Pumped HYDROelectric Storage in post MINEd areas to support regional net-zero emission energy systems development – HYDROMINE

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D 2.1. Results of laboratory testing of materials used in construction of reservoir slopes

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D.2.1. Results of laboratory testing of materials used in construction of reservoir slopes

1. PARAMETERS INFLUENCING SLOPE STABILITY

In order to determine the geotechnical parameters, it is necessary to establish the crucial factors that influence slope stability. These are:

1.1. Geological and hydrogeological factors

➢ ***Geological factor*** - although not a direct cause of landslides, it plays a significant role in their formation and, therefore, the methods and techniques used to estimate slope stability must be chosen according to geological conditions. This requires the geological factor to be expressed as accurately as possible in engineering terms, which determines the degree of validity of the results obtained by the methods applied in stability analyses.

➢ ***Hydrogeological factor*** – plays an important role in the formation of sliding surfaces, as the presence of water in rocks influences the state of unit stresses through the following elements:

- variation in the moisture content of unsaturated soils;
- hydrostatic pressure of water in pores;
- hydrodynamic pressure of water.

1.2. Natural mechanical and geomechanical factors

➢ ***Natural mechanical factors*** - these refer to flowing waters, lakes, torrents, etc., which can cause erosion both on slopes and at their base. In most cases, erosion at the base of a slope or hillside has led to landslides as a result of changes in stress conditions, which occur from the very first signs of erosion.

➢ ***The geomechanical factor*** – this is one of the most important factors and must be taken into account based on how the main parameters of rock mechanical strength, namely cohesion and internal friction angle, are determined in the laboratory and in situ. Consideration of the geomechanical factor always involves determining the strength parameters on the weakest surfaces of the slope, where the sliding forces are concentrated. Such surfaces can be considered stratification surfaces, fracture planes, or contact surfaces

between waste deposits and the base soil. In the case of waste rock dumps, it is considered that in the initial phase the deposited material lacks cohesion. However, due to the action of the geological load, the dump compacts naturally and acquires a certain cohesion, which must be taken into account in stability calculations. By highlighting the geomechanical indices of rocks, conclusions can be drawn about their behavior in different situations of loading, stress, composition, and settlement. The more accurately the physical and mechanical characteristics are determined, the easier it is to interpret the deformation processes that may be encountered in practice, and the more reliable the calculations of strength and stability become, and, implicitly, the choice of certain design solutions, ensuring their stability and effective management of technological processes. The risk of the solutions adopted is related to the choice of calculation parameters involved in estimating the stress states that occur in rock masses.

- ***Physical and State Parameters***
  - *Bulk and specific weight* - the apparent specific weight (γa) expresses the weight of the unit volume of rocks and mineral substances in their natural state and is usually determined in the laboratory using various methods depending on the nature of the rock, with cohesion being the main factor to be taken into account. Thus, in the case of consolidated rocks, test specimens with regular geometric shapes are used for the linear dimension method, while for non-cohesive rocks, the stamp method is used. Some methods, such as the paraffin wax method and the mercury immersion method, are applicable to both hard and less cohesive rocks. The stamping method is used more in the field to determine the apparent specific weight of earthy rocks. The apparent specific weight is commonly used in design calculations to determine the weight of rock masses and calculate pressures, to evaluate the active thrusts and passive resistances of earth masses, to assess the stability of embankments and slopes, as well as to establish reserves of useful minerals and rocks, or to assess other physical characteristics of rocks.
  - *Porosity* - is the ratio between the volume of voids between solid particles and the total volume of the material (including pores). The volume of pores depends on the type of grains that make up the rock, how they are sorted, and how they are arranged.

- *Humidity* - moisture is the ratio between the mass of water contained in pores and the mass of solid material and plays an important role in assessing the stability of embankments and slopes, as it influences the strength characteristics of rocks.

➢ ***Shear Strength Parameters*** - cohesion and internal friction angle are the main mechanical parameters for weakly cohesive and non-cohesive rocks that are taken into account in the stability analysis of slopes and embankments. Cohesion (c) is the binding force between the solid particles of a rock, soil, or useful mineral substance, which opposes their detachment or sliding under the action of external forces.The angle of internal friction (φ) is the angle whose trigonometric tangent represents the coefficient of internal friction between the particles of mobile rocks or soil.

- *Shear strength* (τ) represents the resistance that a rock or soil opposes to breaking by sliding shearing. Breaking into a mass of soil occurs where its shear strength is exceeded. Depending on the nature of the rocks, several methods are used to determine shear strength:
  - for soft and/or fractured rocks – direct shearing;
  - for rocky and semi-rocky rocks – shearing along a forced shear plane;
  - indirect method, by determining the breaking strengths under uniaxial compression and tension.

➢ ***Deformability Parameters (for numerical/FEM analyses)***

- *Young's Modulus (E)* - used to calculate the initial settlements and deformations of the slope under its own weight.
- *Poisson's Ratio* (μ) - defines the transverse deformation and is necessary to establish the three-dimensional stress state.

These rock characteristics are determined both in the laboratory and in the field in situ, on disturbed or undisturbed samples.

1.3. Anthropogenic (technogenic) factors

This refers to changes in the state of stress and tension in slopes and hillsides caused by human engineering activities. These factors include overloading the upper part of slopes by placing and transporting machinery, storing various types of sterile rock or other waste, or excavating rock at the bottom of slopes. These factors alter the ratio between the resistance forces and the forces that cause the slope to slide.

This category also includes the geometric elements of the slope or hillside (slope α and height h) which are established by geotechnical designs and which influence the degree of stability. For example, an increase in slope causes an increase in tangential stress, the maximum value of which is recorded at the foot of the slope.

1.4. Hydrometeorological and seismic factors

- ***Precipitation - t***hey lead to an increase in the moisture content of the rocks that make up the slope and, implicitly, to a reduction in its stability reserve or even to its sliding. It has been found that most landslides occur during periods of heavy rainfall (most often in spring, when there is an increase in rainfall immediately after the snow melts). Heavy rainfall increases the amount of water that infiltrates the ground, which reduces its resistance. Experiments carried out in the construction of artificial slopes have shown that the wetting of the material due to precipitation is greatest at the foot of the slopes, with moisture varying at a depth of 2-3 m from the surface. The unfavorable influence of precipitation, through increased rock moisture, rising water tables, and increased pore water pressure, is particularly evident in waste deposits, where the disaggregated structure of the rock mixture facilitates water infiltration.
- ***Freezing and thawing phenomena -*** through the phenomenon of freezing, rocks undergo a series of significant deformations, which refer to the degradation of their structure, resulting in a sudden reduction in mechanical strength properties. Freezing increases the amount of water contained in rocks, causing them to expand, which can be noticed by a slight rise in the relief, accompanied by an incipient displacement that develops along the line of greatest slope. This displacement is, in fact, the beginning of the slope sliding process. The effect of freezing on slope stability varies depending on the nature of the rocks. Thus, clayey rocks degrade considerably during the freezing process, while sands and gravels behave much better. It is estimated that freeze-thaw phenomena have had and continue to have a considerable influence on the degradation of the rock structure of the slopes "in situ." The fragmentation of some blocks that subsequently moved from the slopes is associated with these phenomena and with the tensile stresses that occur.
- ***Seismic factor*** - seismic shocks generated by earthquakes, massive explosions, or vibrations usually exert both vertical and horizontal forces on slopes, which can cause landslides. Vertical forces reduce the effective normal pressure on the sliding surfaces, while horizontal forces, which are much

stronger, play a decisive role in the stability of slopes. In fact, it is well known that during an earthquake, seismic action can occur in any direction, which is why it is considered horizontal in calculations, as this is the most unfavorable case in terms of its effect on slope stability. Also, the vibrations produced by the operation and movement of machinery on the upper berm of the steps or any explosions occurring nearby can lead to a 10-15% reduction in the stability reserve, their influence being felt especially when the slope is at the limit of equilibrium.

1.5. The biotic factor

It is represented by various types of cereal crops, legumes, fruit trees, or forests. Under these conditions, the load on the slopes, especially due to the weight of the trees, is equivalent to a uniformly distributed load of 250-450 daN/m2. Added to this load is the pressure exerted by the wind, both of which have an effect on stability. It is estimated that the biotic factor has a positive effect on slope stability, manifested by the reinforcement of the soil through roots and the consumption of water from the soil. Consequently, it is considered appropriate to adopt measures for planting trees on sloping land, whether natural slopes or artificial embankments.

2. DETERMINED VALUES OF GEOMECHANICAL PARAMETERS

So far, we have determined, received and processed information regarding the physical and mechanical characteristics of the rocks from the Pesteana Sud/Romania, CSA/Czech Republic, KOSD/Poland and Alchada Nord/Greece open pits (tables 1, 2, 3 and 4).

Table 1 Physical and mechanical characteristics of the rocks from the Pesteana Sud/Romania

Description	UM	PESTEANA SOUTH SITE			
Geotechnical properties for each geotechnical layer:		**SAND**	**CLAY**	**MARL**	**COAL**
Unit weight above water table, γ_{unsat}	[kN/m^3]	17.65	19.12	19.61	11.76
Unit weight below water table, γ_{sat}	[kN/m^3]	19.12	21.08	21.57	12.94

Cohesion, c	[kN/m^2]	4.9	25.49	41.18	147.1
Friction angle, φ	[°]	27	26	20	30
Young's modulus, E	[MPa]	28	35	100	195
Poisson's ratio, v	-	0.3	0.43	0.39	0.37
Horizontal k_h and vertical permeability, k_h	[m/s]	1X10^{-3}	Impermeabil	Impermeabil	Impermeabil

Analyzing the data in the tables, the following preliminary conclusions can be drawn:

- ***Sand*** has the lowest cohesion (4.9 kPa) and the lowest deformability modulus (28 MPa). Therefore, it is susceptible to local deformations and instabilities, especially near the face of the slope. Its high permeability allows water to circulate and can cause it to accumulate on contact with impermeable layers.
- ***Clay*** has moderate cohesion (25.49 kPa), a friction angle of 26° and a Young modulus of 35 MPa. The high Poisson coefficient (0.43) indicates significant lateral deformability within the elastic model. Under conditions of saturation and long-term stresses, clay can contribute to the development of areas of progressive deformation.
- ***Marl*** has a higher cohesion (41.18 kPa) and a significantly higher stiffness than sand and clay (E = 100 MPa). However, the friction angle of only 20° is the smallest of the materials analysed. This can become important for overall stability, especially at high normal stresses or in the case of slip surfaces that follow the marl layers.
- ***Coal*** has the highest cohesion (147.1 kPa), the largest friction angle (30°) and the highest stiffness (E = 195 MPa). Assuming that these parameters are representative of the coal mass, the material has a high shear strength compared to the other units. However, discontinuities and lithological contacts can have significantly lower strengths than intact material.

Table 2 Physical and mechanical characteristics of the rocks from the CSA/Czech Republic

Description	UM	CSA										
Geotechnical properties for each geotechnical layer:		***Q***	***JIL$_1$***	***JIL$_2$***	***JIL$_2$***	***JIL$_3$***	***JIL$_3$***	***C***	***C,RUB***	***TV$_1$***	***TV$_2$***	***B***
Unit weight above water table, γ_{unsat}	[kN/m^3]	20.0	18.8	20.1	19.7	21.0	21.1	14.0	14.0	19.5	19.5	23.0
Unit weight below water table, γ_{sat}	[kN/m^3]	-	-	-	-	-	-	-	-	-	-	-
Cohesion, c	[kN/m^2]	6.0	11.5	35.5	40.0	18.0	24.5	50.0	20.0	20.0	12.0	110.0
Friction angle, φ	[°]	24.0	18.2	15.4	13.8	16.9	17.1	18.0	20.0	15.0	8.0	35.0
Young's modulus, E	[MPa]	200	5000	5000	5000	5000	5000	1000	1000	100	50	100000
Poisson's ratio, v	-	0.30	0.25	0.25	0.25	0.25	0.25	0.30	0.30	0.40	0.40	0.20
Horizontal k_h and vertical permeability, k_h	[m/s]	–	-	-	-	-	-	-	-	-	-	-

The following important conclusions can be distinguished from the table:

- ***Layers JIL1, 2 and 3*** have relatively low internal friction angles, approximately 13.8–18.2°, and variable cohesions, between 11.5 and 40 kPa. These materials can be areas conducive to the development of sliding surfaces, depending on the level of effective stresses.
- ***Layer Q*** has a low cohesion of about 6 kPa and an internal friction angle of 24°. It may be vulnerable to surface instabilities.
- ***Layers C and C,RUB*** exhibit higher cohesion but relatively low friction angles, which can limit their shear strength under high normal loads.

- ***Layers TV1 and TV2*** have low friction angle values, and special attention must be paid their behavior within the sliding mechanisms.
- ***Layer B*** has the highest parameters of strength and rigidity, and can be a relatively competent unit from a geomechanical point of view.

Table 3 Physical and mechanical characteristics/parameters of the rocks from the KOSD/Poland

Description	**UM**	**KOSD**		
Parameter PLAXIS		**BASALT**		
		Slightly weathered basalt	**Weathered basalt**	**Fractured basalt**
Unit weight above water table, γ_{unsat}	[kN/m^3]	27,0	26,0	26,0
Unit weight below water table, γ_{sat}	[kN/m^3]	-	-	-
Cohesion, c	[kN/m^2]	500	250	70
Friction angle, φ	[°]	42	35	32
Young's modulus, E	[MPa]	3500	1000	400
Poisson's ratio, v	-	0.22	0.27	0.30
Horizontal k_h and vertical permeability, k_h	[m/s]	-	-	-
Parameter SLOPE	**UM**	**Slightly weathered basalt**	**Weathered basalt**	**Fractured basalt**
Unit weight, γ	[kN/m³]	27,0	26,0	26,0
Rock Mass Rating (RM)	-	65	44	23*
Litotip/tabel	-	Basalt	Basalt	Basalt
A	-	0,525	0,295	0,172
B	-	0,698	0,691	0,676
T	-	−0,002	−0,003	−0,0001

Uniaxial Compressive Strength (UCS), σc	[MPa]	80	40	80
Parameter SLIDE	**UM**	**Slightly weathered basalt**	**Weathered basalt**	**Fractured basalt**
Unit weight, γ	[kN/m³]	27,0	26,0	26,0
Uniaxial Compressive Strength (UCS), σc	[MPa]	80	40	80
Geological Strength Index, (GSI)	-	65	45	35
mi	-	25	20	25
D	-	1,0	1,0	1,0

- ***Slightly weathered basalt*** presents a geomechanical behavior characterized by high shear strength and high rigidity, as a result of the low degree of alteration of the rock mass and the preservation of its structural and mineralogical characteristics. The cohesion of 500 kPa and the internal friction angle of 42° indicate a high capacity to mobilize shear strength, which favors the stability of the slopes excavated in this material. Young's modulus of 3,500 MPa shows relatively high stiffness, associated with low elastic deformations under normal stress conditions. The Poisson coefficient of 0.22 indicates a relatively low transverse deformation relative to longitudinal deformation, assuming isotropic elastic behavior. From the point of view of stability, the poorly altered basalt has a relatively low susceptibility to the development of subsidence surfaces by the mass of the material, given that the parameters adopted are representative for the entire massif. However, the behavior of the slope can be significantly influenced by the presence of structural discontinuities, such as diaclases, cracks and tectonic fractures. In case of unfavorable orientations towards the slope geometry, local mechanisms of detachment of the blocks, flat sliding or overturning may occur, even if the strength of the material is high.
- ***Weathered basalt*** exhibits an intermediate geomechanical behavior between weakly altered and intensely fractured basalt, being characterized by reduced shear strength and stiffness, as an effect of physical and chemical alteration

processes.The cohesion of 250 kPa, representing 50% of the value corresponding to the weakly altered basalt, indicates a significant decrease in the strength of the material. The internal friction angle of 35° highlights the maintenance of a significant frictional component, but lower than that characteristic of the weakly altered basalt. Young's modulus of 1,000 MPa indicates a stiffness about 3.5 times lower than that of poorly altered basalt. This difference can be manifested by higher deformations under comparable stress conditions and increased sensitivity to excavation-induced stress redistribution. The Poisson coefficient of 0.27 suggests a more pronounced tendency of transverse deformation within the elastic model used. Alteration processes can cause degradation of the bonds between mineralogical constituents, opening and extension of microcracks, and alteration of the mechanical characteristics of discontinuity surfaces. From the point of view of behaviour over time, exposure to atmospheric agents and water infiltration can contribute to the accentuation of alteration, especially in areas with pre-existing fracturing. However, the extent of these phenomena depends on mineralogy, climatic conditions and the actual degree of alteration.

- ***Fractured basalt*** represents the geotechnical unit with the lowest strength and deformability characteristics among the three types of basalt analyzed. Its mechanical behavior is significantly influenced by the degree of fracturing, the density and orientation of the discontinuities, the size of the rock blocks and the mechanical characteristics of the separation surfaces. The cohesion of 70 kPa is approximately 86% lower than that of weakly altered basalt and 72% lower than that of altered basalt. This reduction indicates a significant decrease in the shear strength of the material represented by the geotechnical model. The internal friction angle of 32° highlights the preservation of an important frictional component, but the overall strength can be influenced by the existence of discontinuity surfaces with mechanical characteristics lower than those attributed to the mass. Young's modulus of 400 MPa indicates a reduced stiffness compared to the other two units, which favors the development of higher deformations under similar stresses. The Poisson coefficient of 0.30 indicates a more pronounced transverse deformation in the hypothesis of isotropic elastic behavior. In an intensely fractured massif, the overall deformability can be controlled not only by the deformation of the individual

blocks, but also by the closure, opening and relative displacement along the discontinuities.

Table 4 Physical and mechanical characteristics of the rocks from the Achlada Nord/Greece

Description	**UM**	**ACHLADA NORTH SITE**					
Geotechnical properties for each geotechnical layer:		**C1:** Upper Zone of Silty/Marly Clay (0.0–5.5 to 10.0 m)	**MS1:** Upper Sand/Pebble Sandstone zone (1.5–29.1 m)	**MR1:** Intermediate silt/silt loam zone with the presence of xylite interbeds (11.0–58.0 m)	**MS2:** Lower Zone of Sand/Marly Sandstone (40.0–64.5 m)	**MR2:** Lower Silt/Silt loam zone with the systematic presence of xylite (>51.5 m)	**BDR:** Underlying Marl Formation
Unit weight above water table, γ_{unsat}	[kN/m^3]	20	22	20	22	20	18
Unit weight below water table, γ_{sat}	[kN/m^3]	21	23	21	23	21	19
Cohesion, c	[kN/m^2]	35	10	65	12	50	100
Friction angle, φ	[°]	22	39	26	41	25	35
Young's modulus, E	[MPa]	25	100	160	200	150	100
Poisson's ratio, v	-	0.28	0.3	0.28	0.3	0.35	0.3
Horizontal k_h and vertical	[m/s]	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-8}

permeability, k_h							

- ***Layer C1*** is predominantly made up of fine materials, with a clayey-marly character, having a geomechanical behavior influenced by cohesion, plasticity and humidity conditions. The cohesion of 35 kPa and the internal friction angle of 22° indicate moderate shear strength, while the Young modulus of only 25 MPa highlights low rigidity and relatively high susceptibility to deformation. The Poisson coefficient of 0.28 is compatible with an elastic representation of the material but does not allow the evaluation of plasticity or time-dependent behavior on its own. The low hydraulic conductivity of 1×10^{-7} m/s indicates a slow circulation of water through the material. Under conditions of infiltration, the dissipation of interstitial pressures can be slow, which can negatively affect stability, especially during periods of heavy rainfall.
- ***Layer MS1*** is made up of sandy and conglomerate sandstones, presenting a predominantly frictional behavior. The low cohesion of 10 kPa and the high internal friction angle of 39° indicate that the shear strength is mainly controlled by the frictional component and the level of effective normal stresses. Young's modulus of 100 MPa indicates a higher stiffness than the C1 unit, which translates, under comparable load conditions, into lower elastic deformations. The hydraulic conductivity of 1×10^{-6} m/s is the highest of the analyzed units, favoring the circulation of water through the material. On contact with less permeable units, local water accumulations and changes in pore pressures can occur. These phenomena are important for the stability of the slope, especially if the contact surfaces are oriented towards the outside of the slope.
- ***Layer MR1*** consists predominantly of fine materials, silt and clayey silt, with the presence of xylite intercalations, which can determine a heterogeneous mechanical behavior. The cohesion of 65 kPa and the internal friction angle of 26° indicate a relatively high shear strength compared to the C1 and MR2 units. Young's modulus of 160 MPa suggests moderate to high stiffness compared to the other sedimentary materials analyzed. However, the presence of xylite intercalations can introduce mechanical discontinuities and local contrasts of stiffness and strength. If these intercalations are continuous and unfavorably oriented, they can favor the development of preferential sliding surfaces. The hydraulic conductivity of 1×10^{-7} m/s indicates a reduced permeability, with the

possibility of developing persistent interstitial pressures under slow drainage conditions.

- The MS2 layer exhibits predominantly frictional geomechanical behavior, characterized by an internal friction angle of 41°, the highest of the analyzed units.
- The cohesion of 12 kPa indicates a relatively low contribution of the cohesive component to shear strength.
- Young's modulus of 200 MPa, the largest within the site, indicates relatively high stiffness, which can limit elastic deformations under comparable stress conditions.
- The hydraulic conductivity of 1×10^{-8} m/s is very low, suggesting a low circulation of water through the matrix of the material represented in the model.
- In case of discontinuities, the actual permeability of the mass may be different from the value attributed to the material.
- Due to its position in the lower area of the succession, the MS2 unit can play an important role in the transmission of requests and in the overall behavior of the slope.
- ***Layer MR2*** consists of fine materials, with a silty and silty-clayey character, in which xylite intercalations are systematically present. The cohesion of 50 kPa and the internal friction angle of 25° indicate a moderate shear strength, lower than that corresponding to the MR1 unit for positive effective normal stresses. Young's modulus of 150 MPa exhibits moderate stiffness, close to that of the MR1 unit. The Poisson coefficient of 0.35 indicates a relatively greater transverse deformation than in units C1, MS1 and MR1, assuming isotropic elastic behavior. The systematic presence of xylite intercalations is an important factor for slope stability, as they can constitute areas of mechanical contrast and possible preferential deformation and sliding surfaces. The low permeability of 1×10^{-7} m/s can contribute to the slow dissipation of interstitial pressures.
- ***Layer BDR*** represents the basic marl formation of the analyzed geotechnical succession. It has a cohesion of 100 kPa, the highest of the site units, and an internal friction angle of 35°, indicating a high shear strength according to the adopted parameters. Young's modulus of 100 MPa indicates moderate stiffness, lower than MR1, MS2 and MR2 units, although the shear strength is higher. This difference highlights the fact that strength and stiffness are distinct

properties and should not be considered directly proportional. The hydraulic conductivity of 1×10^{-8} m/s indicates a very low permeability, which may limit the circulation of water through the formation matrix, but may favour the accumulation of water above it if appropriate hydrogeological conditions exist. Under conditions of weathering or cracking, the marl may show a reduction in strength, especially on discontinuity surfaces.

3. SOIL PROPERTIES RELEVANT TO THE DETERMINATION OF BEARING CAPACITY – KOSD QUARRY

The samples collected from the KOSD/Poland quarry are being processed in the Rock Mechanics Laboratory of the University of Petrosani.

For the topsoil layer, the physical and mechanical properties required for calculating the soil's bearing capacity were determined (tables 5, 6 and 7).

Table 5 Natural humidity

Natural humidity					
Sample	Sample no.	Mass of the material in its natural state, m_n [g]	Mass of the material in dry state , m_u [g]	Natural humidity W_n [%]	Average
Sample 1	1	152.78	126.61	20.670	21.282
	2	153.22	125.46	22.127	
	3	154.58	127.70	21.049	
Sample 2	1	140.38	105.38	33.213	28.235
	2	149.33	121.87	22.532	
	3	141.88	110.02	28.958	
Sample 3	1	137.74	111.09	23.990	25.962
	2	140.29	109.44	28.189	

	3	140.10	111.45	25.707	
Sample 4	1	145.10	118.73	22.210	21.966
	2	151.19	124.36	21.574	
	3	145.29	118.98	22.113	
Sample 5	1	146.04	120.62	21.074	21.693
	2	149.92	121.64	23.249	
	3	146.15	121.03	20.755	
Sample 6	1	139.06	114.18	21.790	22.497
	2	139.76	114.14	22.446	
	3	125.4	101.74	23.255	

Table 6 Bulk density

Bulk density (in natural and dry state)											
Sample	Stamp number	Stamp diameter d [cm]	Stamp height h [cm]	Stamp mass m_s [g]	Mass of the material in its natural state + mass of the $stamp_n$ [g]	Mass of the material in a dry state + mass of the $stamp_u$ [g]	Volum of stamp V [cm^3]	Apparent density in the natural state ρa_n [g/cm^3]	Average	Apparent density in a dry state ρa_u [g/cm^3]	Average
Sample 1	1	4	6	65.84	218.62	192.46	75.40	2.026	2.036	1.679	1.679
	2	4	6	66.40	219.62	191.86	75.40	2.032		1.664	
	3	4	6	65.84	220.42	193.55	75.40	2.050		1.694	
Sample 2	1	4	6	65.84	206.22	171.22	75.40	1.862	1.908	1.398	1.491
	2	4	6	66.40	215.73	188.27	75.40	1.981		1.616	
	3	4	6	65.84	207.72	175.86	75.40	1.882		1.459	
Sample 3	1	4	6	65.84	203.58	176.93	75.40	1.827	1.849	1.473	1.468
	2	4	6	66.40	206.69	175.84	75.40	1.861		1.451	
	3	4	6	65.84	205.94	177.29	75.40	1.858		1.478	

Sample 4	1	4	6	65.84	210.94	184.57	75.40	1.924	1.952	1.575	1.601
	2	4	6	66.40	217.59	190.76	75.40	2.005		1.649	
	3	4	6	65.84	211.13	184.82	75.40	1.927		1.578	
Sample 5	1	4	6	65.84	211.88	186.46	75.40	1.937	1.955	1.600	1.606
	2	4	6	66.40	216.32	188.04	75.40	1.988		1.613	
	3	4	6	65.84	211.99	186.87	75.40	1.938		1.605	

Table 7 Mechanical properties

Sample	l	l	N	T	A	σ	τ	C		φ	σ	τ	C		φ	σ	τ	C		φ
	cm	cm	daN	daN	cm^2	daN/cm^2	daN/cm^2	daN/cm^2		°	MPa	MPa	MPa		°	kPa	kPa	kPa		°
Sample 1	6	6	36	32.144	36	1	0.89	0.575	0.298	16.574	0.10	0.09	0.065	0.24	13.39	100.00	89.29	57.54083	0.30	16.57
	6	6	72	40.715	36	2	1.13				0.20	0.11				200.00	113.10			
	6	6	108	53.573	36	3	1.49				0.30	0.15				300.00	148.81			
Sample 2	6	6	36	25.715	36	1	0.71	0.377	0.327	18.128	0.10	0.07	0.038	0.33	18.13	100.00	71.43	37.699	0.33	18.13
	6	6	72	36.429	36	2	1.01				0.20	0.10				200.00	101.19			
	6	6	108	49.287	36	3	1.37				0.30	0.14				300.00	136.91			
Sample 3	6	6	36	25.715	36	1	0.71	0.397	0.298	16.574	0.10	0.07	0.040	0.30	16.57	100.00	71.43	39.683	0.30	16.57
	6	6	72	34.286	36	2	0.95				0.20	0.10				200.00	95.24			
	6	6	108	47.144	36	3	1.31				0.30	0.13				300.00	130.96			
Sample 4	6	6	36	25.715	36	1	0.71	0.417	0.298	16.574	0.10	0.07	0.042	0.30	16.57	100.00	71.43	41.668	0.30	16.57
	6	6	72	36.429	36	2	1.01				0.20	0.10				200.00	101.19			
	6	6	108	47.144	36	3	1.31				0.30	0.13				300.00	130.96			
Sample 5	6	6	36	23.572	36	1	0.65	0.298	0.327	18.128	0.10	0.07	0.030		18.13	100.00	65.48	29.763		18.13

	6	6	72	32.144	36	2	0.89				0.20	0.09		0.33		200.00	89.29		0.33	
	6	6	108	47.144	36	3	1.31				0.30	0.13				300.00	130.96			
Sample 6	6	6	36	32.144	36	1	0.89	0.754	0.149	8.464	0.10	0.09	0.075	0.15	8.46	100.00	89.29	75.398	0.15	8.46
	6	6	72	38.572	36	2	1.07				0.20	0.11				200.00	107.15			
	6	6	108	42.858	36	3	1.19				0.30	0.12				300.00	119.05			

Analysis of the bulk density reveals values ranging from approximately 1.85–2.04 g/cm³ in its natural state to 1.47–1.67 g·cm^{-3} in its dry state, indicating a granular material with a moderate degree of compaction and relatively high porosity.

Grain size analysis showed that the material consists predominantly of sand (≈46–57%), with a significant dust content (≈31–38%) and small amounts of gravel (≈7–21%). In accordance with the SR EN ISO 14688-1:2018 standard, all samples were classified as: “grsiSa – Dusty sand with gravel”

The coefficient of non-uniformity shows high values (12.85–86.66), indicating a material with a non-uniform grain size distribution, a wide range of particle sizes, and good compactability.

Direct shear tests revealed shear strength values ranging approximately from 65 to 149 kPa, depending on the applied normal load and the type of specimen tested. The material exhibits behaviour typical of granular soils with a significant fine-grained fraction, with shear strength increasing as the applied normal pressure increases. The shear strength parameters indicated:

• cohesion values ranging from approximately 29 to 75 kPa;

• internal friction angles ranging from approximately 8° to 18°.

From a geotechnical standpoint, the soil material can be classified as a fine-grained soil with behaviour intermediate between non-cohesive and weakly cohesive materials. Its high silt content affects its permeability, compactability, and sensitivity to changes in moisture content.

The material analysed exhibits favourable characteristics for geotechnical and mining applications; however, its mechanical behaviour depends on the degree of

compaction and the water content, factors that must be taken into account in the design and stability of tailings piles or other engineering structures.

With regard to compressibility, edometric tests have shown that the material's deformation occurs primarily through the rearrangement of particles and a reduction in porosity under vertical loads. This process is influenced by the removal of water and air from the pores, as well as by the material's permeability. The high sand content promotes relatively good compaction and moderate deformation underload, while the silt fraction increases sensitivity to moisture and influences the settlement process over time. From a geotechnical standpoint, the material can be considered to have high compressibility, and its behavior is suitable for use in mining construction and geotechnical works, provided that proper compaction and moisture control are ensured.

In conclusion, the material analyzed exhibits favorable characteristics for geotechnical and mining applications; however, its mechanical behavior depends on the degree of compaction and the water content, factors that must be taken into account in the design and stability of tailings piles or other engineering structures.

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