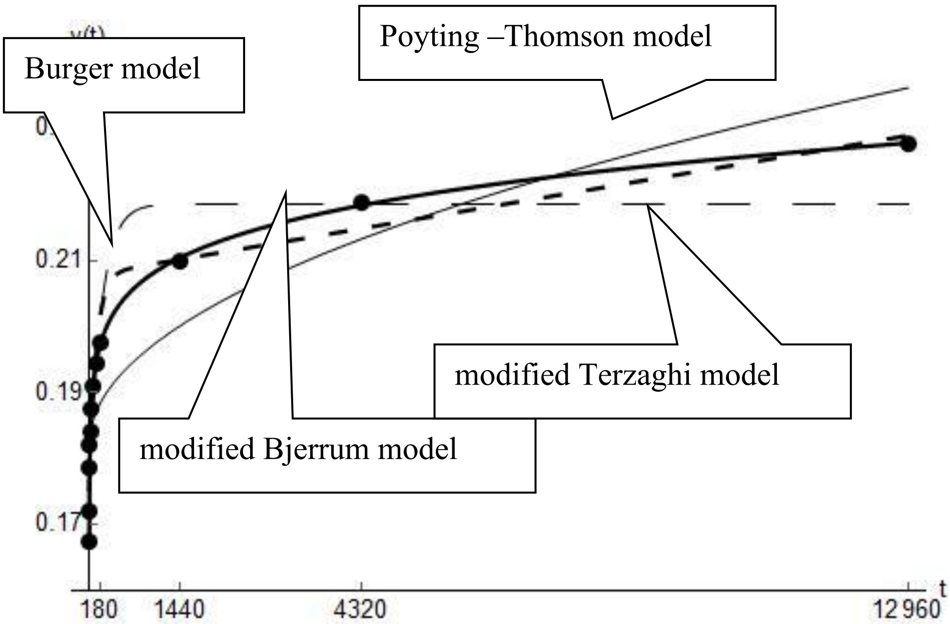


Figure 4 The consolidation of the waste sample (S-2 - 4. step)

The rheological models, degree of degradation and parameters defined according to load are shown in Table 4.

	Poyting -Thomson model			Burger model			
S-1							
load (kN/m²)	E_1 (kN/m²)	E_3 (kN/m²)	η (Ns/m²)	E_1 (kN/m²)	E_3 (kN/m²)	η_1 (Ns/m²)	η_2 (Ns/m²)
5	105	177	26310	117	259	454992	5249
10	42	114	12200	45	189	263181	1913
40	101	1267	12214	101	1337	4.40E+6	7720
80	109	1624	29158	110	1763	6.18E+6	18571
160	183	3256	126669	184	3546	1.15E+7	69816
320	319	7997	187314	320	8589	3.22E+7	120984
640	569	20928	4.25E+6	570	29965	2.06E+8	222367
S-2							
load (kN/m²)	E_1 (kN/m²)	E_3 (kN/m²)	η (Ns/m²)	E_1 (kN/m²)	E_3 (kN/m²)	η_1 (Ns/m²)	η_2 (Ns/m²)
5	151	156	5508	159	171	1.57E+6	3723
10	56	109	73698	59	329	356282	7139
20	57	237	46648	57	309	6.14E+6	33811
40	73	694	165607	74	988	6.68E+6	32622
80	120	1176	172261	121	1394	3.03E+7	104524
160	204	3390	550968	206	4405	2.21E+7	104502
320	362	7759	1.10E+6	365	9172	6.93E+7	238815

640	661	15636	3.04E+6	614	33462	4.92E+8	326783
S-3							
load (kN/m^2)	E_1 (kN/m^2)	E_3 (kN/m^2)	η (Ns/m^2)	E_1 (kN/m^2)	E_3 (kN/m^2)	η_1 (Ns/m^2)	η_2 (Ns/m^2)
5	105	177	3166	117	259	454992	2757
10	42	114	15559	45	189	263181	12282
20	101	1267	71823	101	1337	4.40E+6	20342
40	109	1624	71326	110	1763	6.18E+6	16595
80	183	3256	108260	184	3546	1.15E+7	31320
160	319	7997	635645	320	8589	3.22E+7	87256
320	569	20928	303176	570	29965	2.06E+8	134865
640	759	20745	679807	761	23030	2.36E+8	389163

Table 4 Significant consolidation characteristics of S-1-S-3 samples according to the Poyting-Thomson and Burger model

Mathematica uses Newton's method assuming that the errors are independent and normally distributed. The regression coefficients were above 0.998 in every case (0.998067, 0.999981, 0.998943, 0.999379).

4. CONCLUSIONS

After completing our own examination of the waste samples, evaluating and analyzing the results, the following statements are made:

- The examined waste due to its own weight and external mechanical load also has a vertical compression, which does not depend linearly on the applied normal stress, the waste is getting harder, but as a consequence of degradation, the constants of the material law describing the relationship between the load and settlement change and as the degree of degradation increases waste becomes harder. We propose to approximate the compression curves with a logarithmic function (1-3. equations and Figure 3.).
- It is recommended to use piecewise linearization (E_{oed}), which is useful for later calculations, calculating by the pre-load section and extrapolating it.
- Although it is practical to use one or two types of (fresh and degraded) waste models because of its simplicity, the modelling of compression can be made more precise by taking into account the degradation degree of waste. We recommend to use separate descriptive equations, characterized by different constants, according to the degree of degradation of the waste. Because of its own weight and external mechanical load, the examined waste suffers vertical compression as a function of time, which can be described more accurately by modifying the consolidation models used in soil mechanics. The modification of the consolidation model was the addition of the immediate compression, both in the Terzaghi and Bjerrum models. The applied parameters differ significantly from the ones used for soils. Due to regression testing and crawling as a physical phenomenon, we recommend to use the modified Bjerrum model.
- Modelling of deformation of waste samples can be adequately described by rheological, viscoelastic models, modelling becomes more accurate on one hand, if it is based on the degradation degree of waste, and on the other hand, the short-time behavior is described more precisely by the Burger model, than Poyting -Thomson model, which can be advised to describe long-time behaviour.
- Increasing degradation degree or load decreases value of the Poisson factor.

- Most of the deformities (more than 90%) are irreversible in the rheological sense. Hysteresis effect was not measurable. The reason for the high rate of residual deformations can be found in material composition and transformation happening after loading.
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Overall, it can be stated that the information provided in this article may contribute to a more accurate description of the deformation of municipal solid wastes, to clarify the starting data of a waste boulder modelling (eg FEM).

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