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DETERMINATION OF FRICTIONAL RESISTANCE AT THE CONTACT BETWEEN CHOSEN FURNACE WASTE AND GEOSYNTHETICS

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Abstract. Determination of direct slide coefficient and interfacial frictional resistance at the contact between the fill material and geosynthetic was the purpose of the paper. The fill material was an ash-slag mixture from Skawina Power Plant and from the settler of Arcelor-Mittal Poland Steel Plant in Kraków Płaszów. The shear strength and interfacial frictional resistance tests were carried out in the direct shear box apparatus at the moisture content close to optimal at the compaction indexes 0.90, 0.95 and 1.00. Test results revealed that the shear strength parameters of the analyzed ash-slag were high. The parameters describing the frictional resistance at the contact: ash-slag – geosynthetics were also high, which allowed obtaining high values of the direct slide coefficient as well as the coefficient of interfacial friction.

Key words: ash-slag mixture, shear strength, interfacial frictional resistance

INTRODUCTION

Soil reinforcement using geosynthetics is one of the most important function that they fulfil in civil or hydrotechnical engineering constructions. Reinforcement with geosynthetic improves mechanical properties of the soil thanks to tensile stress that reduces shear forces and thereby increases shear strength of the soil [Duszyńska and Bolt 2004]. Thanks to the geosynthetic reinforcement soil is able to carry a greater load, embankment slopes can be steeper and greater external loads can be applied on road pavements, stacking yards or parking places.

Using geosynthetics requires research on interaction between soil and reinforcement. If a geosynthetic is not chosen properly, it can cause a reduction of shear strength of soil and lead to a construction failure. Another factor that influences proper functioning of

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the reinforced soil is a selection of a fill material and its compaction. Usually it is recommended to use non-cohesive soils, well-grained, with high hydraulic conductivity and shear strength.

Determination of the interaction parameters of soil-geosynthetic system can be carried out based on two tests: the shear box apparatus test, where a layer of soil is moving along the geosynthetic or the pull-out test, where geosynthetic is pulled out from between two layers of soil. Tests on the contact resistance should be carried out for each type of geosynthetic and fill material. Soil compaction has also a significant influence on the values of the resistance; a higher compaction will cause an increase in contact resistance and therefore in coefficients that describe how soil – geosynthetic system works.

PURPOSE, CALCULATIONS AND TESTS METHODS

The purpose of this research was to determine the values of a direct slide coefficient and contact resistance at the contact between fill material and geosynthetic. The fill material was ash-slag mixture from "Skawina" Power Plant (samples 1 and 2) and from the settler of ArcelorMittal Poland Steel Plant in Kraków Płaszów. Nonwoven geotextile Secutex R 1204 and woven geotextile ACETex GT40/40 were used in tests with ash-slag from Skawina and nonwoven geotextile Secutex 401-GRK 5C and R 1204 were used in tests with ash-slag from ArcelorMittal Poland Steel Plant.

Basic physical and compaction parameters of ash-slag mixtures were determined using standard methods. Grain-size distribution was determined using sieve method (for $d \geq 0{,}063$ mm) and hydrometer (for $d < 0{,}063$ mm), whereas specific density – using volumetric flask and distilled water. Optimum moisture content and maximum dry density were determined in Proctor apparatus in the 2.2 dm^3 cylinder at the compaction energy of 0.59 J·cm^{-3}.

Parameters that characterize contact resistance between the ash-slag and geosynthetic were determined as in shear strength test, basing on the linear Coulomb criterion:

$$\tau_{fa} = \sigma_n \cdot \tan\delta + c_a \tag{1}$$

where: τ_{fa} – contact resistance at the moment of shearing [kPa],
σ_n – normal stress [kPa],
δ – interface friction angle [°],
c_a – adhesion [kPa].

Samples for shear strength and contact resistance tests were formed directly in the box of apparatus (Fig. 1) at the moisture content close to optimum (Table 1) at the compaction indexes I_S = 0.90, 0.95 and 1.00. Sample (1) of the ash-slag form Skawina Power Plant and the ash-slag from ArcelorMittal Poland Steel Plant were tested in a 12 × 12 cm box (only grains below 10 mm were used). The height of the sample was 7.7 cm in shear strength tests and 2.9 cm in contact resistance tests. Sample (2) of the ash-slag from Skawina Power Plant was tested in a large shear box apparatus, in a 30 × 30 cm box. The height of the sample in shear strength tests was 13.6 cm and in contact resistance tests – 6.6 cm.

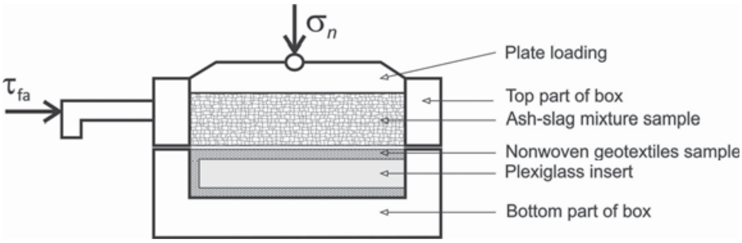

Fig. 1. Diagram of the box from the shear strength apparatus adapted to the contact resistance testing

During contact resistance test the lower part of the box was filled with plexiglas or wooden pad on top of which a geosynthetic was placed and then an ash-slag sample was formed. Samples were subjected to the load from 50 to 400 kPa and then they were sheared till 10% of horizontal deformation was reached. Maximum value of shear stress was accepted as a shear criterion. For design purposes it is recommended to assume the value of slide resistance of the construction with geosynthetic reinforcement based on the equation that describes a direct slide coefficient [Duszyńska and Bolt 2004]:

$$\alpha_{ds} = \overline{\alpha_s} \cdot \frac{\tan\delta}{\tan\phi} + (1 - \overline{a_s}) \tag{2}$$

where: δ – angle of interfacial friction at the contact between soil and flat surface of the reinforcement [°],
ϕ – angle of internal friction [°],
$\overline{a_s}$ – coefficient of the effective surface of reinforcement in a shear plane [–].

For woven and nonwoven fabrics where slide resistance depends on shearing between the soil and flat surface of the reinforcement it is assumed that $\overline{\alpha_s} = 1$, so the direct slide coefficient is calculated as follows:

$$\alpha_{ds} = \frac{\tan\delta}{\tan\phi} \tag{3}$$

Conventional geosynthetics interact with the soil on the basis that adhesion is induced by friction. Therefore the second parameter is the adhesion coefficient, which depends on surface friction that occurs between the reinforcement and the soil and it can be determined as follows [Duszyńska and Bolt 2004]:

$$\alpha_b = \overline{\alpha_s} \cdot \frac{\tan\delta}{\tan\phi} + \left(\frac{\sigma_b}{\sigma_n}\right) \cdot \left(\frac{\overline{a_b} \cdot B}{2S}\right) \cdot \frac{1}{\tan\phi} \tag{4}$$

where: δ, ϕ, $\overline{a_s}$ – as above,
$\overline{a_b}$ – coefficient of the effective surface of reinforcement in a plane perpendicular to the pull direction [–],
B, S – dimensions of ribs in case of net reinforcement [m],

$\frac{\sigma_b}{\sigma_n}$ – ratio of passive pressure to stress perpendicular to the reinforcement surface [–].

For woven and nonwoven geotextiles it can be assumed that $\overline{\alpha_s} = 1$ and $\overline{\alpha_b} = 0$, so direct slide and adhesion coefficients, of these materials equal [Duszyńska and Bolt 2004]:

$$\alpha_b = \frac{\tan\delta}{\tan\phi} = \alpha_{ds} \tag{5}$$

Zabielska-Adamska [2006] and Huang and Bathurst [2009] stated that shear strength at interfacial contact can be analyzed using efficiency factors defined by the following equations:

$$E_\phi = \frac{\tan\delta}{\tan\phi} \text{ and } E_c = \frac{c_a}{c} \qquad (6), (7)$$

where: c – cohesion of the fill material, other symbols defined in equations (1) and (2).

Comparison of the equations (5) and (6) shows full conformity of the direct slide coefficient, adhesion and efficiency factors. It should be emphasized that equations from (2) to (5) do not take adhesion into consideration, so they should be used when the fill material is a non-cohesive soil. However the tests that were carried out show that in case of cohesive soils as well as industrial wastes adhesion occurs at the contact between the fill material and geosynthetic [Zabielska-Adamska 2006]. Bouazza and Wei [1993] proposed to include adhesion in determining the coefficient of interfacial friction at the contact between the fill soil and geosynthetic. This coefficient is determined from the relation:

$$\mu = \frac{c_a}{\sigma_n} + \tan\delta \tag{8}$$

where: c_a – adhesion [kPa],
σ_n – normal stress [kPa],
δ – angle of interfacial friction [°].

GEOSYNTETHETIC CHARACTERISTICS

In contact resistance tests the following geotextiles, produced by NAUE G.m.b.H. & CO.KG., were used: nonwoven Secutex type 401-GRK 5C and type R 1204 and woven ACETex type GT40/40.

Secutex is a needle-punched nonwoven geotextile made from polypropylene fibres, it is resistant to rot, moisture and chemicals [Maro 2010]. Geotextiles used in tests differ greatly in technical parameters (Table 1), which is the result of different kinds of polypropylene fibres that were used to make them. Secutex R 1204 is produced from recycled fibres and GRK from unprocessed ones. Secutex geotextiles are used in water engineering, landfills, highways and tunnels. They can also be used in drainage systems as filters that will prevent soil particles from leaching out [Maro 2010].

Table 1. Technical parameters of used geosynthetics [www.naue.com; www.amago.pl]

No.	Parameter	Unit	Value for		
			nonwoven geotextile		woven geotextile
			Secutex 401-GRK 5C	Secutex R 1204	ACETex GT40/40
1	G.S.M. (mass per unit area)	$g{\cdot}m^2$	400	1200	no data
2	Thickness	mm	3.3	9.5	no data
3	Tensile strength longitudinal/transverse	kN·m	18.0/25.0	22.5/40.0	40/40
4	Elongation at maximum strength	%	60/40	90/60	16/8
5	Static puncture force	N	4000	6000	5000
6	Elongation at static puncture strength	%	35	50	no data
7	Effective opening size	mm	0.08	0.08	no data

ACETex geotextiles are PVC coated and made by weaving polyester fibres. They are characterized by high resistance to mechanical damages, UV radiation or chemical and biological corrosion. Thanks to high strength and deformation resistance ACETex can be used along with any type of fill material. This woven geotextile is also necessary whenever the two functions – reinforcement and separation – are required at the same time [Gasińska 2009].

TESTS RESULTS AND THEIR ANALYSIS

Physical properties

In terms of geotechnics (Table 2) the ash-slag from Skawina Power Plant correspon-ded with poorly graded (sample (1)) or well graded (sample (2)) silty sand and from ArcelorMittal Poland Steel Plant – with poorly graded fine sand.

Sand fraction content was from 57 to 66% and it dominated in grain-size distribution of ash-slag from Skawina Power Plant. There was from 12 to 16% of gravel, from 17 to 25% of silt and close to 2 to 6% of clay. In case of ash-slag from ArcelorMittal Poland Steel Plant sand fraction also dominated – there were almost 90% of sand, 10% of silt, about 0.5% of clay and 0.5% of gravel.

Specific density varied in a quite wide range and equalled from 2.36 $g{\cdot}cm^{-3}$ for ash-slag from ArcelorMittal Poland Steel Plant up to 2.48–2.54 $g{\cdot}cm^{-3}$ for ash-slag from Ska-wina Power Plant. Maximum dry density was from 1.11 to 1.29 $g{\cdot}cm^{-3}$ at the optimum moisture content from 31 to 36%.

Shear strength parameters

Shear strength tests results (Table 3) showed that increase in compaction index from 0.90 to 1.00 caused an increase in the angle of internal friction on average by 20% for ash-slag from Skawina Power Plant and by about 6% for ash-slag from ArcelorMittal Poland Steel Plant. Cohesion of ash-slag from Skawina Power Plant increased along with the increase in compaction on average by 29%, in case of ash-slag from ArcelorMittal Poland Steel Plant a 1.5-times increase of cohesion was noticed.

Table 2. Geotechnical characteristic of ash-slag mixture

No.	Parameter	Value for the mixture from: Skawina Power Plant sample (1)	Skawina Power Plant sample (2)	ArcelorMittal Poland Steel Plant
1	Fraction content [%]:			
	– gravel Gr: 63 ÷ 2 mm	16.0	12.0	0.6
	– sand Sa: 2 ÷ 0.063 mm	65.5	57.0	88.9
	– silt Si: 0.063 ÷ 0.002 mm	17.0	25.0	10.0
	– clay Cl: < 0.002 mm	1.5	6.0	0.5
2	Name acc. to [PN–EN ISO 14688:2006]	siSa silty sand	siSa silty sand	FSa fine sand
3	Uniformity coefficient [–]	8.3	28.3	2.5
4	Coefficient of curvature [–]	1.08	3.89	0.77
5	Specific density [g·cm^{-3}]	2.48	2.54	2.36
6	Optimal moisture content OMC [%]	30.6	36.1	32.5
7	Maximum dry density [g·cm^{-3}]	1.26	1.11	1.285

Table 3. Values of angle of internal friction (ϕ) and cohesion (c) of ash-slag mixtures

Compaction index	Location of sampling – landfill: Skawina Power Plant sample (1)[a]		Skawina Power Plant sample (2)[b]		ArcelorMittal Poland Steel Plant[c]	
I_S [–]	ϕ [°]	c [kPa]	15° [°]	c [kPa]	15° [°]	c [kPa]
0.90	35.2	19.9	28.0	19.8	38.0	18.9
0.95	38.5	23.3	–	–	39.8	31.0
1.00	42.5	26.0	33.4	25.5	40.1	45.8

[a]Acc. to Gruchot and Resiuła [2011].
[b]Acc. to Gruchot and Świgost [2012].
[c]Acc. to Zawisza et al. [2010].

The highest values of angle of internal friction were obtained for ash-slag from ArcelorMittal Poland Steel Plant, which can be the result of high content of sand fraction. In case of cohesion ash-slag mixtures had similar values at the compaction index of I_S = = 0.90. Whereas when I_S = 0.95 and 1.00 the highest values were obtained for ash-slag from ArcelorMittal Poland Steel Plant and they were higher than values for the other samples by adequately 33 and 38%. This could also be caused by high sand fraction content in ash-slag from ArcelorMittal Poland Steel Plant (by over 36 to 56%), where a significant content of fine sinters with high surface roughness was noticed. Therefore high values of cohesion were the effect of particles interlocking and not interparticle bonding that occurs in fine-grained mineral soils.

In general it can be stated that the tested ash-slag has high strength parameters, which is confirmed by results of tests on power plant wastes carried out by the authors [Zydroń et al. 2007, Gruchot and Łojewska 2011, Gruchot and Zydroń 2013] and other authors as well [Kim et al. 2005, Pal and Ghosh 2009, Kumar et al. 2014].

Parameters of contact resistance

Parameters of contact resistance at the contact geosynthetic – ash-slag from Skawina Power Plant depended on its compaction. Increase in compaction index from I_S = 0.90 to 1.00 caused an increase of the angle of interfacial friction by almost 15% for both geotextiles (Table 4). Values of adhesion at the contact with nonwoven Secutex 401 GRK 5C increased by about 17% and at the contact with woven ACETex GT40/10 by 8%. While comparing values of the angle of interfacial friction of ash-slag from Skawina Power Plant and both geosynthetics it was stated that slightly higher values (by about 2°) were obtained for nonwoven geotextile. In case of adhesion higher values, by about 13 to 17 kPa, were also obtained for nonwoven geotextile. Relations between parameters of frictional resistance obtained for both geosynthetics were connected with their roughness. Nonwoven geotextile had much lower roughness in relation to the woven one and therefore it had lower values of frictional resistance.

Values of the angle of interfacial friction of ash-slag from ArcelorMittal Poland Steel Plant at the compaction index of I_S = 1.00 were similar for both nonwoven Secutex geotextiles (Table 4), whereas adhesion was almost 2-times higher for Secutex R 1204.

While comparing the values of the angle of interfacial friction for ash-slag from ArcelorMittal Poland Steel Plant with the values for ash-slag from Skawina Power Plant and both goetextiles it was stated that they were higher by about 2–4°. Whereas values of adhesion for ash-slag from ArcelorMittal Poland Steel Plant (for both geotextiles) were similar to the results obtained on the contact between ash-slag from Skawina Power Plant and woven geotextile ACETex GT40/40 (the differences did not exceed 4 kPa) and from 2- to 3.5-times lower in case of nonwoven geotextile 401-GRK 5C.

Table 4. Values of the angle of interfacial friction (δ) and adhesion (c_a) at the contact between ash--slag and geosynthetic

Compaction index	Location of sampling – landfill:							
	Skawina Power Plant sample (1)[a]		Skawina Power Plant sample (2)[b]		ArcelorMittal Poland Steel Plant[c]			
	Geosynthetic							
	Nonwoven geotextile 401-GRK 5C		Woven geotextile GT40/40		Nonwoven geotextile Secutex			
					401-GRK 5C		R 1204	
I_S [–]	δ [°]	C_a [kPa]	δ [°]	C_a [kPa]	δ [°]	C_a [kPa]	δ [°]	C_a [kPa]
0.90	33.5	22.6	31.7	8.8	–	–	–	–
0.95	35.1	24.2	–	–	–	–	–	–
1.00	37.8	26.5	36.4	9.5	39.8	13.1	39.0	7.7

[a]Acc. to Gruchot [2013].
[b]Acc. to Gruchot and Świgost [2012].
[c]Acc. to Cholewa and Zydroń [2013].

Values of adhesion at the contact between ash-slag from ArcelorMittal Poland Steel Plant and nonwoven and woven goetextiles were relatively small. Similar values of this parameter for nonwoven geotextiles are given by Basudhar [2010], who carried out tests on friction between geosynthetics and compacted sand. Low values of adhesion at the contact between geosynthetics like HDPE and PCV films and soil are also presented in the Wasti and Özdügün's paper [2001]. On the other hand Kumar et al. [2013] indicate that adhesion depends also on the moisture content of the fill material.

Comparison of the results

Figure 2 presents a comparison of the obtained values of the parameters describing shear strength and frictional resistance at the contact ash-slag – geosynthetics. It was stated that values of the angle of interfacial friction at the contact between nonwoven Secutex 401 GRK 5C and ash-slag from Skawina Power Plant were lower than values of the angle of internal friction for ash-slag, whereas for the same geotextile and ash-slag from ArcelorMittal Poland Steel Plant these parameters were almost the same. While comparing values of adhesion and cohesion it can be stated that they were the same in case of ash-slag from Skawina Power Plant and almost 4-times lower in relation to cohesion of ash-slag from ArcelorMittal Poland Steel Plant.

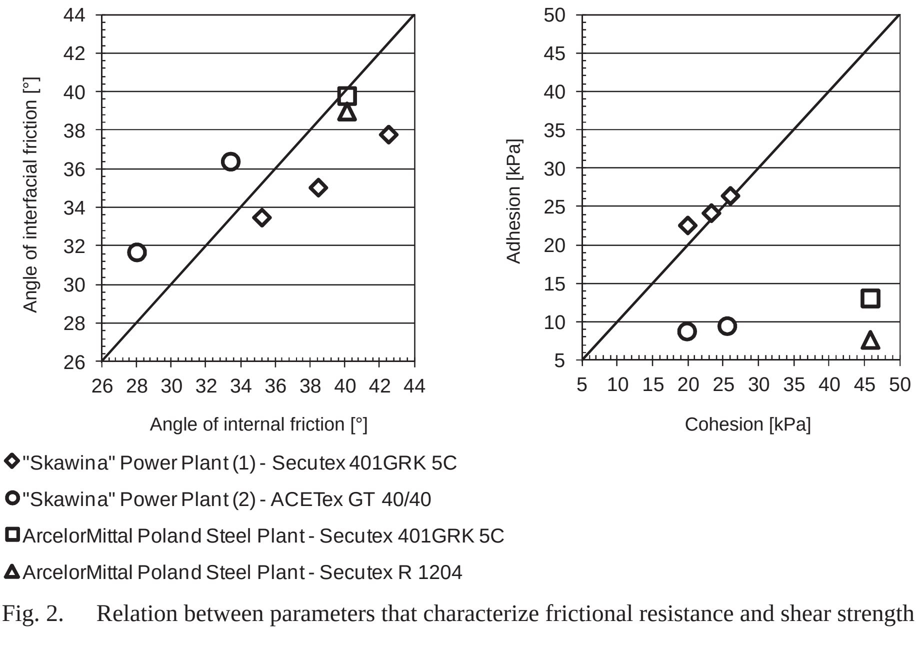

Fig. 2. Relation between parameters that characterize frictional resistance and shear strength

The angle of interfacial friction at the contact between ash-slag from Skawina Power Plant and woven geotextile ACETex GT40/40 was significantly higher in relation to the angle of internal friction, whereas adhesion was on average 2.5-times lower in relation to cohesion.

Frictional resistance tests at the contact between nonwoven geotextile Secutex R 1204 and ash-slag from ArcelorMittal Poland Steel Plant showed that values of angle of interfacial friction and internal friction were similar, but adhesion was about 6-times lower than cohesion.

Tests results show that nonwoven geotextile Secutex has higher parameters of frictional resistance at the contact with ash-slag in relation to woven geotextile ACETex GT40/40. This relation can result from the fact that woven geotextile had lower roughness.

Values of the efficiency factors of interface angle friction and adhesion calculated according to equation (6) are consistent with the values of the coefficient of interfacial friction calculated according to formula (8) and they showed that the highest slide resistance was obtained for woven geotextile ACETex GT40/40 and ash-slag from Skawina Power Plant, whereas the lowest – for nonwoven geotextile Secutex 401 GRK 5C and ash-slag from Skawina Power Plant (Fig. 3). This coefficient was about 1.2 in case of woven geotextile ACETex GT40/40 and close to 1.0 in case of ash-slag from ArcelorMittal Poland Steel Plant and both nonwoven geotextiles. While for the sample (1) of ash-slag from Skawina Power Plant and nonwoven geotextile Secutex 401 GRK 5C the value of the coefficient was about 0.82.

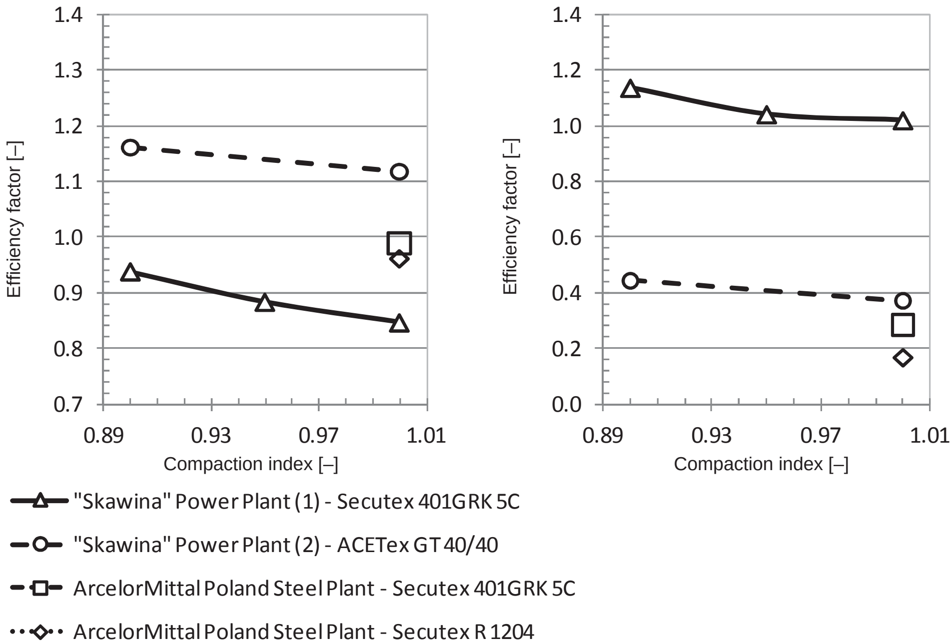

Fig. 3. Relation between the efficiency factor and compaction at the contact between ash-slag mixture and geosynthetic: a – efficiency factor of interface friction angle by formula (6), b – efficiency factor of adhesion by formula (7)

Values of the efficiency factor of adhesion calculated using formula (7) showed that the highest adhesion was at the contact between nonwoven geotextile Secutex 401 GRK 5C and the sample (1) of ash-slag from Skawina Power Plant (the factor was from about 1.0 to nearly 1.2) whereas the lowest – at the contact between the ash-slag from ArcelorMittal Poland Steel Plant and nonwoven geotextile Secutex R 1024 (the factor was 0.19). It should be emphasized that in this case the values of the factor at the contact between the woven geotextile ACETex GT40/40 and the ash-slag from Skawina Power Plant were on average 0.4 so as opposed to the efficiency factor of interface angle friction they were some of the lowest in these tests.

Calculations of the direct slide coefficient also showed a slight decrease in slide resistance of the ash-slag mixture along the geosynthetic and adhesion along with compaction, which was the result of increasing differences between values of the angle of internal friction and the angle of interfacial friction that occurred at high values of compaction index of the ash-slag.

Coefficient of interfacial friction

The friction coefficient calculated using formula (8) depended on the vertical stresses and it decreased along with their increase. Increase in normal stresses caused a decrease of the friction coefficient by about 50% at the contact between ash-slag from Skawina Power Plant and nonwoven Secutex 401 GRK 5C and by about 30% at the contact with woven ACETex GT40/40 (at both tested compaction indexes) (Fig. 4). Calculations of the friction coefficient at the contact nonwoven geotextile – ash-slag from ArcelorMittal Poland Steel Plant showed that along with the increase in normal stress there was a decrease in the friction coefficient by 32% for nonwoven geotextile Secutex 401 GRK 5C and by 24% for Secutex R 1024.

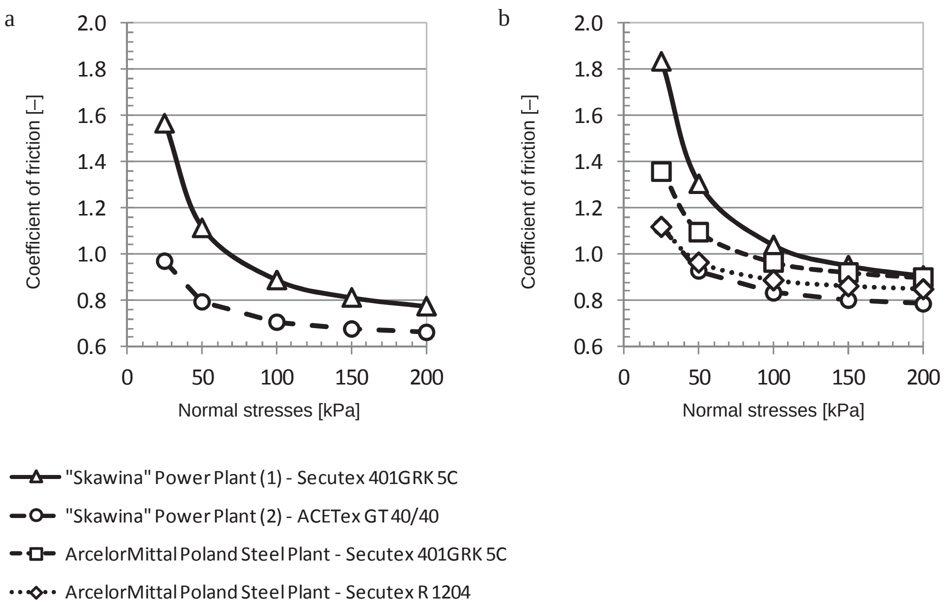

Fig. 4. Relation between the coefficient of friction and normal stresses and compaction at the contact between ash-slag mixture and geosynthetic: a – coefficient of friction at $I_S = 0.90$, b – coefficient of friction at $I_S = 1.00$

Analysis of the obtained values of the friction coefficient at the contact between geosynthetic and ash-slag from Skawina Power Plant showed that increase in compaction index from $I_S = 0.90$ to 1.00 caused increase in the value of the coefficient by about 17%.

In case of all analyzed geosynthetics it can be stated that there is a downward trend in the relation between the friction coefficient and normal stress, although obtained values of this parameter tend to stabilize in the upper range of normal stresses.

On the other hand, assuming that interaction between geosynthetics and soil is based on the friction, the safer method seems to be the one where adhesion is not taken into consideration. This issue is the topic of many scientific publications, where authors propose using nonlinear equations describing friction characteristics in the contact zone between geosynthetics and fill material (Giroud et al. 1993, Wasti and Özdügün 2001, Bacas et al. 2011, Hossain et al. 2012). This way adhesion is omitted and friction resistance depends on normal stress.

CONCLUSIONS

Shear strength parameters of the analyzed ash-slags were high, so earthen constructions built from this material will have high stability. The parameters describing frictional resistance at the contact ash-slag – geosynthetics were also high, therefore high values of the direct slide coefficient as well as the coefficient of interfacial friction were obtained. Hence ground reinforcement using geosynthetics and ash-slag mixtures as earthen materials is an important issue in the aspect of natural materials protection.

The authors propose to omit adhesion in design calculations because of the fact that it is the frictional resistance that plays a significant part in transmitting tensile stress on the reinforcement. Regarding obtained results of frictional resistance in case of woven geotextiles it can be assumed that the value of direct slide coefficient is 1.0 and in case of nonwoven geotextiles – 0.85.

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OKREŚLENIE OPORÓW TARCIA NA KONTAKCIE WYBRANYCH ODPADÓW PALENISKOWYCH Z GEOSYNTETYKAMI

Streszczenie. Celem badań było określenie wartości współczynnika bezpośredniego poślizgu i oporu tarcia międzyfazowego na kontakcie mieszaniny popiołowo-żużlowej pobranej ze składowiska Elektrowni „Skawina” oraz z osadnika Huty ArcelorMittal Poland w Krakowie Pleszowie a geosynetykiem. Wyniki badań wykazały, że parametry wytrzymałości na ścinanie popioło-żużli były duże. Parametry charakteryzujące opory tarcia na kontakcie mieszanina popiołowo-żużlowa – geosyntetyk były również duże, co pozwoliło uzyskać duże wartości współczynnika bezpośredniego poślizgu, jak również współczynnika tarcia międzyfazowego. W związku z tym wzmacnianie podłoża budowli z wykorzystaniem geosyntetyków i stosowanie mieszanin popiołowo-żużlowych do celów budownictwa ziemnego jest ważnym i istotnym zagadnieniem w aspekcie ochrony kruszyw naturalnych.

Słowa kluczowe: mieszanina popiołowo-żużlowa, wytrzymałość na ścinanie, opór tarcia międzyfazowego

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