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THE INFLUENCE OF PHYSICAL PARAMETERS ON THE MECHANICAL CHARACTERISTICS OF SOME VOLCANIC MAGMATIC ROCKS OF THE ANDESITE TYPE

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Abstract: *The factors that influence the strength characteristics of rocks can be different in nature, being divided into external and internal factors. The mechanical properties of hard rocks are a result of geological, physical and chemical factors. In order to highlight the physical parameters that influence the strength characteristics of the rocks, in this paper there were analyzed six types of volcanic magmatic rocks such as andesites. In terms of stress behavior, rocks are directly influenced by their physical properties, such as volumetric density, porosity, compactness, moisture and the degree of alteration of mineral components. For this purpose, several sets of tests were performed to determine the physical and mechanical characteristics of the rocks, based on which it was possible to analyze how the physical parameters influence the strength characteristics.*

Keywords: *andesite, volumetric density, porosity, compactness, moisture, uniaxial compressive strenght, bending strenght, cohesion, internal friction angle*

1. Introduction

The interpretation of mechanical behavior of rocks, quantitatively and qualitatively, can be rendered only by knowing the geological, physical and chemical characteristics. The mechanical characterization of rocks implies the knowledge of those parameters that influence their mode and behavior when subjected to various types of stress.

The effect of various physical parameters (moisture, volumetric density, porosity, compactness, water absorption) on the mechanical behavior of rocks has been the subject of many studies presented in speciality literature. There is a general agreement in rock mechanics that the strength characteristics change under the influence of these factors.

In this sense, in the laboratory of Rock Mechanics of the University of Petroşani, several sets of physical-mechanical tests were performed on different types of andesites.

The physical-mechanical characteristics were made in accordance with the standards in force, the recommendations of the International Bureau of Rock Mechanics and of the International Society of Rock Mechanics. These tests aimed to elucidate the mechanical behavior of rocks under the influence of physical parameters.

2. Research methodology

The physical-mechanical characterization of andesites could be achieved only by laboratory tests, which gave the research a very practical character. Regarding experimental research methodologies literature provides a wealth of information [1], [2], [3], [4], [5]. In order to establish the way in which the physical

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parameters influence the mechanical behavior of the analyzed andesites, it was necessary to go through some mandatory stages.

The sampling process was accurate and specific to the problem pursued, preceded by a series of observations and determinations that correspond to the researched objective [2]. Sampling of andesite from the massif was done in the form of monolithic blocks. The criterion for collecting the analyzed rocks aimed at eliminating certain factors, so that the study focused only on the physical parameters of the rocks. In this sense, six types of andesites were harvested: 1. Valea Căpitanului (Hunedoara), 2. Dealul Motor (Hunedoara), 3. Crişcior (Hunedoara), 4. Săcărâmb (Hunedoara), 5. Albinii-Haneș (Alba), 6 Roșia-Poieni (Alba), their mineralogical-petrographic characteristics being presented in table 1.

From the colected blocks, cylindrical test tubes with different sizes were made depending on the type of test to be done. The processing of samples and the number of test tubes was performed in accordance with the recommendations (BIMR, ISRM) and the norms in force (STAS, SR EN, EN).

3. Methods and results

All the rocks were previously analyzed both macroscopically and microscopically to determine the mineralogical-petrographic characteristics necessary to study the physical parameters that define the mechanical behavior.

The mineralogical-petrographic study was performed by means of the analysis of thin sections using the polarizing microscope.

Fig. 1. Determination of mineralogical-petrographic characteristics

Microscopic analysis allowed us to set up the mineralogical composition, the structural-textural characteristics and to determine the petrographic types.

Based on the macroscopic and microscopic examination, a detailed description of these rocks was obtained.

Knowing the physical condition of the rock helped us to make a quantitative description, but also an estimate of the influence on the strength characteristics. This could be achieved only by determining the physical characteristics (Tables 2 and 3): specific density, bulk density, porosity, compactness, natural moisture, water absorption.

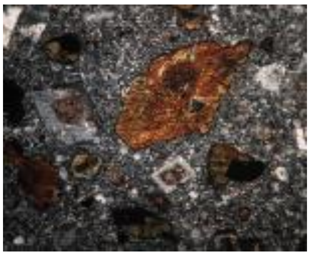
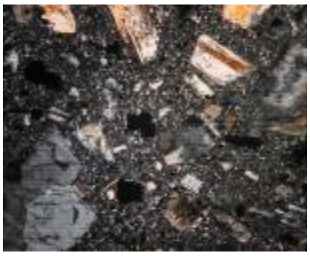
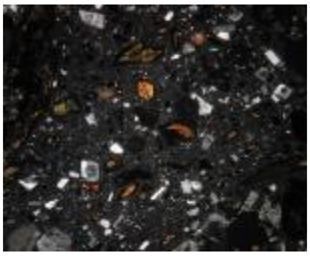
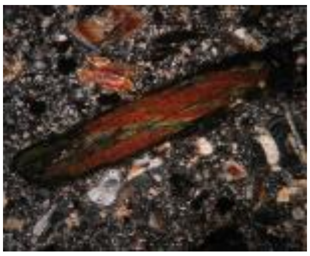
Density is the mass of the effective volume of rock (without gaps or pores), expressed in g / cm^3 or kg / m^3 [2].

The actual (specific) density was determined in the laboratory by the pycnometer method, according to SREN1936 and calculated with relation 1.

$$\rho_r = \frac{m_e}{m_2+m_e-m_1}\rho_{rh}[kg/m^3] \quad (1)$$

where:
m_e - mass of the material to be analyzed, in g;
m_2 - mass of the pycnometer filled with liquid, in g;
m_1 - mass of the pycnometer with material and liquid, in g;
ρ_{rh} - the specific density of the reference liquid, at a temperature of 20 °C, in kg / m^3.

Table 1. Mineralogo-petrographic description

No.	*Macroscopic analysis*	*Microscopic analysis*	*Mineralogo-petrographic description*
1.			GEOLOGICAL FRAMEWORK: Neogene eruption of the Apuseni Mountains (Metalifers); ROCK TYPE: magmatic, effusive (neovulcanic), neutral; STRUCTURE: semicrystalline (hypocrystalline), porphyry-vitreous; TEXTURE: unoriented (massive), compact; COLOR: gray, mottled; MINERALOGICAL COMPOSITION: plagioclase feldspars, hornblende, microlithic paste; NAME OF THE ROCK: Andesite with hornblende
2.			GEOLOGICAL FRAMEWORK: Neogene eruption in the Mureş Valley; ROCK TYPE: magmatic, effusive (neovulcanic), neutral; STRUCTURE: semicrystalline, porphyry-vitreous; TEXTURE: compact, unoriented (massive); COLOR: gray; MINERALOGICAL COMPOSITION: neutral plagioclase feldspar, hornblende, rare biotite slides and microlithic paste; NAME OF THE ROCK: Andesite with hornblende and biotite.
3.			GEOLOGICAL FRAMEWORK: Neogene magmatism, cycle II; ROCK TYPE: magmatic, effusive (neovulcanic), neutral; STRUCTURE: semicrystalline (hypocrystalline), porphyry-vitreous; TEXTURE: unoriented (massive), compact; COLOR: dark gray; MINERALOGICAL COMPOSITION: plagioclase feldspar, hornblende, vitro-microlithic paste, secondary minerals. NAME OF THE ROCK: In vitro andesite - porphyry.
4.			GEOLOGICAL FRAMEWORK: Neogene eruption of the Apuseni Mountains (Metaligferi), cycle II; ROCK TYPE: magmatic, effusive (neovulcanic), neutral; STRUCTURE: hypocrystalline (semicrystalline), porphyry-vitreous; TEXTURE: massive (unoriented), compact; COLOR: gray, slightly mottled; MINERALOGICAL COMPOSITION: plagioclase feldspar, hornblende, microlithic-glassy paste, secondary minerals; NAME OF THE ROCK: Andesite with partially altered hornblende.
5.			GEOLOGICAL FRAMEWORK: Neogene eruption of the Apuseni Mountains (Metalifers); ROCK TYPE: magmatic, effusive (neovulcanic), neutral; STRUCTURE: hypocrystalline (semicrystalline), porphyry-vitreous; TEXTURE: unoriented (massive), compact; COLOR: gray, mottled; MINERALOGICAL COMPOSITION: plagioclase feldspar, hornblende, microlithic paste; NAME OF THE ROCK: Andesite with hornblende.

6.			GEOLOGICAL FRAMEWORK: Neogene eruption (cycle II), represented by rooted bodies, lava flows and andesitic pyroclastitis; ROCK TYPE: magmatic, neovulcanic, neutral (intermediate); STRUCTURE: hypocrystalline (semicrystalline), porphyry-vitreous; TEXTURE: unoriented (massive), compact; COLOR: gray, mottled; MINERALOGICAL COMPOSITION: plagioclase feldspar, hornblende, calcite, pyrite; NAME OF THE ROCK: Poieni hornblendic andesite

Fig. 2. Determination of real (specific) density in the laboratory

The apparent density was achieved according to SR EN 1936 and consisted in determining by weighing the dry test tube mass at 105±5°C and its ratio to its apparent volume, determined by the hydrostatic method, after the material was saturated in previously with water.

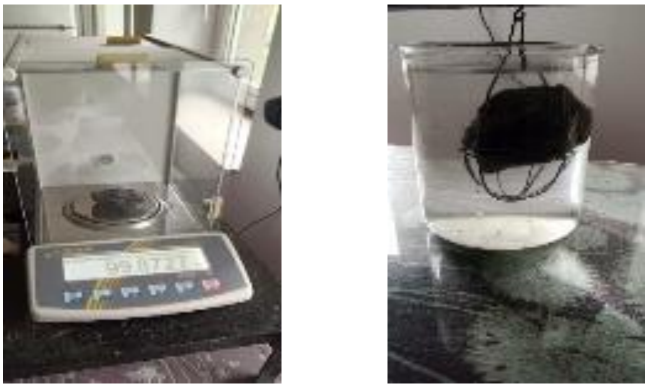


Fig. 3. Determination of bulk density (volumetric) in the laboratory

$$\rho_a = \frac{m_d}{m_s - m_h}\rho_{rh} \text{ [kg/m}^3\text{]} \qquad (2)$$

where:
m_d - mass of the dry test tube, in g;
m_s - mass of the test tube saturated in water, g;
m_h - mass of the test tube immersed in water, in g;
ρ_{rh}– water density, in kg / m^3.

Porosity is defined as the ratio between the total volume of the holes and the total volume of the rock, expressed as a percentage [3]. This property was determined indirectly using the linking relationships between actual density and bulk density according to SR EN, 1936.

$$n = \left(1 - \frac{\rho_a}{\rho_r}\right) \cdot 100[\%] \qquad (3)$$

where:
ρ_a– bulk density, in kg / m^3;
ρ_r– real density, in kg / m^3.

The open (apparent) porosity is expressed by the ratio between the volume of open pores and the apparent volume of the test tube, expressed as a percentage [6].

The apparent porosity was calculated with relation 4.

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$$n_a = \frac{m_s - m_d}{m_s - m_h} \cdot \rho_{rh} [\%] \quad (4)$$

where:
m_d - mass of the dried test piece, g;
m_s– mass of the specimen saturated in water, g;
m_h - mass of the test tube immersed in water, g.

Closed porosity is the volume of closed pores (non-communicating) in the unit of apparent volume of the rock and is expressed as a percentage [7].

The closed porosity was determined with relation 5.

$$n_{\hat{i}} = n - n_a [\%] \quad (5)$$

where:
n - total porosity of the rock,%;
n_a– open porosity,%;

Compactness is the volume of the mineral skeleton Vs in the unit of apparent volume of rock Va (including the volume of voids or pores) and is expressed as a percentage [2].

The compactness was calculated with relation 6, based on the actual density and the apparent density.

$$c = \frac{\rho_a}{\rho_r} \cdot 100 [\%] \quad (6)$$

where:
ρ_r - specific rock density, kg / m^3;
ρ_a– the apparent density of the rock in dry state, kg / m^3;

Natural moisture is defined as the mass of water m_w lost by a rock by drying at 105±2°C, relative to its dry mass m_s [1].

Experimentally, the natural moisture was obtained in the laboratory by determining the mass of a rock sample having a natural moisture and obtaining the mass after the sample was dried in the oven to a constant mass.

$$w_n = \frac{m_w}{m_s} \cdot 100 [\%] \quad (7)$$

where:
m_w - mass of water lost by a rock by drying, g;
m_s - mass of dry material, g.

Water absorption is the amount of water retained in the pores to saturation by the unit of dry mass of the rock [8].

The test for determining the water absorption was performed according to STAS, 6200 / 12-73 and consisted in determining by weighing the amount of water absorbed from the sample, which was previously dried at 105±5°C and then saturated with distilled water under different conditions of pressure and temperature (at normal pressure and by boiling).

$$a_i = \frac{m_i - m}{m} \cdot 100 [\%] \quad (8)$$

where:
m - represents the mass of the dry specimen, in g;
m_i - mass of the saturated specimen under conditions specific to the wetting mode (at normal pressure; at a pressure of 20 mm mercury column; at boiling; at a pressure of 150 daN / cm^2), in g.

Fig. 4. Determination of water absorption

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The saturation coefficient represents the degree of filling of open pores with water, at normal pressure and temperature, compared to that obtained in other conditions of temperature and pressure [8].

The saturation coefficient was calculated with relation 9.

$$s = \frac{a_i}{a_j} \qquad (9)$$

where:

a_1 - water absorption at normal pressure and temperature, in%;

a_j - water absorption depending on how the absorption was performed (at a pressure of 20 mm Hg, by boiling, respectively at a pressure of 150 daN / cm^2), in %.

The results were validated following the calculations and are presented in the form of average values in the tables below.

Table 2. Average values of the physical characteristics of the rocks

No.	Name of the rock	***Physical characteristics***					
		Specific density (actual), ρ_r x 10^3 [kg/m^3]	**Apparent density (volumetric), ρ_a x 10^3 [kg/m^3]**	**Total porosity, n [%]**	**Open porosity, n_a [%]**	**Closed porosity, n_i [%]**	**Compactness, c [%]**
1.	Andesite	2,7712	2,6682	3,7167	2,2795	1,4372	96,2831
2.	Andesite	2,7325	2,6129	4,3744	2,8730	1,5014	95,6254
3.	Andesite	2,6558	2,6397	0,6061	0,3297	0,2765	99,3937
4.	Andesite	2,6515	2,4574	7,3201	5,9546	1,3655	92,6797
5.	Andesite	2,6931	2,6734	0,7339	0,3819	0,3520	99,2660
6.	Andesite	2,7124	2,6440	2,5229	1,5098	1,0132	97,4769

Table 3. Average values of the physical characteristics of the rocks

No.	Name of the rock	***Physical characteristics***			
		Natural moisture, w_n [%]	**Water absorption, a_i [%]**		**Saturation coefficients**
			at normal pressure	by boiling	
1.	Andesite	0,9595	1,6190	2,0296	0,8025
2.	Andesite	1,0867	1,6690	1,7562	0,9505
3.	Andesite	0,7963	1,4089	1,5315	0,9224
4.	Andesite	2,7668	3,4895	3,8036	0,9178
5.	Andesite	0,6404	1,1652	1,2375	0,9416
6.	Andesite	1,1630	1,9805	2,0164	0,9822

The methods of determination and the calculus relations used are in accordance with the STAS in force, the recommendations of the International Bureau of Rock Mechanics and of the International Society of Rock Mechanics, and some of them can be found in the specialized works [1], [2] , [3], [4], [5].

The uniaxial compressive strength is defined as the strength that the test tubes subjected to external compressive forces have at the time of breaking [2], [3], [4], [5].

The determination of the uniaxial compressive strength consisted in subjecting the test tubes to a progressive loading (of 0.5 - 1 MPa·s) until breaking, the test tubes being placed between the plates of the hydraulic press.

The uniaxial compressive strength was achieved according to SR EN 1926, on cylindrical test tubes with a diameter of approximately 52 mm and a coefficient of slenderness λ = 2 (λ = h/d), required in the direction of the main axis.

They were subjected to monoaxial compression testing, dry test tubes, saturated with water at normal pressure and after 25 freeze-thaw cycles.

$$\sigma_{rc} = \frac{F_r}{A} \quad [MPa] \qquad (10)$$

where:

F_r - maximum force recorded at the moment of breaking the test piece, daN;

A - cross - sectional area of the test tubes, cm^2.

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Fig. 5. Determination of uniaxial compressive strength

The bending strength represents the resistance that the samples subjected to bending stresses have at the moment of rupture [3].

The determination of the bending strength consisted in the application on a test tube supported on two horizontal supports, of vertical forces acting on the test tube in the middle of the distance between the supports, forces which increased uniformly by 0,5 MPa·s, until rupture.

The bending tensile test was performed on cylindrical test tubes, with the distance between supports between 150 - 200 mm.

The bending strength was achieved for each of the three states: dry, saturated and after freeze-thaw cycles.

Fig. 6. Determination of bending strength

$$\sigma_{r\hat{\imath}} = \frac{8 \cdot F_r \cdot l}{\pi \cdot d^3} \quad [\text{MPa}] \qquad (11)$$

where:

F_r - represents the maximum force recorded at the moment of rupture, in daN;
d - diameter of the test piece, in cm;
l - distance between supports, in cm.

The tensile strength by splitting (Brazilian method) was achieved according to STAS 6200 / 6-71 and consisted in compressing the cylindrical test tubes after two diametrically opposed generators, by progressive loads, which had the effect of transverse tensile stresses, which caused the test tubes to split according to a median plane. The application speed of the splitting test specimens was maintained at 0,5 MPa·s.

The tensile breaking strength by splitting was calculated with relation 12.

$$\sigma_{rt} = \frac{2 \cdot F_{rt}}{\pi \cdot d \cdot h} \quad [\text{MPa}] \qquad (12)$$

Fig. 7. Determination of tensile strength by splitting (Brazilian method)

where:

F_{rt} - represents the maximum force registered at the moment of breaking the test piece, in daN;
d - diameter of the test piece, in cm;
h - height of the test piece, in cm.

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The softening coefficient is defined as the ratio between the resistance of the rock to compression, stretching, shearing in the saturated state or after freeze-thaw cycles and the same resistance in the dry state [1], [2].

Because the strength of rocks can vary after water saturation or after freeze-thaw cycles, the softening coefficient was determined after water saturation and after freeze-thaw cycles.

$$\eta_s = \frac{\sigma_{ru} - \sigma_{rs}}{\sigma_{ru}} \cdot 100[\%] \quad (13)$$

and

$$\eta_s = \frac{\sigma_{ru} - \sigma_{rî-d}}{\sigma_{ru}} \cdot 100[\%] \quad (14)$$

where:

σ_{ru} - represents the breaking strength in dry state, MPa;

σ_{rs} - breaking strength in saturated state, in MPa;

$\sigma_{rî}$ - breaking strength after freeze-thaw cycles, in MPa

Cohesion is considered to be the connecting force between the component particles of a rock, which opposes their detachment or sliding under the action of external forces [3].

The interior friction angle is considered the angle whose trigonometric tangent is represented by the internal friction coefficient between the rock particles [3].

The cohesion and the internal friction angle were determined indirectly on the basis of the uniaxial compressive strength and the tensile strength by splitting, according to the Mohr method.

$$C = \sqrt{R \cdot r} \ [MPa] \quad (15)$$

$$\varphi = \frac{R - r}{2 \cdot C} \quad [^o] \quad (16)$$

where:

$R = \frac{\sigma_{rc}}{2}$ and $r = \frac{\sigma_{rt}}{2}$

where:

σ_{rc} - uniaxial compressive strength, MPa;

σ_{rt} - tensile strength, MPa;

The results of the mechanical tests obtained for the volcanic magmatic rocks of the andesite type are presented in tables 4 to 8.

Table 4. Average values of the uniaxial compressive strength and softening coefficients

No.	**Name of the rock**	**Resistance characteristics**				
		Uniaxial compressive strength, σ_{rc} [MPa]			**Softening coefficient after saturation, η_{sc} [%]**	**Softening coefficient after freeze-thaw, η_{gc} [%]**
		Sample Status				
		dried	saturated	freeze-thaw		
1.	Andesite	110,194	93,622	91,039	15,044	17,383
2.	Andesite	131,934	110,707	105,181	16,093	20,234
3.	Andesite	143,538	129,774	125,297	9,565	12,715
4.	Andesite	123,674	101,398	94,235	17,956	23,819
5.	Andesite	142,404	127,852	122,420	10,226	13,997
6.	Andesite	129,632	108,049	103,753	16,627	19,949

Table 5. Average values of tensile strength by splitting and softening coefficients

No.	**Name of the rock**	**Resistance characteristics**				
		Tensile strength by splitting (Brazilian Method), σ_{rt} [MPa]			**Softening coefficient after saturation, η_{st} [%]**	**Softening coefficient after freeze-thaw, η_{gt} [%]**
		Sample Status				
		dried	saturated	freeze-thaw		
1.	Andesite	13,594	11,737	11,337	13,594	16,411
2.	Andesite	15,035	12,268	11,941	18,281	20,537
3.	Andesite	14,976	13,637	13,022	8,941	12,965
4.	Andesite	12,264	10,304	9,246	15,779	24,578
5.	Andesite	18,430	16,729	16,255	9,191	11,718
6.	Andesite	14,013	11,457	11,108	18,324	20,760

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Table 6. Average values of bending strength and softening coefficients

No.	Name of the rock	Resistance characteristics				
		Bending strength, $\sigma_{r\hat{i}}$ [MPa]			Softening coefficient after saturation, $\eta_{s\hat{i}}$ [%]	Softening coefficient after freeze-thaw,, $\eta_{g\hat{i}}$ [%]
		Sample Status				
		dried	saturated	freeze-thaw		
1.	Andesite	19,613	15,915	15,472	18,823	21,029
2.	Andesite	21,010	17,555	16,649	16,380	20,751
3.	Andesite	17,107	14,791	14,264	13,597	16,594
4.	Andesite	13,075	10,422	9,492	20,132	27,328
5.	Andesite	21,686	18,418	17,427	14,932	19,634
6.	Andesite	16,114	13,017	12,537	19,259	22,178

Table 7. Average values of cohesion and softening coefficients

No.	Name of the rock	Resistance characteristics				
		Cohesion, **C [MPa]**			Softening coefficient after saturation, η_s [%]	Softening coefficient after freeze-thaw, η_g [%]
		Sample Status				
		dried	saturated	freeze-thaw		
1.	Andesite	19,340	16,564	16,054	14.3537	16.9907
2.	Andesite	22,261	18,421	17,711	17.2499	20.4393
3.	Andesite	23,174	21,030	20,190	9.2517	12.8765
4.	Andesite	19,457	16,156	14,745	16.9656	24.2175
5.	Andesite	25,609	23,120	22,298	9.7192	12.9290
6.	Andesite	21,303	17,566	16,966	17.5421	20.3586

Table 8. Average values of the internal friction angle

No.	Name of the rock	Resistance characteristics		
		Internal friction angle, φ [MPa]		
		Sample Status		
		dried	saturated	freeze-thaw
1.	Andesite	51,315	51,011	51,141
2.	Andesite	52,678	53,167	52,735
3.	Andesite	54,190	54,080	54,248
4.	Andesite	55,024	54,644	55,213
5.	Andesite	50,430	50,224	49,955
6.	Andesite	53,582	53,919	53,751

4. Data interpretation and discussions

Based on the data in Tables 4-8, it can be seen that the strength of the analyzed andesites depends on a number of physical parameters (bulk density, natural moisture, porosity, compactness, water absorption) and varies within fairly large limits, even if it is the same rock type (Fig. 8-12).

From the tests performed on the different types of andesite saturated with water and subjected to freeze-thaw cycles, it was observed that in general their resistance to compression and stretching decreases compared to the resistance of the tested specimens in the dry state (Fig. 8).

This phenomenon can be reversible by drying in the case of saturated rocks, only if the mineral components did not react with water during the saturation process. The same cannot be concluded about the rocks that have been subjected to freeze-thaw cycles. In this case due to the pressure created in the pores of the rock during the freeze-thaw cycles, the water contained in the rock pores increases its volume, creating a state of intergranular tension and through thawing, the material relaxes. As a result of these freeze-thaw cycles, there is an increase in pore size and an increase in the size of pre-existing cracks.

The influence of moisture on the mechanical characteristics is given by the softening coefficient, which is a consequence of the interaction between water and the mineral skeleton of the rock. Such a coefficient actually characterizes the reduction of the mechanical characteristics of the rocks at long contact with water [4].

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As the compressive and tensile strengths were lower after saturation with water and subjected to freeze-thaw cycles, it is obvious that the cohesion of the rock also decreased after the saturation and freeze-thaw processes.

The effect of water can be explained by the fact that it penetrates through pores and cracks in the rock mass, wetting all the free surfaces of the mineral granules with which it comes in contact and reducing the bonding force between particles and weakening the adhesion cohesion, thus the mineral components slid much easier.

Figure 10 shows the influence of porosity on mechanical properties. Thus, for an increase of the porosity from 0.6% to 3.7%, the uniaxial compressive strength decreases by 33.34 MPa. The porosity has the same effect on the tensile strength by splitting, where it can be seen that an increase in porosity by 6.5% results in a decrease in the resistance value by 8.6 MPa. For the same porosity growth interval, the rock cohesion is reduced by 6.1 MPa.

It is known that the high porosity favors a higher water absorption, which contributes to a decrease in the strength of the tested material in a saturated state and even more so in the case of undergoing cycles of frost thawing. As with porosity, the mechanical properties of the analyzed andesites decrease with increasing water absorption.

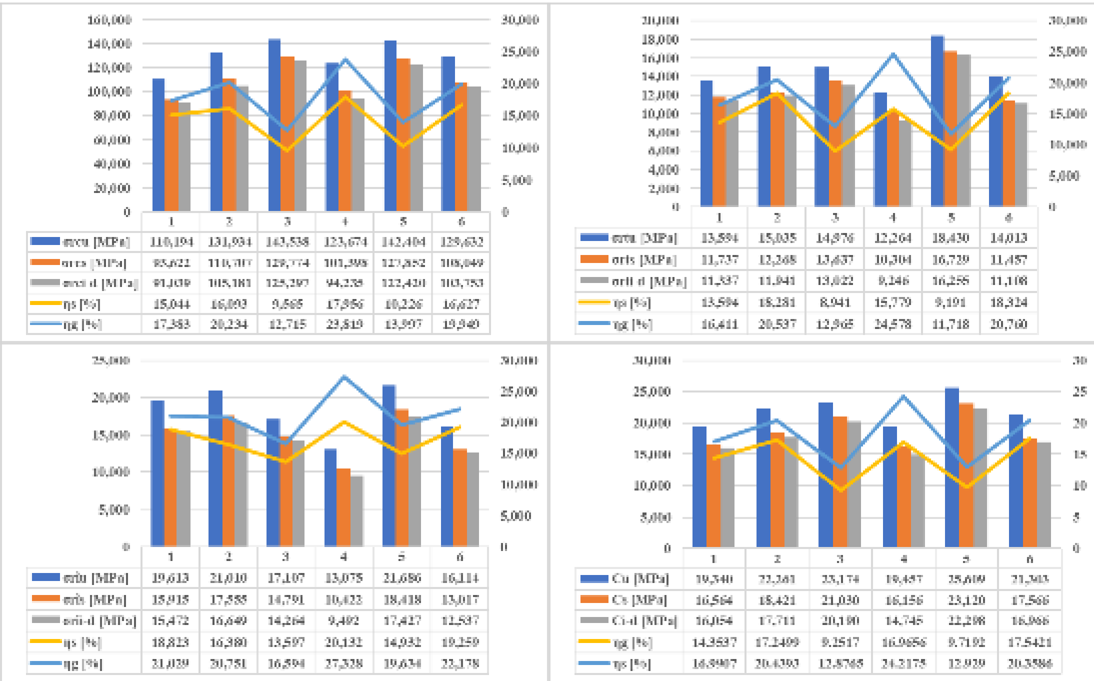

Fig. 8. The influence of water saturation and freeze-thaw cycles on the mechanical properties of rocks

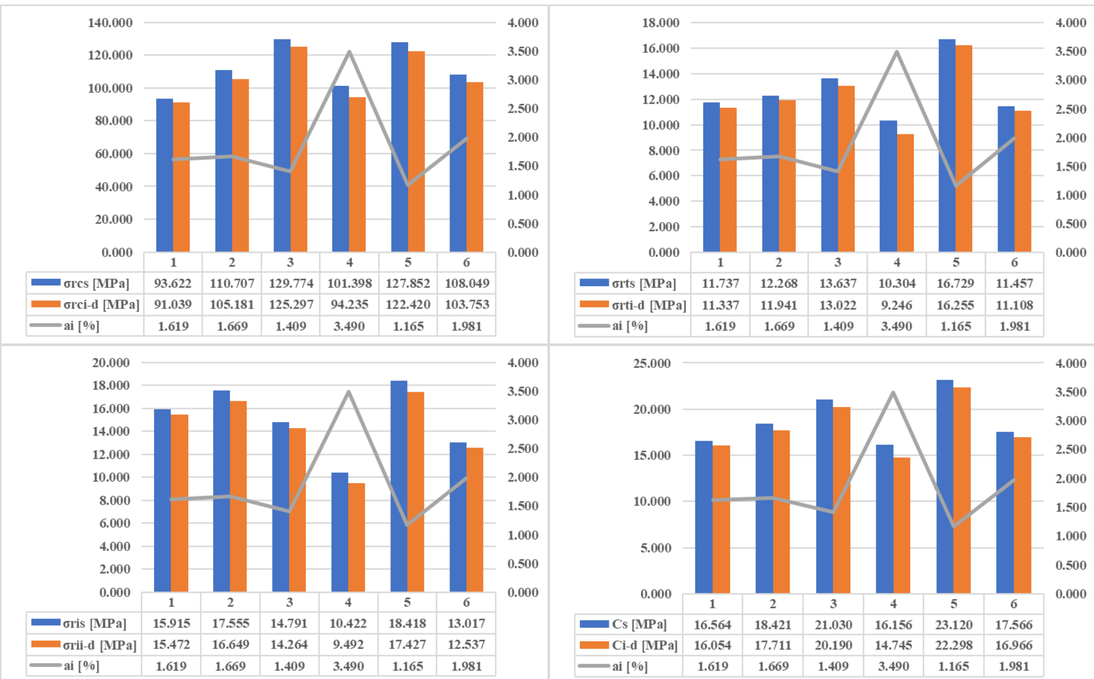

Fig. 9. The influence of water absorption at normal pressure on the mechanical characteristics of the rocks tested in the saturated state and after freeze-thaw cycles

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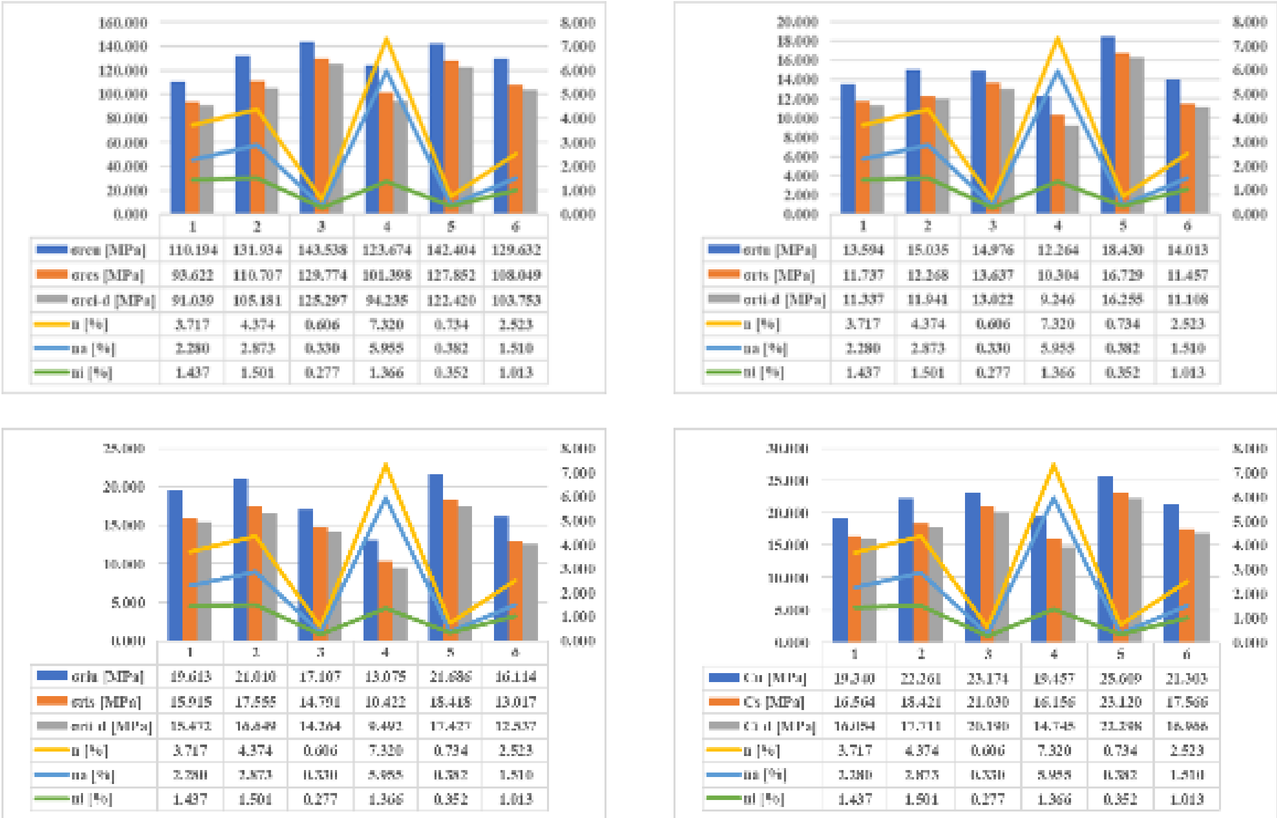

Fig. 10. The influence of porosity on the mechanical characteristics of rocks

Fig. 11. The influence of compactness on the mechanical characteristics of the tested rocks in dry, saturated state and after freeze-thaw cycles

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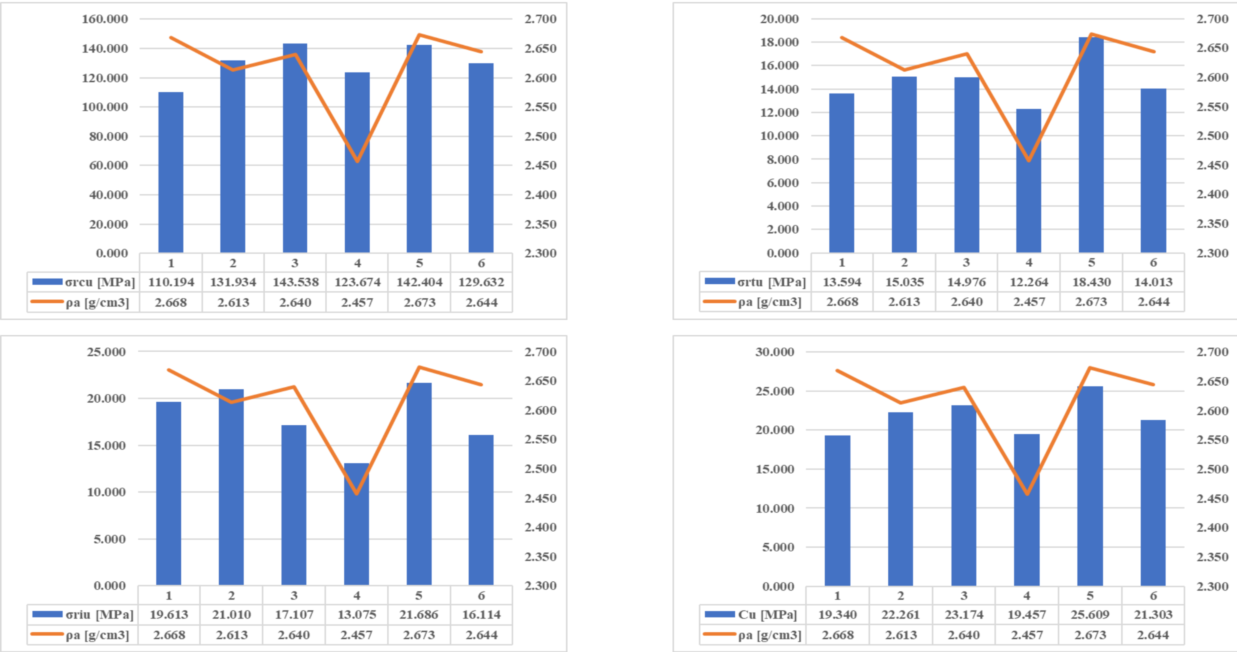

Fig. 12. The influence of the apparent density on the mechanical characteristics of the rocks tested in the dry state

5. Conclusions

The mechanical characteristics of the analyzed andesites are strongly influenced by the growth and the presence of water in rocks (saturation, frost), producing significant decreases in compressive strength and tensile strength, as well as cohesion.

Porosity is another physical parameter that has a significant influence on mechanical properties, it is observed from the data obtained that with the increase of total porosity and even more of the apparent porosity there is a decrease in strength of the material.

The mechanical properties of the rocks are significantly influenced by the apparent density. Thus andesites that recorded higher volumetric densities have better strength characteristics.

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