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Industrial pollution

GEOTECHNICAL CHARACTERISTICS OF INDUSTRIAL WASTE SLAG AND SLUDGE FROM SMEDEREVO STEEL MILL, SERBIA

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Abstract. In 2011, steel mill in Smederevo has started with the construction of the first certified plant for the industrial waste management in the Republic of Serbia. The most important facility of this plant is the industrial waste landfill with independent cells: bigger – for non-hazardous waste disposal and smaller – for hazardous waste disposal. Since this is the earthfill structure with a planned height of 50 m, one of the main geotechnical problems, which is being analysed in these cases, is landfill slope stability. Geotechnical parameters, especially shear strength parameters (internal friction angle – φ' and cohesion c') as well as general physical parameters (unit weights, moisture content, particle size distribution, permeability) are used in these analysis. Their values, obtained by laboratory geomechanical tests on different samples of slag and sludge, are presented in this paper.

Keywords: industrial waste, steel slag, sludge, geotechnical parameters, shear strength.

AIMS AND BACKGROUND

In Serbia, only in manufacturing plants of the steel mill Smederevo, over 1 150 000 t of industrial waste generate each year. Almost half of it (500 000 t) is been reused, either within the steel mill or beyond. The rest of waste, which includes solid industrial waste (slag) and sludge from the industrial waste water treatment plant are been permanently disposed. Thereby, the steel mill started with the construction of the first certified plant for industrial waste management in the Republic of Serbia. The aim of this plant, from the aspect of environmental protection, is to provide the space in a rational and safe way, i.e. to build a landfill for permanent disposal of eleven types of industrial waste and for temporary storage of certain waste types which are listed as secondary raw material. The total available capacity of the landfill is 4 685 000 m^3, of which 4 450 000 m^3 are planned for non-hazardous waste disposal and 235 000 m^3 for hazardous waste disposal.

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Estimated quantities of certain waste types, which would be disposed annually, are presented in Table 1 (Ref. 1).

Besides these estimated annual quantities, at the landfill will be disposed and 900 000 m^3 of slag from the blast furnace which is located at the site (Table 2) (Ref. 2).

Waste management plant has the following functional units: landfill body (consists of two separate cells: bigger – for non-hazardous waste disposal and smaller – for hazardous waste disposal, Fig. 1), manipulative-service plateau, internal roads and system of protective boundary channels.

Table 1. Annual quantity of waste for disposal[1]

Waste types	Classification	Quantity (t/year)	Reuse (%)	Density (t/m^3)	Volume (m^3)
BF lump slag	nHZW-solid	253685	20	1.553	130681
Convertor slag	nHZW-solid	260784	40	1.553	100754
Mixer slag	nHZW-solid	78201	25	0.894	65605
BF sludge	HZW-sludge	15361	0	1.606	9565
Neutralisation sludge	HZW-sludge	8477	0	1.111	7630
Refractory waste	HZW-solid	5286	30	1.960	1888
Steel turnings	nHZW-solid	147	50	1.842	40
Roll shop machinery waste	nHZW-solid	53	50	2.400	11
Tandem mill sludge	HZW-sludge	456	0	1.111	411
Filter cake	HZW-sludge	950	0	1.111	855
Tin mill sludge	HZW-sludge	13	0	2.000	6
Total		623413			317446

Table 2. Waste volumes for disposal from 1 year till 10 years[1]

Type of cell	Present waste (m^3)	Yearly production for landfilling (m^3)	Years	Total capacity needed (m^3)
nHZW-solid	900000	297091	1–5	2385455
HZW-solid	0	1888		9440
HZW-sludge	0	18467		92335
nHZW-solid	0	297091	6–10	1485455
HZW-solid	0	1888		9440
HZW-sludge	0	18467		92335

Fig. 1. Location of the waste management plant with the final look of landfills for hazardous and non-hazardous waste

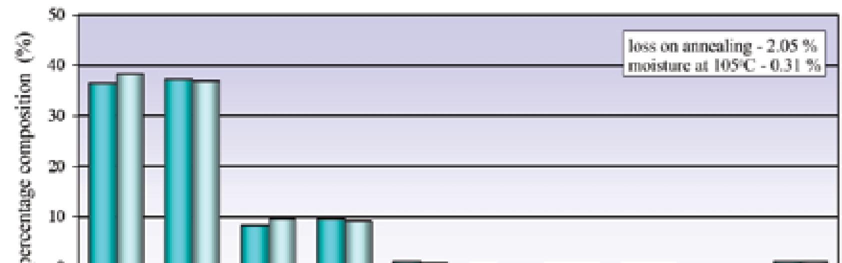
EXPERIMENTAL

There is no internationally accepted standard sampling procedure of industrial waste for the purpose of geomechanical tests. The reason for this is the extreme waste heterogeneity (by chemical and mineral composition, size and shape of fractions, different characteristics of individual waste types). Analysis of literature data showed that researchers used different sample sizes and different compositions of industrial waste for determination of physical-mechanical characteristics[2,3]. Prior mechanical preparation was mostly performed in terms of grinding (milling, crushing or simply removal of larger pieces) or tests included only small fractions of industrial slag from steel mills[4].

Results presented in this paper were obtained by tests on artificially prepared samples, taking into account moisture content, density, shape of waste particles and with respect to recommendations related to dimensions of used apparatus and size of the largest fractions in sample. For the first sample group formation non-hazardous industrial waste (nHZW) was used, which was taken from the location where it has already been disposed. The sample of hazardous waste (HZW) was taken directly from the process of industrial waste waters treatment (Fig. 2). Geomechanical laboratory tests of non-hazardous waste were carried out on 4 samples (U-1A,B and U-2A,B), and one sample of hazardous waste (U-3) was also laboratory tested. Both groups of industrial waste were treated as ‘artificial soil’, so the laboratory testing methods used in soil mechanics were applied for the definition of physical-mechanical parameters.

Fig. 2. Layout of hazardous waste (sludge) and non-hazardous waste (slag) which will be disposed at the landfill

The average values of chemical composition of non-hazardous waste samples (blast furnace slag – BF lump slag), on which laboratory geomechanical tests were performed, are presented in Fig. 3.



	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	K_2O	Cl	MnO
U-1A	36.42	37.16	8.22	9.47	1.03	0.47	0.37	0.50	0.012	1.09
U-1B	38.28	36.94	9.51	9.05	0.94	0.31	0.34	0.52	0.007	1.00

Fig. 3. Chemical composition of blast furnace slag

The results of performed particle size distribution analysis, without previous material preparation, for all three waste types, are presented in Fig. 4 (Ref. 5).

Shear strength is defined by direct shear test, using the direct shear apparatus. Material is previously crumbled, homogenised and mixed in order to ensure an adequate ratio of particle size distribution, i.e. ratio of characteristic apparatus dimension (L) and fraction size (d), $L/d \geq 5$. All tested samples had over 90% of particles smaller than 20 mm, and the rest (6–9%) were larger particles with maximum size of 40 mm.

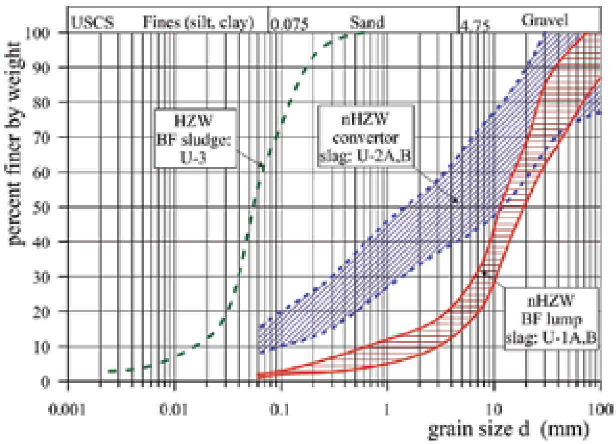


Fig. 4. Particle size distribution curves of tested industrial waste samples

RESULTS AND DISCUSSION

Industrial waste slag has quite good physical-mechanical characteristics[6]: specific gravity G_s = 3.2–3.6, dry unit weight γ_d = 16–19.2 kN/m^3, water absorption up to 3%, Los Angeles – abrasion 20–25%, hardness between 6 and 7 and California Bearing Ratio (CBR) can be over 100%. The results of performed laboratory tests showed that waste slag can be used in road construction, since it shows a good compaction characteristic and bearing capacity. Value of CBR ranged from 21.2 to 30.2%, and dry unit weight was in range γ_{dmax} = 16.4–18.9 kN/m^3 at the optimum moisture content w_{opt} = 6.6–11.1% (Fig. 5) (Ref. 5).

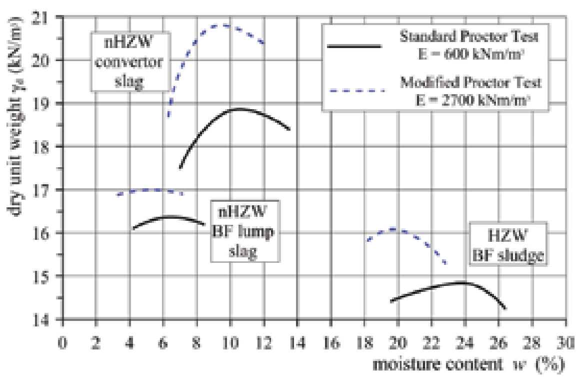


Fig. 5. Comparison of standard Proctor test and modified Proctor test of different industrial waste material

Correct design of landfill slopes implies knowledge of industrial waste shear strength, whether it refers to the contact of waste and natural soil, waste and natural protective systems or waste and artificial (geosynthetic) materials used as protective systems[7]. Tests in the direct shear apparatus showed that stress – displacement relationship has a different character in different industrial waste types, regardless to their density. So, for non-hazardous waste samples (U-1: BF lump slag and U-2: conv. slag), with unit weights γ = 15.5–16.5 kN/m^3 and under higher normal stresses (σ'_n = 200 kPa), this relationship for initial and medium displacements (Δl < 6 mm), is the most similar to behaviour of material with deformation hardening. The peak shear strength mobilises only at horizontal displacements large enough. Under lower normal stresses (σ'_n < 100 kPa), the stress-displacement relationship was mostly indicated the behaviour of waste similar to the behaviour of material with distinct plastic failure (Fig. 6).

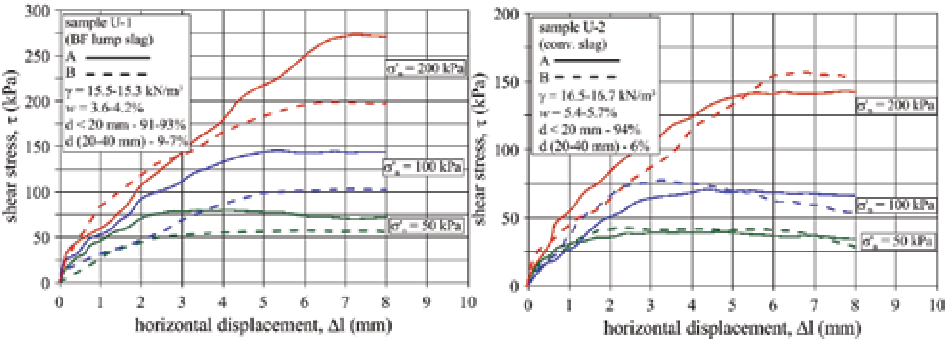


Fig. 6. Characteristic stress-displacement relationship for the non-hazardous waste samples

Stress-displacement relationship on a hazardous waste sample (U-3: BF – sludge), despite its better density (γ = 17.0 kN/m^3) and value of normal stresses, had different character. The stress-displacement behaviour of this sample is similar to the behaviour of soil with distinct plastic failure at small horizontal displacements (Δl < 3 mm, Fig. 7).

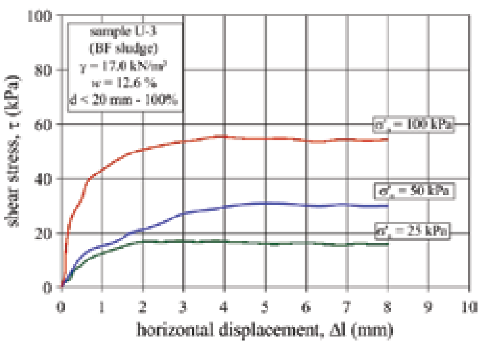


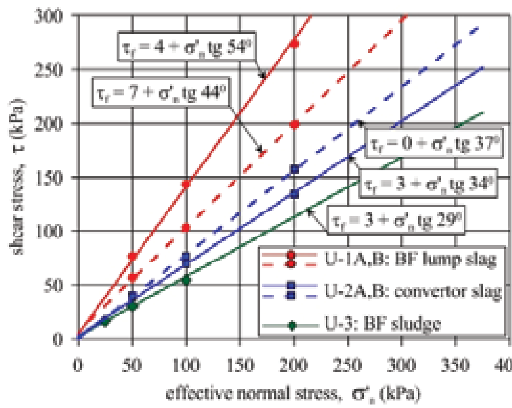
Fig. 7. Characteristic stress-displacement relationship for the hazardous waste sample

For defining the industrial waste shear strength (τ_f), a linear Coulomb-Mohr-Terzaghi equation is usually proposed[8]. This equation is a function of normal total stresses $\tau_f = f(\sigma_n)$, i.e. a function of normal effective stresses $\tau_f = f(\sigma'_n)$, using effective cohesion (c') and effective internal friction angle (φ'):

$$\tau_f = c' + \sigma'_n \operatorname{tg} \varphi' \tag{1}$$

Since that for all samples, regardless of normal stress levels, is clearly expressed failure, the peak values of shear strength were determined. The obtained values for linear form of Coulomb-Mohr-Terzaghi equation, are presented in Fig. 8, where they are compared with values of other authors that can be found in the literature[6,9]. This relationship is the simplest approximation of stress at failure, which is in reality presented with complex mechanism of interaction between grains of different sizes, shapes and even composition. Therefore, the interpretation was also performed based on the nonlinear failure envelope, using relations that correspond to the so-called hyperbolic shape[10]. Change of the effective secant shear strength angle is expressed as a function of normal stress in the following form

$$\varphi' = \varphi'_B + \frac{\Delta\varphi'}{1 + \sigma'_n / p_N}; \qquad \tau_f = c' + \sigma'_n \cdot \tan\left(\varphi'_B + \frac{\Delta\varphi'}{1 + \sigma'_n / p_N}\right) \tag{2}$$



Author		shear strength parameters c' (kPa)	φ' (°)
Noureldin and McDaniel (1990)		-	40 - 50
I. Z. Yildirim and M. Prezzi (2009)	BOF slag R_c=95-100% w=4-8%	-	45.3-48.3
	EAF slag R_c=95-100% w=10-14%	-	40.4-40.8
Rakić et al.	BF lump slag	4 - 7	44 - 54
	Convertor slag	0 - 3	34 - 37
	BF sludge	3	29

Fig. 8. Comparative display of proposed linear failure envelopes with literature data

On the BF lump slag samples (γ = 15.3–15.5 kN/m^3), analyses were performed with cohesion of c' = 0 and 4 kPa. This way, the nonlinear envelopes were obtained, which showed good matching with linear Coulomb-Mohr-Terzaghi shear strength equation (Fig. 9).

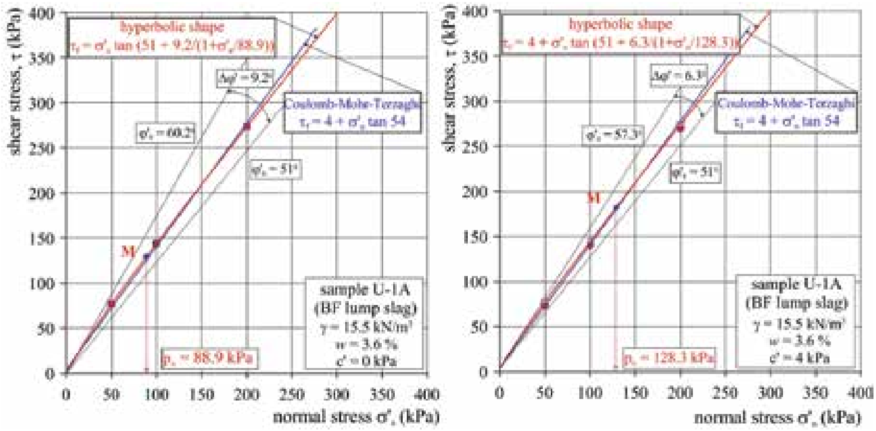


Fig. 9. Nonlinear shear strength equation of hyperbolic shape for BF lump slag

The same analyses were performed on the convertor slag samples (γ = 16.5–16.7 kN/m³), with cohesion values c' = 0 and 3 kPa. For the convertor slag also, nonlinear envelope showed good matching with linear Coulomb-Mohr-Terzaghi shear strength equation (Fig. 10).

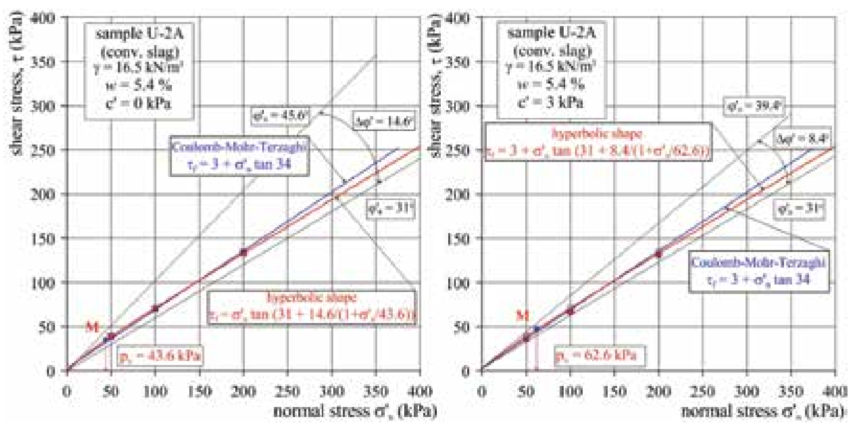


Fig. 10. Nonlinear shear strength equation of hyperbolic shape for convertor slag

Analysis with cohesion c' = 0 and 3 kPa was performed on BF sludge sample (γ = 17.0 kN/m³), and nonlinear and linear shear strength equations for both cohesion values are presented in Fig. 11.

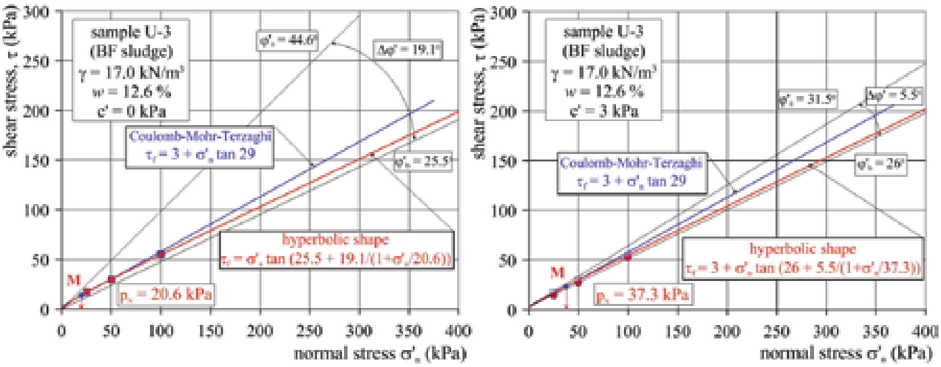


Fig. 11. Nonlinear shear strength equation of hyperbolic shape for BF sludge

Hyperbolic shape of shear strength equation has not been used so far for description of industrial waste shear strength, and therefore obtained nonlinear failure envelopes are compared with linear Coulomb-Mohr-Terzaghi equation and cumulatively presented in Fig. 12. To highlight the importance of using the nonlinear failure envelope and a significantly higher range of normal stresses, relationships for normal stresses interval from 0 to 1000 kPa are presented in Fig. 12. It can be seen that the proposed hyperbolic shape of nonlinear failure envelope showed good matching for the normal effective stresses interval $\sigma'_n = 0\text{–}200$ kPa, while for the normal effective stresses $\sigma'_n > 200$ kPa, deviation trend is expressed in terms of getting smaller values of internal friction angle, i.e. decrease of shear strength. Since the planned landfill height was 50 m, and that in these conditions the vertical effective stresses will be significantly higher than 200 kPa, for the stability analysis needs the nonlinear failure envelope of hyperbolic shape was used.

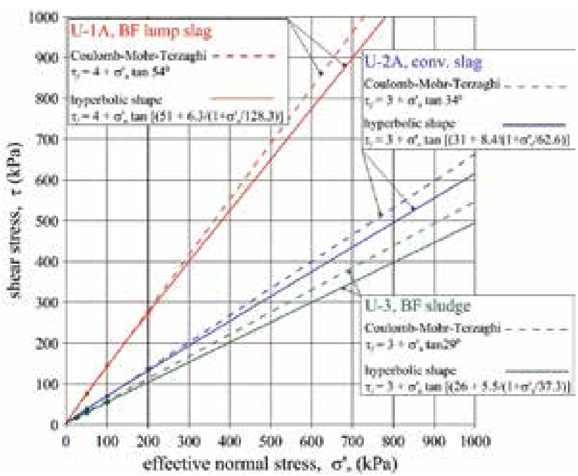


Fig. 12. Comparative review of proposed linear and nonlinear shear strength envelope of different industrial waste material

CONCLUSIONS

Problem of industrial waste disposal does not generally fall into any traditional engineering disciplines, but it is an interdisciplinary scientific area. However, despite the use of prescribed regulations, certain problems often occur because of insufficient knowledge of waste material in the landfill body. Waste material in the landfill body changes physical and mechanical characteristics over time due to constant circulation of leachate. Therefore, landfills that are more often designed are those that exceed requirements defined in the regulations in some key aspects that can endangered safety and certain technological systems and cause specific ecological consequences on the environment. One of these requirements is the analysis of the most important geotechnical aspects, primarily the landfill slope stability and prediction of size and time of waste settlement. This includes knowledge of physical-mechanical parameters of waste material (primarily the shear strength parameters). Values of the shear strength parameters, which are presented in this paper, vary depending on the industrial waste type, and therefore values that can be found in the world literature are different. The composition of steel slag varies from one region to another and from one country to another, which significantly affects the physical-mechanical properties. That is why these values cannot be directly taken from literature data without previous knowledge of chemical composition of steel slag, preparation method during the sample formation and performed procedure for their determination.

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