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NEW RESULTS OF UNDERWATER ROCK CUTTING BY PURE WATERJET

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ABSTRACT

Few years ago we have constructed a pressure vessel and we performed basic tests presented in Minneapolis in the 2001. Then the vessel has been improved, especially its seal part, and the electrical part of the device for sample holding and movement has been also remade to enable more precise setting of traverse rate. The paper is aimed at experiments performed in the modified vessel with several kinds of rock like materials (sandstones, marbles, granites, concretes) in several conditions – in the air, in the non-pressurized water and in the pressurized water without previous wetting of the sample. Our new results are discussed with regard to the theory reliability and the underwater applications.

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1. INTRODUCTION

Our former research presented by Hlaváč (2001) was a part of the project devoted to the interaction of water jets with rock type materials situated in the non-traditional conditions. The decrease of the efficiency of the tools with rotating, swinging or vibrating nozzle heads in water (oil or another liquid) was studied then. After the end of the project this branch of our research was terminated. Nevertheless, there are still some problems in practice that need some additional research in this branch and, therefore, we started to study the problem again. The first results of our retrieved research are summarized in this paper. There were focused at the further prove of the theory published by Hlaváč in 2001. This theory describes the water jet efficiency in a certain depth under the water level simulated by water pressure inside a special pressure vessel (Fig. 1).

2. THEORETICAL BACKGROUND

The basic theoretical presumptions presented by Hlaváč et al. (1999) concerning the attenuation of water jet in the continuum between nozzle outflow and target material surface were based on theories of cumulative charge (Lavrentjev, 1957). The equation for evaluation of the attenuation coefficient was derived based on parameters of the liquid continuum surrounding the nozzle. According to the theoretical assumption the uniform equation can be prepared for evaluation of the coefficient characterizing the attenuation of the liquid jet energy inside any continuum, which is passing through. This coefficient is determined directly by the density of the continuum and of the jet forming liquid, their viscosities and characteristic jet cross-section dimension:

$$\xi = \frac{C_x(p_e)}{\mu} \frac{\rho_e}{\rho_o d_o} \frac{\eta_a}{\eta_o} \tag{1}$$

Then the theory derived and presented by Hlaváč several times (1992, 1995, 1999, 2001) can be used for description of the jet penetration process. The equations resulting from the theory and applied for calculations of the theoretical curves in this paper are presented in the modification valid for only one pass of the jet. The most important equation is the one for determination of the jet penetration into the target material, as the depth of penetration (depth of cut) is the basic criterion of the jet efficiency.

$$h = \frac{\pi d_o \sqrt{2 \rho_o \mu^3 p^3 \gamma_R^3 e^{-5(\xi L)}}\,(1-\alpha^2)\cos\theta}{4 \chi \rho_M \nu^{\frac{\rho_o}{\rho_M}} \left[\alpha^2 e^{-2(\xi L)} \mu p \gamma_R + \frac{\rho_o}{\rho_M} \sigma \right]} \tag{2}$$

3. DESCRIPTION OF EXPERIMENTAL MATERIAL

The blocks were prepared from sandstone (the light green glauconite sandstone, medium grain size, homogeneous, from the Godula Unit in the Beskydy Mountains, Czech Republic), from granodiorite (the light gray biotite granodiorite, medium grain size, homogeneous, from the quarry near Žulová (town) in the Jeseníky Mountains, Czech Republic), from the marble (the white marble, medium grain size, homogeneous, from the locality Lipová-Supíkovice in the Jeseníky Mountains, Czech Republic) and from the high-strength concrete (the cement type CEM I 42.5, the water coefficient 0.4, the aggregate Moravian wacke from locality Bohučovice with fractions 0-4, 4-8, 8-16, plasticizer). The average specific density of the sandstone is 2640 kg.m^{-3}, the average uniaxial compression strength and tensile strength are 128 MPa and 9.5 MPa respectively. The average specific density of the granodiorite is 2648 kg.m^{-3}, the average uniaxial compression strength and tensile strength are 145 MPa and 11.3 MPa respectively. The average specific density of the marble is 2678 kg.m^{-3}, the average uniaxial compression strength and tensile strength are 70 MPa and 7,5 MPa respectively. The average specific density of the concrete is 2750 kg.m^{-3}, the average uniaxial compression strength is 62.8 MPa. Nevertheless, this concrete is very heterogeneous material and therefore the local strength can substantially differ from the declared average value.

4. EXPERIMENTAL PROCEDURE

The dimensions of the blocks were approximately 100 x 100 x 30 mm. Each block was fixed into the support of the motional device inside the pressure vessel in the beginning of the experiment. The vessel was closed and filled with water except the case when the tests were performed in air. Water inside the vessel was either without any pressure or pressurized up to 0.6 MPa or 1.2 MPa. Pressurizing of water was ensured by inflow from the cutting nozzle and regulating overflow valve. The water pressure inside the vessel was measured. The mechanical pressure meter installed at the vessel body was used. The operator checked the value during each cut made in material. The kerfs were made at various traverse rates. Pump pressure was 400 MPa, nozzle diameter 0.1 mm, stand-off distance 10 mm (from nozzle outlet), angle of impingement 0 rad. The depths of kerfs were measured in ten or more points assigned on the sample surface. Then the average values for all kerfs were evaluated by the standard processing of measured data and they were used for comparison of the theory of Hlaváč (1992, 1995) with the experimental data. The comparison is presented in a graphic form in Fig. 2 through 5. Photos of the samples cut in air and water are presented in Fig. 6 through 9.

5. RESULTS AND DISCUSSION

The experiments presented here were oriented at two main problems. Proving of the conclusions of the preliminary tests published in 2001 was the first of them. The second aim was to gain more information about breaking of the brittle material in pressurized water medium. As it is evident from the comparison between theoretical (calculated) curves and experimental data obtained for respective parameters of cutting (see Fig. 2 through 5), the correlation between theory prepared by Hlaváč (1992, 1995, 2001) and experimental results is feasible. The worse correlations for granite and concrete are caused by high non-homogeneities of the local material properties due to the variation of the material microstructure. The particular material unites have different compositions and, therefore, another resistances to the impact forces of the jet. Nevertheless, the values calculated from the theory for the global material properties generally differ from the average experimental values only within the standard deviation of measurement. Therefore, there can be conclude, that there is no special need for using of the statistically determined material properties (evaluated from the percentage of particular material units and respective properties of their matter) in calculations.

Studying of the kerfs cut in sample materials shows an important, but rather expected, fact that attenuation of jet energy in water is very rapid. Even though the gap between sample surface and nozzle holder was reduced to the operational minimum (about 2 mm), the marks on materials prove this conclusion. There is evident that material destruction in water (and even pressurized water) at the same conditions as in air (except the surrounding medium) yields more volume breach than cutting. This is typical for cutting at pressures that are close to the material resistance or for jets with high dynamics (modulated and pulsing ones). Nevertheless, there are not any valid arguments proving that penetration through the water causes modulation or pulsation of the studied jets. As concerning the use of water jets for a destruction of material under the water level, however, there is necessary to account for high attenuation of jet efficiency. Nevertheless, material with inner failures, such as crannies, fissions or cavities, can be substantially more disintegrated than the intact one.

6. CONCLUSIONS

The most important results can be summarized to the following points:

- the theoretical model prepared in past by Hlaváč correlates well with experimental data, both qualitatively and quantitatively;
- the up-to-date results show that attenuation of water jet in water strongly depends on the depth under the water level;
- the most appropriate application of pure water jets under the water level is removing of the eroded brittle non-homogeneous material.

7. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

α	coefficient of losses in liquid jet velocity during interaction with material ...[-]
γ_R	compressibility factor ...[-]
$C_x(p)$	pressure dependent coefficient of liquid (water) jet forehead shape inside the medium (continuum) ranging between the nozzle outlet and the target surface respectively ...[-]
d_o	liquid (water) nozzle diameter ...[m]
η_o	liquid (water) dynamic viscosity ...[N.s.m^{-2}]
η_a	air dynamic viscosity ...[N.s.m^{-2}]
h	depth of disintegration in material ...[m]
θ	angle of an incidence of the liquid (water) jet measured between a normal line at the point of jet's axis projection through the material surface and the jet axis ...[rad]
L	stand-off distance ...[m]
μ	nozzle discharge coefficient ...[-]
ξ	coefficient of the jet attenuation caused by resistance of the medium between the nozzle outlet and the target surface ...[m^{-1}]
p	liquid (water) pressure before the nozzle inlet ...[Pa]
p_e	pressure of the medium ranging between the nozzle outlet and the target surface ...[Pa]
ρ_o	liquid (water) density in a non-compressed state ...[kg.m^{-3}]
ρ_e	density in a non-compressed state of the medium ranging between the nozzle outlet and the target surface ...[kg.m^{-3}]
ρ_M	density of material ...[kg.m^{-3}]
σ	material compressive strength or combined strength ...[Pa]
v	modified traverse rate ...[m.s^{-1}]
χ	coefficient of reflected jet expansion due to mixing with disintegrated material ...[-]

10. GRAPHICS

Fig. 1. View of the mobile pressure vessel, the high-pressure pump for water jet generation and vessel feeding and their location in our laboratory.

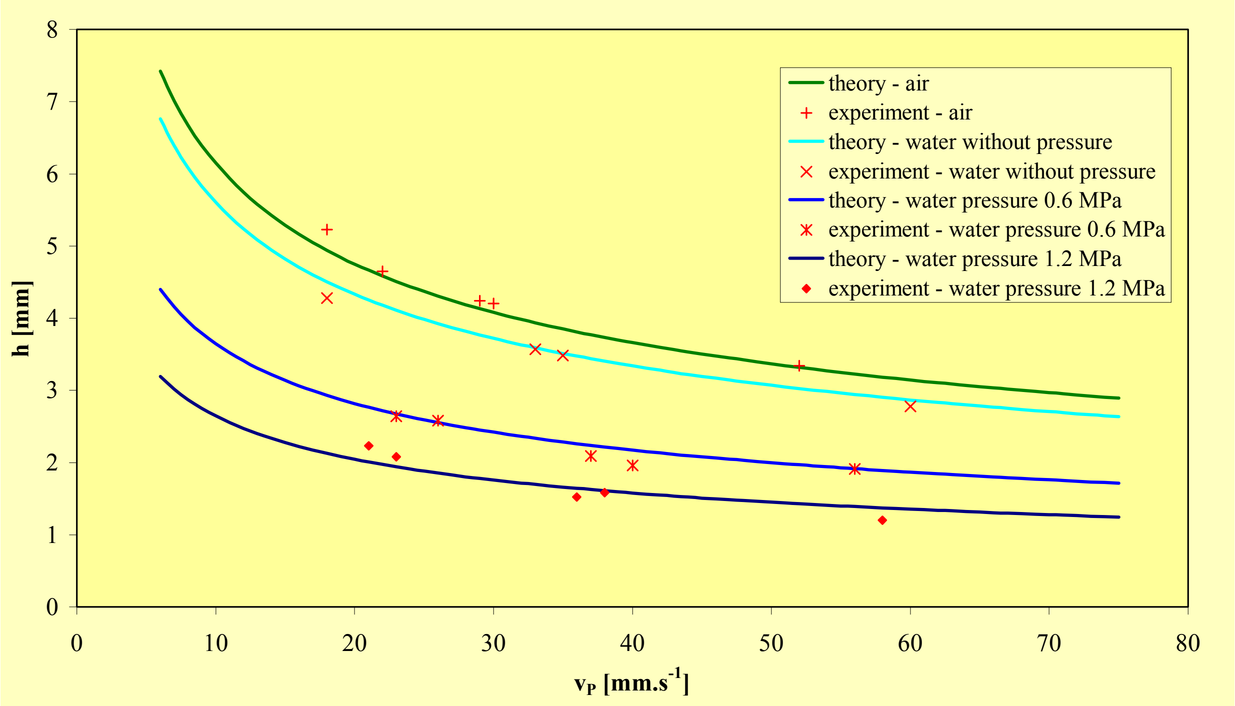

Fig. 2. Visual correlation of theoretical curves and experimental data for sandstone.

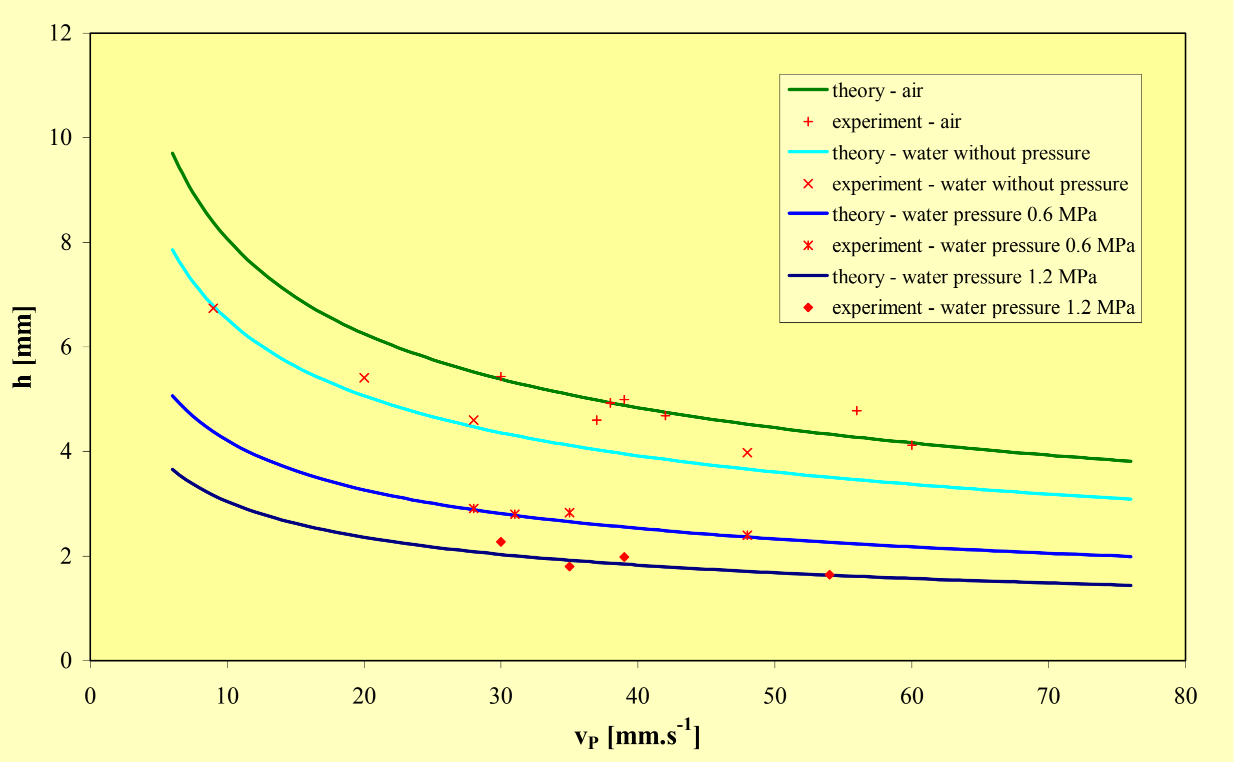

Fig. 3. Visual correlation of theoretical curves and experimental data for marble.

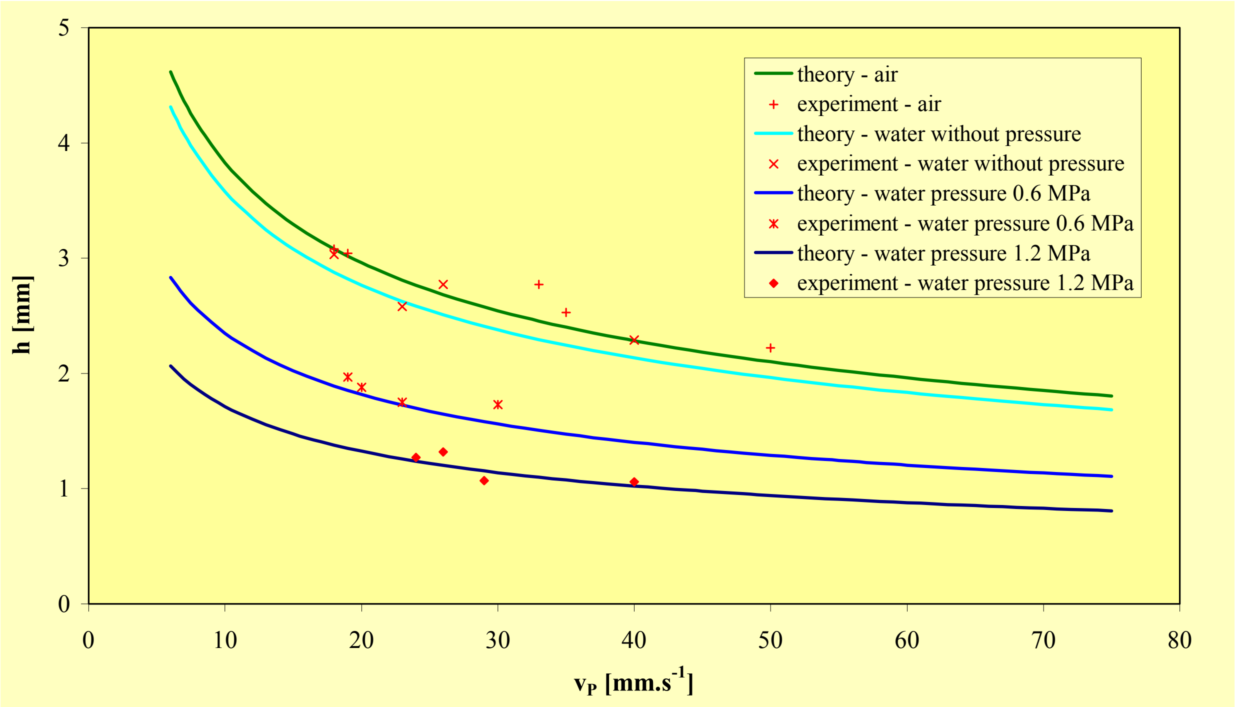

Fig. 4. Visual correlation of theoretical curves and experimental data for granite.

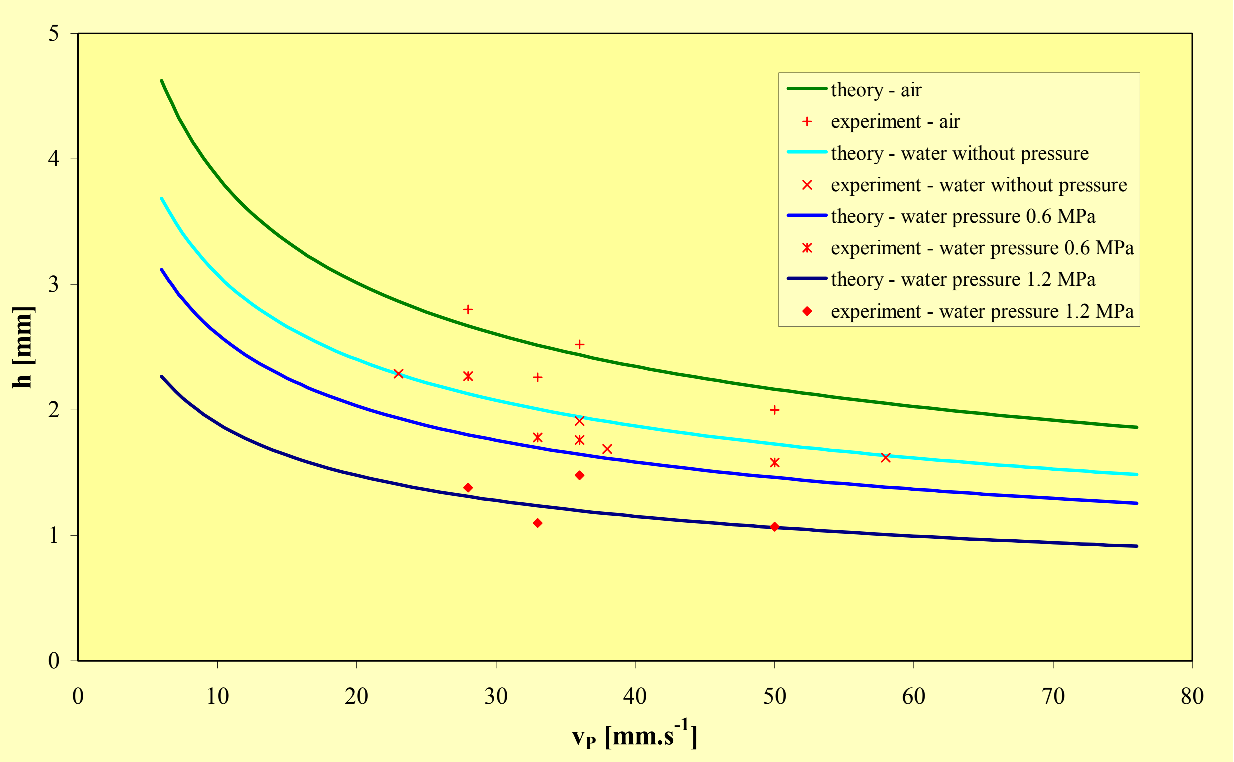

Fig. 5. Visual correlation of theoretical curves and experimental data for concrete.

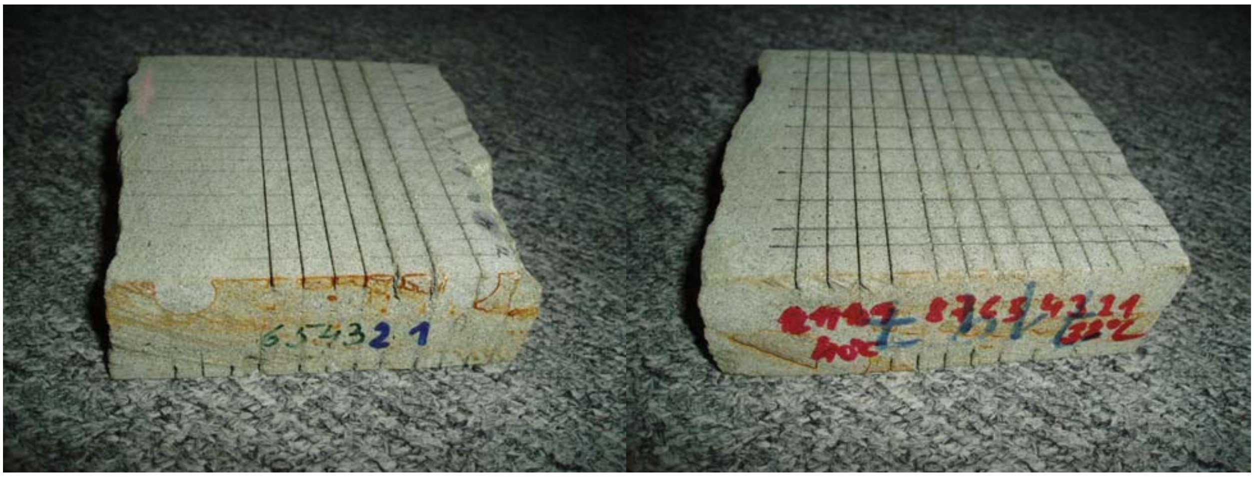

Fig. 6. Sample of sandstone: blue marked kerfs 1, 2 are cut inside water with pressures 1.2 MPa and 0.6 MPa respectively. Green kerfs 3 through 6 are cut in air at four different traverse rates. Red kerfs are cut in water: 1 through 4 in pressure 1.2 MPa, 5 through 8 in pressure 0.6 MPa and 9 through 12 in 0.1 MPa (without any additional pressure, just near the water level). Four traverse rates were used with each pressure inside the pressure vessel.

Fig. 7. Sample of marble: blue marked kerfs 1 through 4 are cut in air at four different traverse rates. Red kerfs are cut in water: 1 through 4 in pressure 1.2 MPa, 5 through 8 in pressure 0.6 MPa and 9 through 12 in 0.1 MPa (without any additional pressure, just near the water level). Four traverse rates were used with each pressure inside the pressure vessel.

Fig. 8. Sample of granite: blue marked kerfs 0 through 4 are cut in air at five different traverse rates. Red kerfs are cut in water: 1 through 4 in pressure 1.2 MPa, 5 through 8 in pressure 0.6 MPa and 9 through 12 in 0.1 MPa (without any additional pressure, just near the water level). Four traverse rates were used with each pressure inside the pressure vessel.

Fig. 9. Sample of concrete: blue (green) marked kerfs 1 through 4 are cut in air at four different traverse rates. Red kerfs are cut in water: 1 through 4 in pressure 1.2 MPa, 5 through 8 in pressure 0.6 MPa and 9 through 12 in 0.1 MPa (without any additional pressure, just near the water level). Four traverse rates were used with each pressure inside the pressure vessel.