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Review on the mechanical properties of frozen rocks

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Review scientific paper

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Abstract

The freezing technique has been employed for a long time to strengthen the mechanical properties of intact rock and rock mass; however, it has not received as much attention as it deserves. This paper thoroughly reviews the effect of freezing on the essential mechanical properties, including uniaxial compressive strength, tensile strength, and Young's modulus. The laboratory tests include the determination of density, ultrasound speed propagation, and strength parameters, such as uniaxial compressive strength, tensile strength, and Young's modulus. According to previously published results, the strength of different rocks such as marl, limestone, sandstone, tuff, granite, and marble increased significantly due to freezing when the samples were tested in frozen conditions. However, there is variation in strength increase based on rock type. It is outlined here that freezing increases rock strength by a factor of 4 in porous rock and by a factor of 1.8 in crystalline rock. Additionally, Young's modulus increases with a decrease in temperature; however, a further decrease in temperature from -10 to -20°C has no effect on Young's modulus. Moreover, mathematical modelling for frozen rock has been reviewed comprehensively. It was found that porosity, the density of rock grains, density of water, residual unfrozen water content, minimum unfrozen water content at freezing point, material parameters, the initial temperature of rock, crystal size, orientation and alignment of minerals, and the loading rate are the most critical parameters that influence frozen rock strength.

Keywords:

frozen rock; strength parameters; Young's modulus; mathematical modelling

1. Introduction

Freezing has been used widely to increase the stability of rock mass. Understanding the strength parameters of the frozen intact rock and rock mass is vital for the design procedure. There are several papers that address the determination of strength parameters (**King, 1983; McCann and Entwisle, 1992; Ashby and Sammis, 1995**; **Hoek, 2007; Török and Vásárhelyi, 2010; Palchik, 2011; Heidari et al., 2012; Azimian and Ajalloeian, 2015; Vásárhelyi and Kovács, 2017; Lógó and Vásárhelyi, 2019; Palchik, 2019; Ma et al., 2020; Davarpanah et al., 2020, Davarpanah et al., 2021**) and the impact of water on the strength of rocks (**Hawkins and McConnell, 1992; Li et al. 2020; Vásárhelyi and Davarpanah, 2018; Vásárhelyi and Ván, 2006; Daraei and Zare, 2018; Vásárhelyi, 2002; Vásárhelyi, 2003; Vásárhelyi, 2005; Wong et al. 2016**). However, there is limited research on the effect of freezing on mechanical properties of intact rock and rock mass (**Coussy, 2005; Gambino and Harrison, 2017; Török et al., 2018; Andersland, 1994; Diamantis et al., 2011; Esmaeili-Falak et al., 2018; Paterson, 2001; Petrovic, 2003; Tounsi et al., 2019; Davarpanah et al., 2020; Davarpanah et al., 2021, Bar and Barton, 2021**). Most of these studies concluded that samples tested when they are frozen have higher strength; however, repeated freeze-thaw cycles reduce the mechanical parameters of rocks.

The first application of ground freezing was to support vertical openings in South Wales, Australia, in 1862 and patented by Pietsch in Germany in 1883 (**Harris, 1995**). Artificial ground freezing is typically regarded for excavation support in deep, difficult, disturbed, or sensitive ground or when complete groundwater cut-off is critical (**Schmall et al., 2005**).

It has historically been used in shaft sinking through wet loose soils and recently for temporary support or as an aid to recovery due to collapsed soils in other areas, such

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as underpinning, mining, deep excavations, and groundwater cut-offs. Artificial ground freezing for deep excavation support has been applied in shaft sinking up to 900 m in Saskatchewan for difficult ground conditions and rock/soil interfaces producing large water inflows. The freezing steps can be summarised as follows (**Mellor, 1970; Mellor, 1971; Mellor, 1973; Schulson, 1999**):

1. Freezing under the temperature variation of 0 to −5°C;
2. Freezing under the temperature changes of −5°C to −10°C;
3. Freezing with temperature below −10°C.

There is still water that cannot be frozen at a lower freezing point owing to capillary force and surface adsorption of mineral grains. Strength parameters of rocks, including the uniaxial compressive strength, tensile strength, and point load strength, are reported to increase at subzero temperatures compared to room temperature. Different kinds of rock types have been tested, including highly porous rocks, such as limestone (**Davarpanah et al., 2020**), rhyolite tuff (**Török et al., 2018**), basalt (**Heins and Friz, 1967**), granite (**Mellor, 1970; Inada and Yokota, 1984)**, sandstone (**Dwivedi et al. 1998**), andesite (**Inada and Yokota, 1984; Kodama et al. 2013**), marble (**Dwivedi et al. 1998**), and welded tuff (**Kodama et al. 2013**). Also, deformability characteristics of rocks such as limestone, granite, sandstone (**Dwivedi et al. 1998**), Indiana limestone, and Barre granite demonstrate a significant increase due to freezing (**Heins and Friz, 1967; Mellor, 1970**). **Glamheden and Lindblom** (**2002**) investigated frozen rock mass properties and completed numerical modelling for an unlined hard rock cavern measuring 7 m diameter and 15 m high in Gothenburg, Sweden. It was observed that tensile strength increases with decreasing temperature, and Young's modulus and Poisson's ratio marginally increase with decreasing temperature. As practical case studies, the application of freezing to improve rock mass quality was reported by **Wardrop** (**2005**) for several underground mines in Russia and Canada. According to the reports, significant improvement was observed in RMR and Q due to freezing.

Roworth (**2005**) conducted a series of USC experiments (hematized sandstone, bleached sandstone, and basement rock made of graphitic metapelaite). According to his observations, freezing resulted in a significant increase in strength. The weakest rock samples are expected to have the most significant gain in strength due to freezing. He also established the link between the stress-strain behaviour of tested samples and freezing temperature. Frozen earth exhibits time and temperature-dependent rheological behaviour. In other words, strength is based on the temperature of the rock and the duration of the loading**. Yang et al.** (**2018**) investigated the mechanical properties of frozen rock mass with two diagonal intersected fractures and concluded that the dips significantly influenced the results.

Mellor (**1970**) evaluated the uniaxial compressive and tensile strengths of saturated and dry granite, limestone, and sandstone rock core under temperatures changing from 25 to -195ºC. It was observed that the compressive strength increases with decreasing temperature. As the temperature drops, mineral grains shrink and the formation of ice in pore spaces contributes directly to the strength of the material. Freezing was noted to increase rock strength by a factor of 4 in porous rock and by a factor of 1.8 in crystalline rock. Also, Young's modulus increases with a decrease in temperature; however, a further decrease in temperature from -10 to -20ºC has no effect on Young's modulus (**Yamabe and Neaupane, 2001**).

Mamot et al. (**2018**) studied the effect of temperature fluctuation on slope stability, and they conducted shearing experiments with rock–ice–rock samples at constant strain rates. Acoustic emission (A.E.) has been successfully used to characterise fracturing activity and predict rock–ice failure. All failures are preceded by an A.E. hit increase with peaks just before failure.

Kodama et al. (**2009**) examined how Shikotsu welded tuff behaved over time at subzero temperatures. The results showed that frozen wet specimens had higher uniaxial compressive strengths than frozen dry specimens; nevertheless, frozen wet samples had shorter creep lifetimes than frozen dry ones. Furthermore, the frozen wet samples had substantially higher stresses than the frozen dry specimens. It has to do with the mechanical behaviour of pore ice changing over time. Furthermore, because the fracture initiation stresses of the pores in a frozen wet specimen are on average higher than those in a frozen dry sample, the UCS of a frozen wet sample can be higher.

Jia et al. (**2020**) probed into how the initial water content affected the mechanical properties of frozen argillaceous siltstone (at a temperature of 20°C). Frozen argillaceous siltstone with six saturation degrees was examined for strength (uniaxial compressive strength, tensile strength, and point-load strength) and deformability. Surprisingly, they discovered that the initial degree of saturation significantly impacted the strength of frozen intact rock. In other words, mechanical properties are governed by unfrozen water content at low initial saturation degrees (less than 40%). Ice has a role in reinforcing frozen rock as the initial saturation degree of the rock rises above 40%, corresponding to the second stage of growth. Frost damage begins to degrade frozen objects when the initial saturation degree exceeds the threshold saturation degree for frost damage (in this example, 80 percent) (see **Figure 1**).

Ma et al. (**2020**) did a series of triaxial tests on western Jurassic sandstone and found that mechanical characteristics like peak strength, cohesiveness, internal friction angle, residual strength, and elasticity modulus rose dramatically as the temperature dropped. The rock's strength increases as the temperature drops under steady

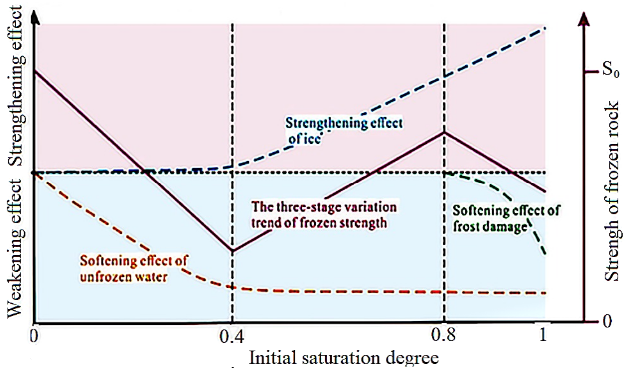

Figure 1: Influence of freezing on the strength and deformability of frozen argillaceous siltstone

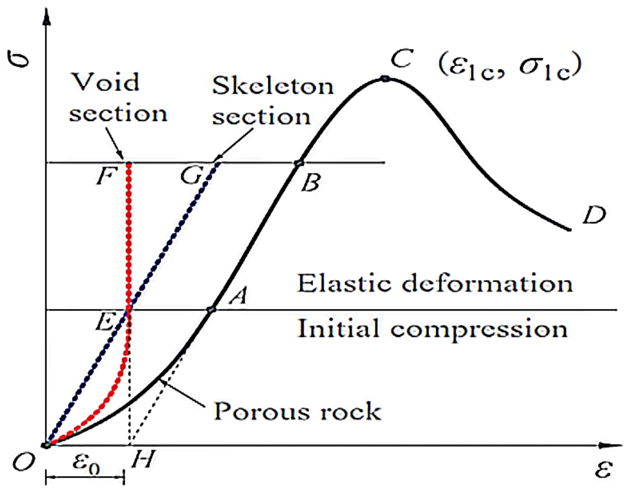

Figure 2: Deformation process of the frozen red sandstone (rock skeleton deformation and void closure deformation, blue and red line, respectively)

confining pressure. The compaction stage can be shortened when the temperature drops and the slope of the elastic stage rise, causing the yield phenomena to become less visible, resulting in increased elastic modulus and brittleness. The maximum axial strain reduces under steady confining pressure, and brittleness becomes increasingly apparent as the temperature drops.

In another study (**Liu et al., 2020**), it was discovered that freezing increased crack initiation stress and crack damage stress in sandstone and mudstone. Pore ice minimises stress concentration around a crack and improves mineral particle cementation. As a result, the peak stresses of sandstone and mudstone rise linearly as the freezing temperature drops.

In other research conducted by **Weng et al.** (**2020**), the relationships between energy dissipation density, rock fragments, and energy consumption were investigated at different strain rates under dry, saturated, and frozen conditions. They realised that the energy dissipation density of the dry and saturated specimen increases with the increase in strain rate at all subzero temperatures. Moreover, three different mechanisms, including the shrinkage of mineral grains, enhancement of ice strength, and interaction of water/ice with rocks, contribute to the change in the microstructure of saturated specimens. **Bai et al.** (**2019**) studied the effect of freezing on sandstone strength and deformation behaviour at subzero temperature using X-ray diffraction and meso-structured observation and proposed the statistical damage constitutive model. The obtained results demonstrated that the frozen red sandstone's peak strength and elastic modulus increase with increasing confining pressure; however, frozen red sandstone's peak strength and elastic modulus rise as temperature decreases, but peak strain is unaffected by this temperature. At lower temperatures, biting force between minerals and friction angle plays a significant role in rock mass strength. In contrast, cohesion plays an essential role in rock mass strength at a lower temperature due to the close structural connection between minerals. The deformation characteristics of the frozen red sandstone are divided into four stages: initial compaction stage (O.A.), elastic deformation stage (A.B.), plastic yield stage (B.C.), and post-peak softening stage (CD), as shown in **Figure 2**.

The novelty of this research is related to the comparison between the obtained results for different rock types. In other words, the amount of change in linear elastic properties such as uniaxial compressive strength, and Young`s modulus, is material dependent. In addition to perfect elasticity, the more extensive study yields exact connections between rock strength and deformation parameters. Internal variables characterise structural changes in the rock depending on different lithologies, and the observed relationships may be interpreted in a universal thermodynamic framework.

2. Mathematical modelling for frozen rock

The micromechanical damage model **Ashby and Sammis** (**1990**) can be used to explain why porous and crystalline rocks have different strengths when they freeze. A mathematical model for the collapse of porous granite and marble by ice development in cracks is presented in **Walder and Hallet** (**1985**). The model predicts crack growth rates, revealing that temperatures between -4 and 15°C are most effective in inducing crack growth. Thermodynamic limits prohibit ice pressure from building up significantly at higher temperatures, whereas water migration for crack formation is restricted at lower temperatures. **Yang et al.** (**2012**) explored the application of Hoek-Brown brittle parameters to frozen ground. They found it helpful in low-stress situations but did not correspond well in high confining stress environments.

The influence of water saturation and freezing on the strength and deformation behaviour of Noboribetsu welded tuff, and Soubetsu andesite was examined by **Kodama et al.** (**2013**). Because of a reduction in stress concentration in the pores or interstitial spaces inside the rock, the strength of the rock mass is assumed to increase in frozen rock due to a rise in the fracture initiation stress, which follows the elastic deformation zone. Tension was shown to have a higher reduction in stress concentration than compression, resulting in more significant increases in tensile strength than compressive strength. The fracture initiation stress surrounding a pore was calculated using an inclusion model for a 3-D flat spheroid to understand this phenomenon better (**Equation 1-Equation 4**).

$$\tau = \frac{2T_m}{b}\sqrt{1-\frac{a_\sigma}{T_m}} \quad (1)$$

$$a = \frac{8}{2\pi q_o + \frac{4(1-\nu)K'}{G} + \frac{16}{3(1-\upsilon)G'} / G} \quad (2)$$

$$b = \frac{8}{(2-\upsilon)\pi q_o + 4(1-\upsilon)G' / G} \quad (3)$$

$$q_o = \frac{1}{\sqrt{S^2 - 1}} \quad (4)$$

Where:

- τ – shear stress (MPa),
- σ – everyday stress (MPa),
- T_m – theoretical tensile strength of body (MPa),
- s – the ratio of the major axis to minor axis,
- G – shear modulus (GPa),
- ϑ – Poisson ratio of the medium respectively,
- G' – shear modulus of inclusion (GPa),
- K' – bulk modulus of inclusion (GPa).

Krautblatter et al. (**2013**) developed modified Mohr-Coulomb failure criteria for ice-filled rock fractures, representing ice-creaming ice in an ice-filled rock joint, failure of rock–ice contacts, friction of rough fracture surfaces, and fracture of cohesive rock bridges. The frictional resistance of rock can thus be formulated as (**Equation 5**).

$$|\tau_p| = \frac{\varepsilon_w}{A_0 \exp\left(-\frac{16700}{T_K}\right)} + \left(-144 * T_C + 0.42 * \sigma' + 41.3\right) + $$

$$+ \sigma' \tan\left(JRC * \log\left(\frac{\sigma_u}{\sigma'}\right) + \varphi_r\right) + \frac{K_C\sqrt{\pi a}}{2w} \quad (5)$$

Where:

- K_c – critical fracture toughness,
- σ_c – uniaxial compressive strength (MPa),
- T_c – the temperature in C,
- T_k – the temperature in Kelvin,
- σ_u – joint wall compressive strength (MPa),
- A_0 – Arrhenius factor A depends mainly on ice temperature, crystal size and orientation, impurity content, and water content in the ice,
- σ' – effective everyday stress,
- φ_r – residual friction angle of smooth unweathered rock surface, rock dependent parameter,
- ω – water content,
- τ_p – peak shear strength (MPa).

Loria et al. (**2017**) proposed a simple elastoplastic constitutive model for modelling the nonlinear mechanical behaviour of frozen silt. The model is built on a set of flow principles. The model's capacity to reflect the nonlinear mechanical response of frozen silt subjected to both low and high confining pressures is demonstrated by comparisons with experimental triaxial test results published in the literature.

Lv et al. (**2019**) proposed the Empirical Frost Heave Model to calculate the frost heaving strain variation of saturated rocks with freezing temperature under uniform and unidirectional freezing conditions. They concluded that saturated rocks with high porosity show significant frost heave, and generally, frost heave increases with the increase of porosity but decreases with the growth of elastic modulus. Thus, porosity and freezing temperature together determine the frost heave potential. The observed frost heaving strains of saturated rock under unidirectional freezing conditions are (**Equations 6** and **7**).

$$\varepsilon_{\parallel}^f = \frac{3k}{k+2}\left\{0.03\zeta\left\{n - \frac{(1-n)\rho_s}{\rho_w}\left[\omega' + (\omega_0 - \omega')e^{a(T-T_0)}\right]\right\} + \right.$$

$$\left. + \alpha_T(T - T_{ini}) \right\} \quad (T < T_{ini}) \quad (6)$$

$$\varepsilon_{\perp}^f = \frac{k}{k+2}\left\{0.03\zeta\left\{n - \frac{(1-n)\rho_s}{\rho_w}\left[\omega' + (\omega_0 - \omega')e^{a(T-T_0)}\right]\right\} + \right.$$

$$\left. + \alpha_T(T - T_{ini}) \right\} \quad (T < T_{ini}) \quad (7)$$

Where:

- $\varepsilon_{\parallel}^f$ – observed frost heaving strain parallel to the freezing direction (%),
- $\varepsilon_{\perp}^f$ – observed frost heaving strain perpendicular to the freezing direction (%),
- n – porosity,
- ξ – constrain coefficient,
- ρ_s – density of rock grains,
- ρ_w – density of water,
- ω^* – residual unfrozen water content,
- ω_0 – minimum unfrozen water content at freezing point T_0
- a – material parameter,
- α_T – thermal expansion coefficient,
- T – freezing temperature,
- T_0 – freezing point of pore water,
- T_{ini} – initial temperature of the rock,
- K – anisotropic frost heave coefficient.

Huang et al. (**2018**) pronounced advanced couple T-H-M model for freezing rock, including critical param-

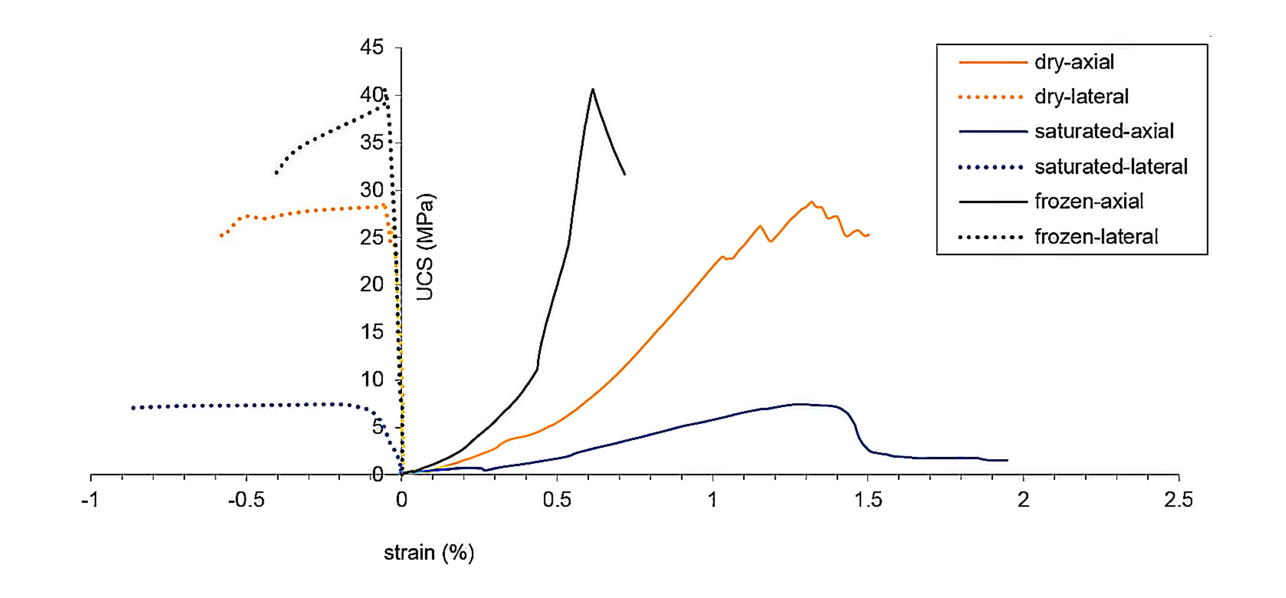

Figure 3: A typical stress-strain curve of Marl sample under dry, saturated, and frozen condition

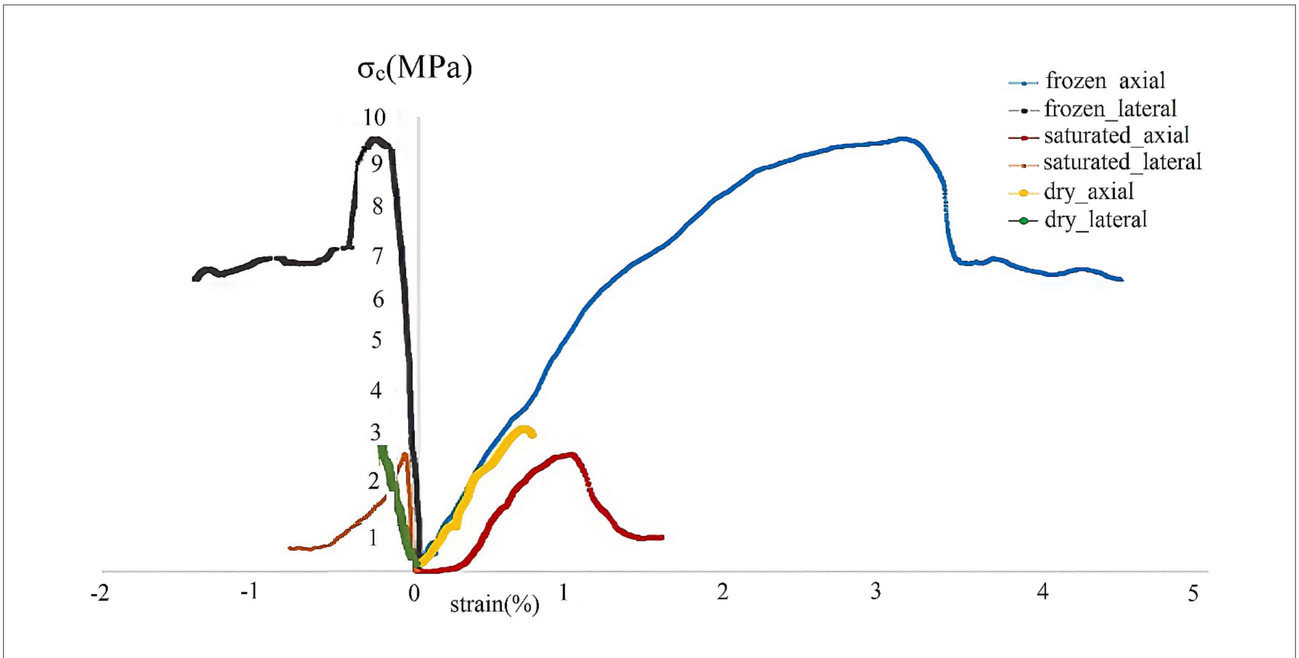

Figure 4: A typical stress-strain curve of highly porous limestone under dry, saturated, and frozen condition

eters, such as unfrozen water content, ice pressure, permeability, thermal conductivity, volumetric strain. They considered energy conservation, continuity, and equilibrium equations in their calculations.

Liu et al. (**2018**) carried out a series of uniaxial tests on frozen saturated silty mudstones from a coal mine shaft in Shanxi, China, to probe the uniaxial compressive strength and deformation behaviour of frozen studied rocks. The compressive peak strength of saturated silty mudstone was related parabolically to temperature. The effect of temperature on the compressive peak strength was greater than that of the loading rate. The proposed empirical prediction model describes the relationship between the compressive peak strength, axial strain at peak strength, temperature, and loading rate (**Equations 8** and **9**).

$$\sigma_s = \sigma + \exp(-T/10) + (1/20\vartheta)(dT + e) \tag{8}$$

$$\varepsilon_s = dT + e \tag{9}$$

Where:

σ_s – compressive peak strength of mudstone (MPa),

σ – natural compressive peak strength (MPa),

T – temperature.

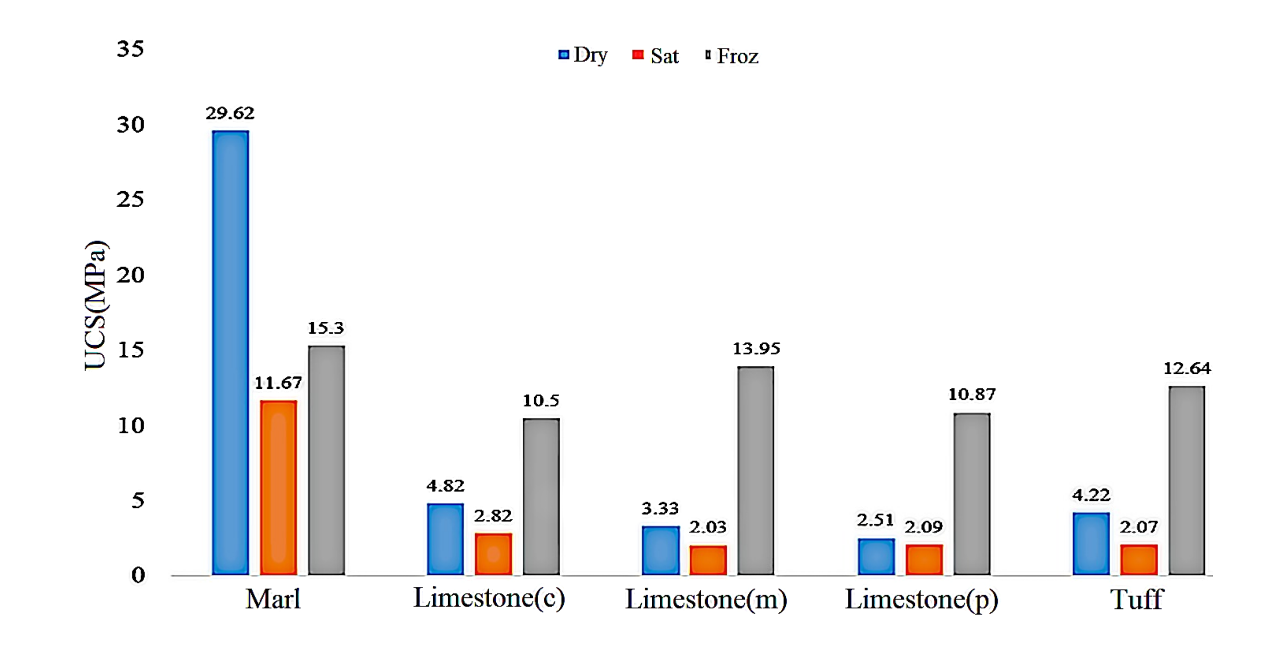

Figure 5: Uniaxial compressive strength under dry, saturated, and frozen conditions for marl, limestone (coarse grain), limestone (medium grain), limestone (porous), and tuff

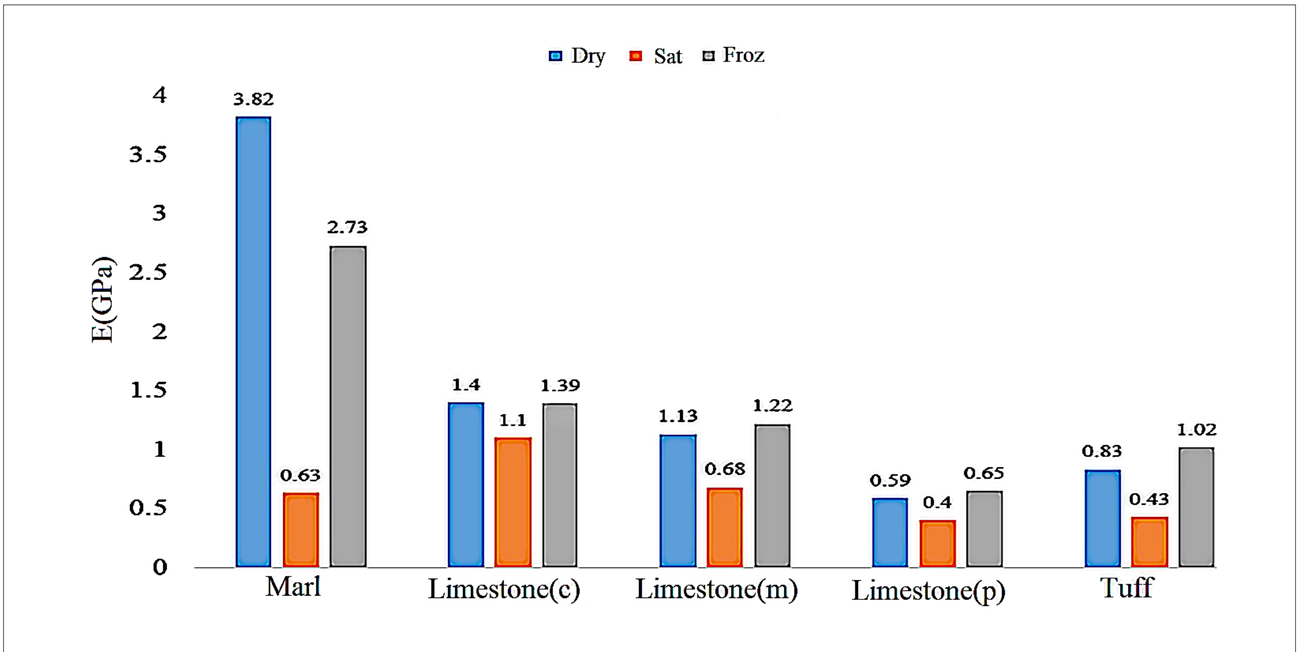

Figure 6: Young's modulus under dry, saturated, and frozen conditions for marl, limestone (coarse grain), limestone (medium grain), limestone (porous), and tuff

3. Results

In this research, we reviewed and analysed many laboratory tests to investigate the effect of freezing on the mechanical properties of different kinds of rocks. Most of the data are collected from different parts of Hungary, including sedimentary rocks like limestone, marl, and tuff as illustrated in **Table 1-3**.

The studied materials include highly porous limestone (**Davarpanah et al., 2020**), coarse grain limestone, medium grain limestone, tuff (**Török et al. 2018; Görög, 2007**), bleached sandstone, hematised sandstone, basement rock made of graphitic metapelite (**Roworth, 2005**), and marl (**Davarpanah et al., 2021**). The previously published results have been summarised in **Tables 1, 2 and 3**. A typical stress-strain curve of highly σt(d)(MPa)

Table 1: Mechanical properties of dry samples

Rock type	Sample no.	$\rho_d(\frac{g}{cm^3})$	E_d (GPa)	$\sigma_{c(d)}$ (MPa)	$\sigma_{t(d)}$ (MPa)	$\varepsilon_{amax\ (d)}$ (%)	$M_{R(d)}$	Ultrasonic wave velocity(d) (km/s)	Rigidity ($\sigma_{c(d)}/\sigma_{t(d)}$)
marl	1	2.47	6.20	28.17	4.20	1.26	220.11	2.83	6.71
	2	2.40	3.30	29.51	3.05	0.96	111.83	2.67	9.69
	3	2.42	3.76	35.39	6.22	1.26	106.25	2.55	5.69
	4	2.41	3.60	28.80	6.29	1.31	125.01	2.29	4.58
	5	2.47	8.60	37.52	3.47	0.89	229.20	3.41	10.82
	6	2.44	4.10	35.62	4.39	0.63	115.09	3.27	8.11
	7	2.44	4.40	27.15	5.28	0.78	162.04	2.86	5.14
	8	2.37	2.65	23.58	4.83	1.00	112.40	2.33	4.88
	9	2.43	1.63	26.56	3.43	0.91	61.37	3.35	8.04
	10	2.40	1.97	28.48	4.25	0.99	69.17	3.47	6.7
	11	2.35	3.88	27.55	5.51	0.94	140.82	2.33	5.00
	12	2.42	1.82	27.14	6.02	1.72	67.05	2.12	4.51
highly porous limestone	1	1.49	0.2	2.17	0.37	0.8	92.17	2.55	5.86
	2	1.5	0.66	3.13	0.39	0.7	210.86	2.73	8.03
	3	1.52	0.91	2.63	0.39	0.34	346.01	2.73	6.74
	4	1.54	0.48	1.95	0.37	0.45	246.15	2.93	5.27
	5	1.53	0.58	2.48	0.24	0.5	233.87	2.58	10.33
	6	1.52	0.39	2.94	0.28	0.75	132.65	2.57	10.50
	7	1.51	0.94	2.27	0.38	0.7	414.10	2.79	5.97
bioclastic coarse grain limestone	1	1.6	1.40	3.07					
	2	1.61	2.20	6.10					
	3	1.63	1.25	5.49					
	4	1.62	0.75	4.62					
medium-grain limestone	1	1.65	1.27	3.69					
	2	1.62	0.65	3.89					
	3	1.63	0.532	2.39					
	4	1.65	1.702	4.38					
	5	1.64	2.026	4.03					
	6	1.61	0.596	1.59					
tuff	1	1.47	0.463	4.15					
	2	1.46	0.924	4.45					
	3	1.49	0.983	4.36					
	4	1.36	0.97	3.92					

porous limestone samples and marl specimens is very different under dry, water-saturated, and frozen conditions (see **Figures 3** and **4**). As shown, as the temperature drops, the compaction stage shortens, and the slope of the elastic stage rises, the yield phenomenon becomes increasingly unobvious, implying increases in elastic modulus and brittleness.

Table 1 illustrates the mechanical properties of different kinds of rocks such as uniaxial compressive strength, modulus of elasticity (E) tensile strength, ultrasonic wave velocity ($V_{.P.}$), Modulus ratio ($M_{.R.}$) and the (s_c/s_t) of studied rock samples in dry condition. **Table 2** shows the mechanical properties under saturated conditions. **Table 3** exhibits the mechanical properties under frozen conditions. For marl samples, the range of modulus of elasticity (E) for dry samples is between 1.63 and 8.6 GPa with a mean value of 3.83 GPa; for saturated samples is between 0.63 and 4.52 GPa with a mean value of 2.36 GPa, and for frozen samples is between 0.64 and 12.7 GPa with a mean value of 2.74 GPa. The range of $M_{.R.}$ for dry samples is between 61.37 and 229.2, with a mean value of 126.7, for saturated samples is between 94.53 and 333.93 with a mean value of 193.83, and for frozen samples is between 35.89 and 312.49 with a mean value of 110.28. The range of s_c for dry samples is between 23.58 and 37.52 with a mean value of 29.62 MPa, and for saturated samples are between 4.64 and 19.5 with a mean value of 11.76 MPa and for frozen samples is between 9.90 and 40.65 with a mean value of 21.93 MPa. For highly porous limestone, the range of module

Table 2: Mechanical properties of saturated samples

Rock type	Sample no	$\rho_s(\frac{g}{cm^3})$	E_s (GPa)	$\sigma_{c(s)}$ (MPa)	$\sigma_{t(s)}$ (MPa)	$\varepsilon_{amax(s)}$ (%)	$M_{R(s)}$	Ultrasonic wave velocity(s) (km/s)	Rigidity ($\sigma_{c(s)}$/ $\sigma_{t(s)}$)
marls	1	2.51	4.52	19.5	3.04	1.07	231.8	3.84	6.42
	2	2.50	0.7	7.41	0.79	1.29	94.52	2.34	9.32
	3	2.54	3.7	15.08	3.04	0.25	245.35	4.04	5.09
	3	2.51	4.08	17.17	1.19	0.57	237.56	3.31	0.57
	4	2.54	1.95	5.84	1.99	0.41	333.93	3.73	2.94
	5	2.54	1.43	9.85	1.12	0.86	145.22	2.62	8.79
	6	2.52	3.14	18.35	1.27	0.77	171.16	3.61	14.46
	7	2.55	1.17	9.58	1.13	0.92	122.15	3	8.46
	8	2.51	3.5	14.36	1.08	0.3	243.73	3.8	7.81
	9	2.49	1.13	6.61	0.88	0.62	171.01	2.06	7.52
	10	2.52	0.63	4.64	1.66	0.8	135.7	2.41	2.79
highly porous limestone	1	1.73	0.43	1.76	0.35	0.56	244.32	2.45	5.03
	2	1.7	0.58	2.12	0.40	0.86	273.58	2.50	5.30
	3	1.73	0.26	1.49	0.23	0.85	174.50	2.65	6.48
	4	1.78	0.39	1.94	0.20	0.53	201.03	2.58	9.70
	5	1.78	0.33	2.68	0.28	0.98	123.13	2.53	9.57
	6	1.75	0.49	2.2	0.16	0.67	222.73	2.48	13.75
	7	1.8	0.37	2.5	0.19	0.96	148.00	2.56	13.16
bioclastic coarse grain limestone	1	1.92	1.68	3.92					
	2	1.93	1.08	2.27					
	3	1.95	0.68	2.38					
	4	1.92	0.95	2.7					
medium-grain limestone	1	1.93	1.92	2.13					
	2	1.94	1.62	2.73					
	3	1.93	0.4	2.19					
	4	1.87	0.9	1.15					
	5	1.90	0.89	2.23					
	6	1.98	0.68	1.76					
tuff	1	1.91	0.25	1.82					
	2	1.93	0.62	2.50					
	3	2.14	0.51	1.74					
	4	1.83	0.33	2.21					

of elasticity (E) for dry samples is between 0.2 and 0.94, for saturated samples is between 0.26 and 0.58 (GPa) and for frozen samples is between 0.3 and 1.32 (GPa). For dry samples, the range of M.R. for dry samples is between 92.17 and 414.10, saturated samples are between 123.18 and 253.78, and frozen samples are between 26.93 and 144.15. The range of s_c for dry samples is between 1.95 and 3.13 (MPa), and for saturated samples are between 1.49 and 2.5 (MPa) and for frozen samples is between 9.45 and 12.5 (MPa).

Figure 5 shows that the average uniaxial compressive strength of dry marl samples is greater than the saturated and frozen ones, whereas, for other rock types, the strength under frozen conditions is greater than saturated and dry ones. It is probably due to the existence of clay minerals in marl samples. **Figure 6** indicates that the increase in average Young's modulus due to freezing in marl samples is more significant than other types of rocks, which is associated with the presence of clay minerals in marl samples.

4. Discussion

Marl samples have an average maximum uniaxial compressive strength of 21.93 MPa in the frozen state, 86 percent higher than saturated samples (11.76 MPa). Similarly, **Török et al.** (**2018**) investigated the effect of freezing on the strength of porous limestone and found

Table 3: Mechanical properties of frozen samples

Rock type	Sample no.	$\rho_f(\frac{g}{cm^3})$	E_f (GPa)	$\sigma_{c(f)}$ (MPa)	$\sigma_{t(f)}$ (MPa)	$\varepsilon_{amax(f)}$ (%)	$M_{R(f)}$	Ultrasonic wave velocity(f) (km/s)	Rigidity ($\sigma_{c(f)}$/ $\sigma_{t(f)}$)
marl	1	2.52	4.96	22.71	4.18	1.03	218.37	4.72	5.43
	2	2.50	12.70	40.65	2.83	0.61	312.44	4.94	14.37
	3	2.51	0.64	14.61	8.17	2.47	43.80	3.34	1.79
	4	2.49	2.41	20.13	4.63	1.68	119.74	4.39	4.35
	5	2.59	2.30	24.40	2.56	0.85	94.28	4.88	9.54
	6	2.47	2.37	14.81	5.51	0.79	160.03	4.76	2.69
	7	2.54	1.51	19.31	7.47	1.66	78.19	4.60	2.58
	8	2.46	2.20	23.51	3.78	1.02	93.56	4.56	6.23
	9	2.55	1.34	30.94	7.19	0.82	43.31	4.22	4.30
	10	2.51	0.64	9.90	7.09	1.43	64.67	3.42	1.40
	11	2.54	0.84	23.41	3.89	2.57	35.89	4.49	6.02
	12	2.52	2.75	25.47	4.01	1.04	107.97	4.53	6.35
	13	2.47	0.94	15.30	3.45	1.81	61.42	4.17	4.44
highly porous limestone	1	1.68	0.88	10	2.52	1.07	88.00	4.25	3.97
	2	1.74	0.68	9.45	3.26	2.73	71.96	10.05	2.90
	3	1.72	0.41	9.52	2.63	3.07	43.07	4.43	3.62
	4	1.74	0.31	11.51	2.37	4.33	26.93	4.46	4.86
	5	1.71	1.32	9.84	3.77	1.98	134.15	4.41	2.61
	6	1.78	0.52	12.73	2.98	4.38	40.85	4.48	4.27
	7	1.78	0.46	12.9	2.90	3.78	35.66	4.57	4.45
bioclastic coarse grain limestone	1	1.90	1.52	7.95					
	2	1.88	1.58	10.88					
	3	1.91	1.08	12.67					
medium-grain limestone	1	1.89	0.93	11.34					
	2	1.90	0.6	16.45					
	3	1.88	1.78	16.52					
	4	1.89	1.60	16.14					
	5	1.89	1.05	11.13					
	6	1.88	1.36	14.93					
	7	1.83	1.22	11.28					
tuff	1	1.75	1.09	14.1					
	2	1.66	1.10	10.98					
	3	1.74	1.10	13.59					
	4	1.74	1.05	13.96					
	5	1.69	0.76	10.6					

that the frozen saturated limestone is 50 percent stronger than the saturated limestone. **Davarpanah et al. (2021)** conducted similar research on highly porous limestone and found that freezing increased strength by 80%. Strength parameters of rocks, including the uniaxial compressive strength, tensile strength, and point load strength, are reported to increase at subzero temperatures compared to room temperature. Different rock types have been tested, including limestone (**Davarpanah et al., 2020**), basalt (**Heins and Friz, 1967**), granite (**Mellor, 1970; Inada and Yokota, 1984**), sandstone (**Vásárhelyi and Ván, 2005**), andesite (**Kodama et al., 2013**), marble (**Dwivedi et al., 1998**), and welded tuff (**Kodama et al., 2013**). Also, deformability characteristics of rocks such as limestone (**Davarpanah et al., 2020**), granite (**Mellor, 1970**), sandstone (**Vásárhelyi and Ván, 2005**) demonstrate a significant increase due to freezing.

Similarly, the strength increase due to freezing is 86 percent, based on our recent measurements on marl (**Davarpanah et al., 2021**). In addition, the average maximum uniaxial compressive strength in dry conditions is

Table 4: Previously published linear regression(Y=ax+b) between UCS (MPa) and Vp (km/s) for different rock types in dry conditions

Rock type	a	b	R^2	author
Igneous rocks	35.54	55	0.80	Turgrul and Zarif (1999)
Sandstone, limestone, and cement mortar	56.71	192.93	0.67	Cobanoglu and Celik (2008)
Sedimentary, metamorphic, and igneous rocks	64.2	117.99	0.90	Sharma and Singh (2008)
Peridotites	140	899.33	0.83	Diamantis et al. (2011)
Different rocks	38	50	0.93	Sarkar et al. (2012)
Different rocks	33	34.83	0.87	Kandelwal (2013)
Marly rocks	26	20.47	0.91	Azimian and Ajalloeian (2015)
Travertine	27.4	62.78	0.80	Jamshidi et al. (2016)
Marl	4.81	15.35	0.6	Davarpanah et al. (2021)

29.62 MPa, which is around 60% higher than saturated conditions (11.76 MPa). This result is consistent with a previously reported result for Miocene Limestone, which indicated a 60% strength decrease owing to saturation. The strength properties of rock increase as the temperature drops. This occurrence is consistent with the acquired results. Several authors have investigated the relationship between ultrasonic wave velocity (Vp) and UCS. (**Turgrul and Zarif, 1999; Kahraman, 2001; Yasar and Erdogan, 2004; Sharma and Singh, 2008; Cobanoglu and Celik, 2008; Kilic and Teymen, 2008; Diamantis et al., 2011; Yagiz, 2011; Sarkar et al., 2012; Khandelwal, 2013; Azimian and Ajalloeian, 2015; Jamshidi et al., 2016; Davarpanah et al., 2021**). Their results are presented in **Table 4**.

Table 4 summarises the linear regression analysis between uniaxial compressive strength and ultrasonic wave velocity for different rock types under dry conditions. In general, the coefficient of determination (R^2) for igneous rocks is higher than sedimentary and metamorphic rocks.

5. Conclusions

Through reviewing several laboratory test results, including uniaxial compressive strength, Brazilian test, and ultrasonic wave velocity test performed to provide more insight into crucial mechanical properties of highly porous limestone specimens, tuff and marl samples, the following conclusions are drawn:

- Frozen marl samples had an average uniaxial compressive strength of 21.93 MPa, which is 86 percent higher than saturated marl samples (11.76 MPa). The cementation of ice and particles increases the integrity of the rock mass under freezing conditions, making the rock viscoplastic and brittle.
- Frozen marl samples have a tensile strength of 4.98 MPa, which is 219 percent higher than saturated marl samples (1.56 MPa). Consequently, the rise in tensile strength is 2.5 times more than the increase in uniaxial compressive strength. This is because, in tension, the reduction in stress concentration is more significant than in compression, resulting in more considerable increases in tensile strength than in compressive strength.
- An average maximum axial failure strain of frozen samples is 1.37%, about 50% more than saturated ones (0.71%).
- The average Young's modulus of frozen samples is 2.74 GPa, which is 13% more than saturated ones (2.36 GPa).
- The maximum uniaxial compressive strength of highly porous samples in the frozen condition is about 13 MPa, and 3.5, 2.7 MPa in dry and saturated, respectively. Namely, the strength in the frozen state is about 80% more than in dry and 65% more than in saturated conditions.

It is worth mentioning that more detailed analyses beyond ideal elasticity give exact relationships between the strength and deformation parameters of rock. Particularly, the observed relations can be explained in a universal thermodynamic framework where internal variables characterise the structural changes in the rock based on different lithologies.

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SAŽETAK

Pregled mehaničkih svojstava smrznutih stijena

Tehnika smrzavanja već se dugo koristi za jačanje mehaničkih svojstava netaknute stijene i stijenske mase. Međutim, nije dobila toliko pažnje koliko zaslužuje. Ovaj rad detaljno razmatra učinak smrzavanja na bitna mehanička svojstva, uključujući jednoosnu tlačnu čvrstoću, vlačnu čvrstoću i Youngov modul. Laboratorijski testovi uključuju određivanje gustoće, širenja ultrazvučne brzine i parametara čvrstoće kao što su jednoosna tlačna čvrstoća, vlačna čvrstoća i Youngov modul. Sukladno ranije objavljenim rezultatima, čvrstoća različitih stijena poput lapora, vapnenca, pješčenjaka, tufa, granita i mramora znatno je porasla zbog smrzavanja, kada su uzorci ispitani u smrznutim uvjetima. Međutim, postoje razlike u povećanju čvrstoće ovisno o vrsti stijene. Ovdje je istaknuto da smrzavanje povećava čvrstoću stijene za faktor 4 u poroznoj stijeni i za faktor 1,8 u kristalinskoj stijeni. Dodatno, Youngov modul uglavnom raste sa sniženjem temperature, dok daljnji pad temperature s -10 na -20 °C nema utjecaja na Youngov modul. Štoviše, matematičkim modeliranjem smrznute stijene utvrđeno je da poroznost, gustoća zrna stijene, gustoća vode, rezidualni sadržaj nesmrznute vode, minimalni sadržaj nesmrznute vode na točki smrzavanja, parametri materijala, početna temperatura stijene, veličina kristala, orijentacija i poravnanje minerala te brzina opterećenja predstavljaju najkritičnije parametre koji utječu na čvrstoću smrznute stijene.

Ključne riječi:
smrznuta stijena, parametri čvrstoće, Youngov modul, matematičko modeliranje

Author’s contribution

Seyed Morteza Davarpanah (Ph.D. candidate) data analysis, conceptualisation and writing. **Ákos Török** (Professor Full) methodology, and **Balázs Vásárhelyi** (Associate Professor) supervision and project administration.