IMPROVEMENT OF MECHANICAL TOOL PERFORMANCE BY WATERJET ASSISTANCE

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The problems arising in the excavation of hard rocks with the use of mechanical tools consist chiefly in a slow advance rate accompanied by an intensive wear due to the toughness and abrasiveness of the rock. In order to allow the further extension of mechanical excavation beyond the limits of the presently available technology, the assistance of waterjet aiming at improving the performance of the equipment while reducing the wear rate of the tools, has been recognised as one of the most interesting technical solutions. The paper illustrates the improvement of the performance of both disk cutters and picks obtained with the waterjet assistance at the Waterjet Laboratory of the University of Cagliari on a medium-hard rock .

Keywords: Rocks, Mechanical excavation, Disk cutters, Picks, Waterjet

1. INTRODUCTION

The technological developments in the construction of excavation machines and mechanical tools enable now mechanical excavation to compete with traditional explosive-based methods. Further research is being carried out in order to extend the application even in the case of very hard rocks.
Although drilling and blasting can be applied successfully for winning a great variety of rocks, a number of drawbacks are often encountered such as noise, airblast, flyrock and vibrations that are generally not acceptable especially in an urban environment. Moreover, the lack of accuracy in the cross section profile and the damage induced by overbreak may render the roof support and the concrete lining more expensive, thus upsetting the economic advantage of a cheaper excavation.
Finally the D&B tunnelling cost increases gradually with length, when mucking and ventilation become critical. On the other hand, the use of mechanical tools for the excavation of hard rock is characterised by slow excavation rate and intensive tool wear due to the toughness and abrasiveness of the rock (Vasek, 1996).

In order to allow the extension of mechanical excavation beyond the limits of presently available technology the assistance of waterjet has been investigated in the case of picks and disks applied to roadheaders and full-facers.
A long-term research program has been undertaken at the University of Cagliari aiming at developing a hybrid system based on the synergetic action of mechanical excavation tools with high-velocity waterjet.

2. PREVIOUS RESEARCH

A mechanical tool can be put out of service either by rupture caused by excessive mechanical stress or by wear due to thermal overload (Alehossein and Hood, 1999).
During the last ten years attempts have been made to improve the tool performance and life by:
- Studying special material technologies;
- Applying internal and external cooling actions;
- Resorting to the assistance of a water jet.

The chief advantage of using high velocity waterjet would be the reduction of the resistance of the rock to the action of the cutting tool and thence an expected decrease of the forces shared at the tool/rock contact area. The importance of this synergy depends on the jet power beyond the pressure threshold typical of a particular rock.
A second, important, advantage is represented by the cooling action exerted by the jet on the rock-tool contact area.
During the last 30 years many research have been developed with the aim of assessing the effectiveness of the waterjet assistance. The results appear to be very dissimilar and sometimes contradictories due to the variety of the test conditions. In general it has been proved that the following parameters play the most important role in determining the effect of waterjet application:

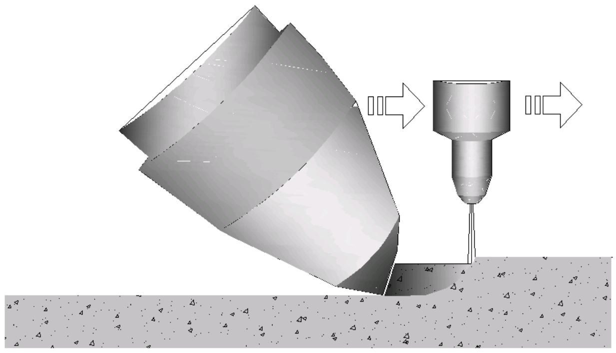
- water pressure
- nozzle diameter
- velocity of the tool on the rock
- position of the jet

In the following the findings of the main experimental works have been reassumed separately for disk cutters and drag tools; the research developed at DIGITA are then presented and the results analysed and discussed with the aim of assessing the effectiveness of the waterjet assistance.

Drag tools
The earliest research at the DIGITA's Waterjet Laboratories concerning the synergetic action of mechanical instruments and jets of water was firstly focused on drag tools using the "through-the-pick" and the "front-of-pick" configurations.
Results show that an increase in cutting rate (around 30%) can be achieved with waterjet assistance with a certain reduction of the forces at equal performance level.
Waterjet also proved to be and efficient cooling system enabling to reduce considerably the wear rate (Ciccu et al. 1999, 2004, 2004).
A second group of tests was aimed at investigating the contribution of waterjet in the "front-of-tool" configuration (figure 1) in the disintegration of a much harder granite rock (compressive strength around 180 MPa) using special tools with a flat tip coated with polycrystalline diamond (Field E.J, 1992). During these tests the wear process was studied and a significant increase of the tool life was achieved. Furthermore the effects previously

observed concerning the forces and the mechanical energy consumed were again confirmed (Ciccu et al. 1999).
The most interesting findings attained in the course of past experiments can be summarized as follows:

- with the jet in front and behind the pick, a considerable reduction (at least 30%) of the applied forces can be obtained at low displacement velocity whereas it becomes insignificant for the highest values typical of industrial practice (2-3 m/s).
- the amplitude of oscillations of the forces around the average value is reduced resulting in a lower chance of rupture of the picks;
- less mechanical energy is consumed, although the total energy (mechanical plus hydraulic) employed in the excavation can be considerably higher.
- wear rate is substantially lowered resulting in a longer duration of the technical life of the tool.



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- Figure 1. Waterjet assistance with the jet directed in front of the tool

Rolling Tools
Many research have been developed on the waterjet assistance of rolling tools. At the Rand Afrikans University a machine was used for linear tests that can apply a vertical load of up to 900 kN to the cutting head fitted with disks having different shape (either sharp-edged, flat or fitted with peripheral buttons), beneath which the rock sample carrier can travel at a maximum velocity of 1 m/s. A 55 kW pump can issue one or more jets of water under a pressure of 45 MPa and a flowrate of 82 l/min. In a particular configuration, two Leach and Walker 1.2 mm nozzles are placed at both sides of the disk.
Tests have been made with each type of disk with or without waterjet assistance (figure 2), in single or multiple passes, on a homogeneous rock (norite having a compressive strength of 250 MPa and high abrasivity).
The main result using the sharp-edged disk was a considerable decrease in vertical and horizontal forces with the application of water jets, but the effect faded gradually at increasing spacing from the disk as well as at increasing depth of slot due to the limited reach of the jet, suggesting that an increase in jet-forming pressure could be beneficial.

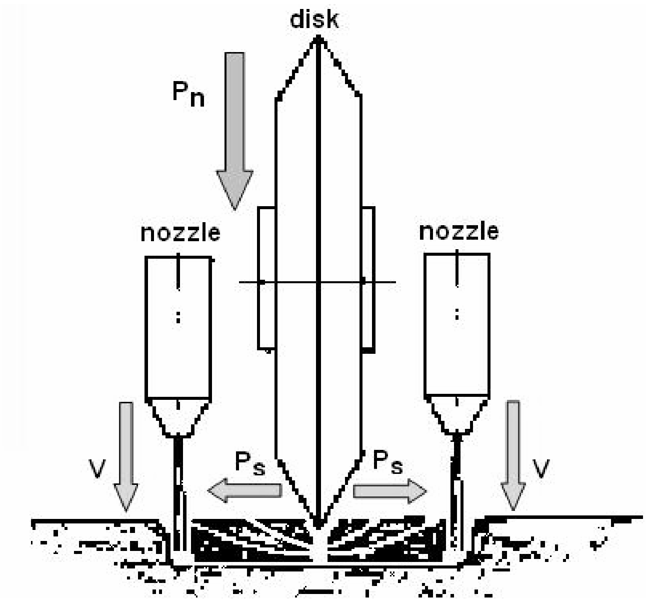

Figure 2. The concept of waterjet assistance

Deep tests using cutting tools assisted by waterjet have been carried out at the face of a sandstone quarry by Bergbau-Forschung GmbH, in co-operation with the some German mining industries. The equipment consisted of a tunnel boring machine with a diameter of 2.6 m. The results of the tests show a 50% reduction of the thrust forces with waterjet assistance which is a great advantage since lighter and cheaper machines can be built. Important benefits concerning the wear rate of the tools and the generation of dust have also been demonstrated (Knickmeyer and Baumann, 1983).

The research carried out at Skochinsky Institute of Mining concerns the process of hard coal breakage in underground mines using water jets in assistance to revolving tools, with the purpose of creating slots at both sides of the disk cutter. Different configurations have been studied including the position of the jet and the type of tool employed. It has been observed that deeper slots decrease the strength of the coal and thence produce a higher reduction in the forces and in the specific mechanical energy. In particular, the rolling force and the thrust force resulted to be about 1.5-2 times and 1,2- 1,4 times lower, respectively, while a 99.75 abatement of the dust was achieved (Kouzmich and Merzlyakov, 1983).

3. PURPOSE OF THE RESEARCH

The experimental work developed at DIGITA's laboratory was focused on the evaluation of the benefits introduced in the mechanical excavation by the waterjet assistance. Different aspects were studied: contact forces reduction, excavation rate increment, tool wear reduction. This note discusses in particular the increasing of the excavation performance (excavation rate) achieved for drag and rolling tools.

4. EQUIPMENT

The tests have been carried out using the apparatus installed at the DIGITA's laboratories (figure 3). It reproduces the tool/rock interaction in the case of tunnel boring machines, where a continuous contact with constant penetration takes place under a steady normal force along circular paths with variable radius. However instead of moving the tool (either a pick, a disc or a roller) against a fixed workpiece, the relative motion is obtained by rotating a cylindrical sample of rock and pushing the tool onto its upper planar surface. The drag force is determined by the torque applied to the shaft. The rotation power is supplied by means of an electric motor provided with an adjustable mechanical gearbox, while the vertical load is provided by a hydraulic piston actuated by a pump through an accurate control system (oil pressure and flowrate).

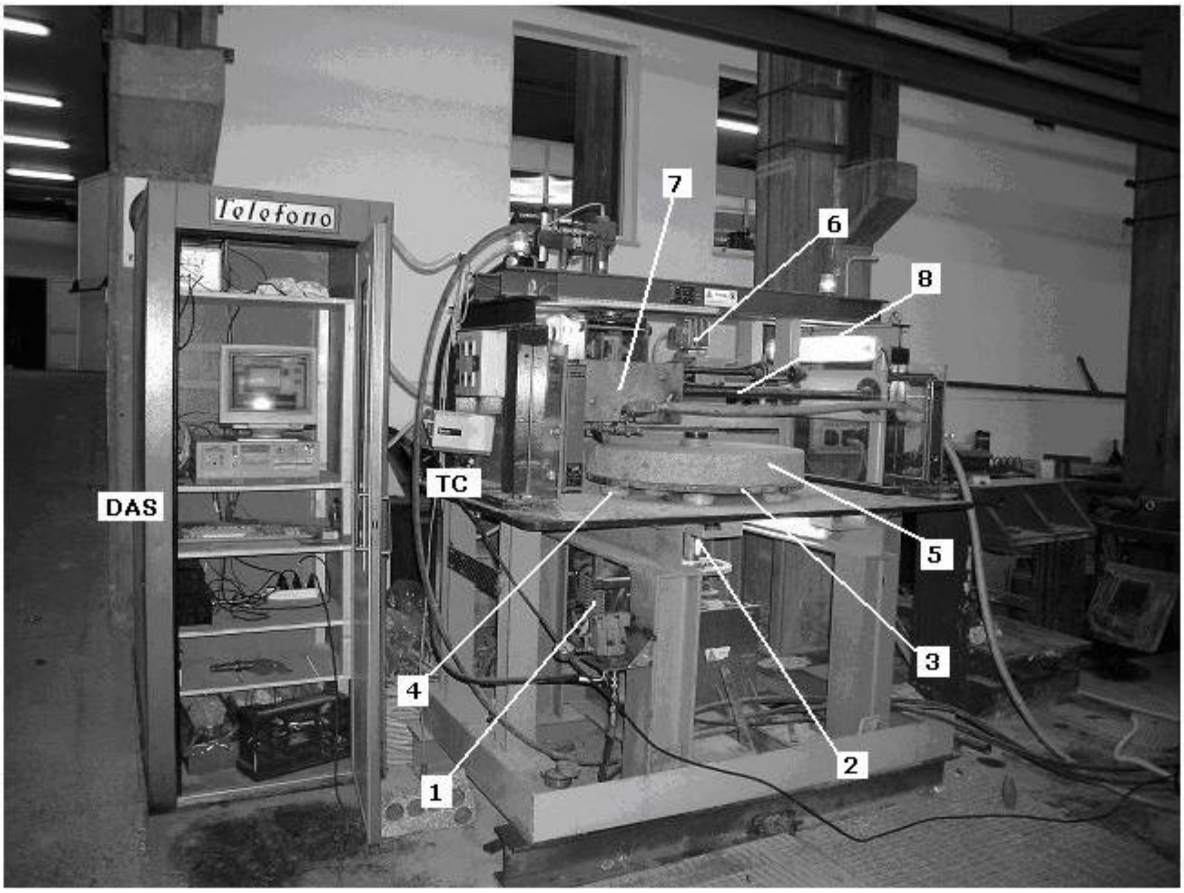

Figure 3. The experimental apparatus. TC = Thermocamera; DAS = Data Acquisition System

The electric motor (1), with a nominal power of 7.5 kW, rotates the vertical shaft (2) rigidly connected at its top end to a 80 cm diameter platform (3) supported at its bottom by a set of spherical bearers (4). The maximum speed allowed by the system is about 60 rpm.
The cylindrical sample of rock (5) is fastened onto the platform by means of a central screw with the help of three metal pins matching corresponding holes in the rock.
The position of the tool along the platform diameter is set by means of a 0.37 kW secondary motor (6) that drives the cutting head (7), guided by horizontal rods and axial bearings (8), by means of snail/thread couplings .
The reaction force transmitted to the piston is discharged on a pair of horizontal beams (8) at the top of a stiff frame through spherical bearings (9) allowing the lateral displacement of the tool under load.
Vertical load and of the horizontal force are directly measured by means of two piezoelectric transducers, the first placed between the end of the piston stem and the fixture and the second between the inner box and the contrast beam.

Drag Tool

The tool used for the experiments was a drag bit having the shape of a conventional conical tool but with a flat cut tip so that its frontal face is a semicircle with a diameter of 12 mm, entirely covered with a 0.8 mm thick layer of polycrystalline diamond. The bit attack angle is 98 degrees. The tool was set in the holder as shown in figure 4 so that the rake and the clearance angles were 20 and 12 degrees, respectively.

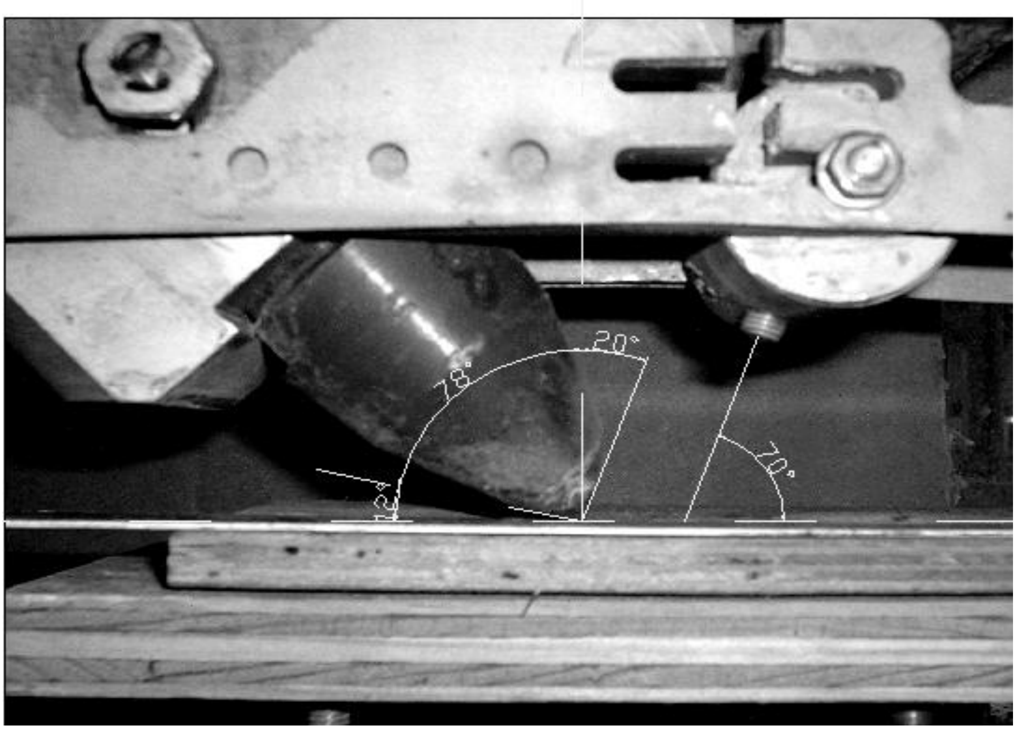

Figure 4. Details of the diamond tipped cutting tool

The pick was assisted by a water jet positioned in front of the tool wit 40 mm of stand-off distance. The jet was directed so as to impinge on the rock sample with a forward angle of 70° at a point 2 cm away from the tip, corresponding to the mean size of the scales detached by the tool in the dry tests.

Rolling Tool

In this case the cutting head was fitted with a 10 cm diameter disk having a 60° tip angle to the side of which the nozzles were placed (figure 5).

The parameters kept constant for all he tests were:

- Normal load applied to the tool: 10 kN;
- Jet inclination from the vertical line: 20°;
- Distance of the jet impingement point from the disk tip: 2 cm;
- Stand-off distance of the nozzle: 3 cm.

Waterjet setting parameter

The waterjet parameters kept constant for all the tests were:

- Nozzle diameter: 0.4 mm;
- Jet-forming pressure: 150 MPa;
- resulting flow rate: 2,5 l/min

Figure 5. Detail of the cutting head as seen from below

5. Test material

The material used for the experiments was a volcanic rock classified as rhyolite or dacite outcropping in Sardinia near the village of Serrenti from which it takes the name. It is a medium-hard rock characterised by: unit weight 22.7 kN/m^3, uniaxial compressive strength 37 up to about 80 MPa, tensile strength: 6.7 MPa, cohesion: 11.5 MPa, friction angle: 56°.

6. Experimental plan

Both for drag and rolling tools, two series of tests have been performed: the first with the mechanical tool only (dry tests); the second with the assistance of a water jet. A test begins with 6 idle rotations of the circular sample until reaching a constant value of the rotation speed. Then the tool is pushed against the sample while the jet impinges the rock upon opening the cut off shutter; after the active rotation the tool is raised and the jet stopped again.

Measured parameter

During the tests vertical and horizontal forces were measured and recorded with a frequency of 1000 Hz.

The depth of cut and the excavated volume were evaluated for each test. The depth of cut was measured every 30° along the trajectory. The excavated volume was estimated for the entire trajectory using a fine granular material with known specific gravity poured into the groove until filling it completely and then weighted.

7. RESULTS AND DISCUSSION

In what follows, only the data of the excavated volume and excavation rate are presented with the purpose of assessing the improvement introduced by the waterjet assistance.

7.1. Drag tools

Each series consisted of grooving tests on three circular trajectories having different radius (150, 250, 350 mm) (figure 6). The rotation velocity of the sample was set at 42.42 rpm. For each radius the test was repeated three times. The pick was pushed against the sample with a vertical load of 3 kN for all the tests. During the tests, normal and cutting forces, pick vertical position and angular velocity were measured with an acquisition frequency of 1 kHz.

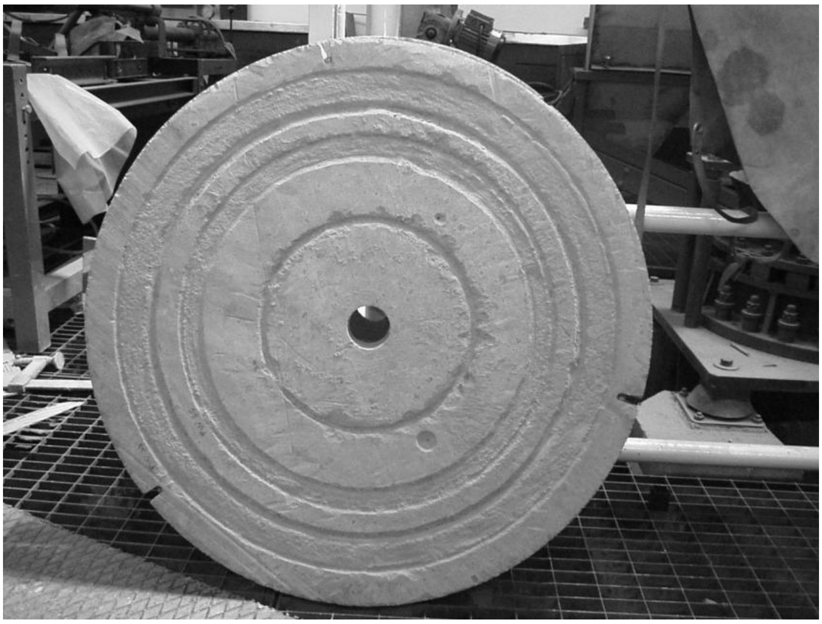

Figure 6. A rock sample after a series of grooving tests

The average value of the depth of cut is expressed as a function of the trajectory radius in the diagram of figure 7. The positive effect of the waterjet is clear: the depth of the cut produced by the mechanical tool in the case of waterjet assistance is 20 -25% higher for all trajectories.
The improved tool performance is also displayed by the curves of figure 8 concerning the comparison between the excavated volume per unit length achieved in the dry tests and that achieved in the waterjet assisted tests, as a function of the trajectory radius.
The relative position of the two curves corroborate the fact that the waterjet support to the tool action determines a significant increase in the excavated volume per unit length (about 20%).
As a direct consequence of the above results, the mechanical specific energy is substantially lower in the case of waterjet assistance.

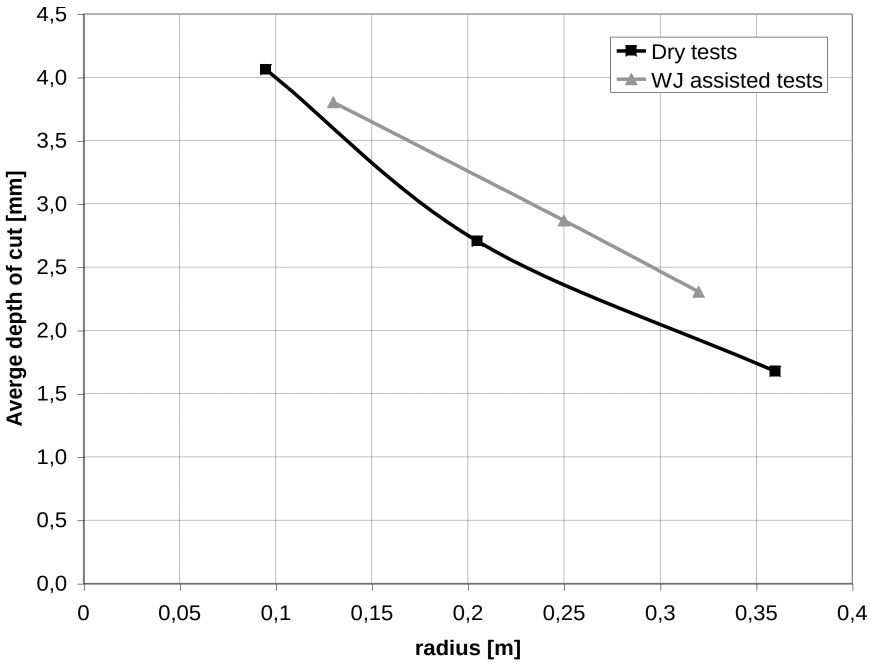

Figure 7. Average depth of cut for dry and waterjet assisted tests as a function of the path radius. (Normal load: 3.2 kN - Rotation speed:42.42 rpm)

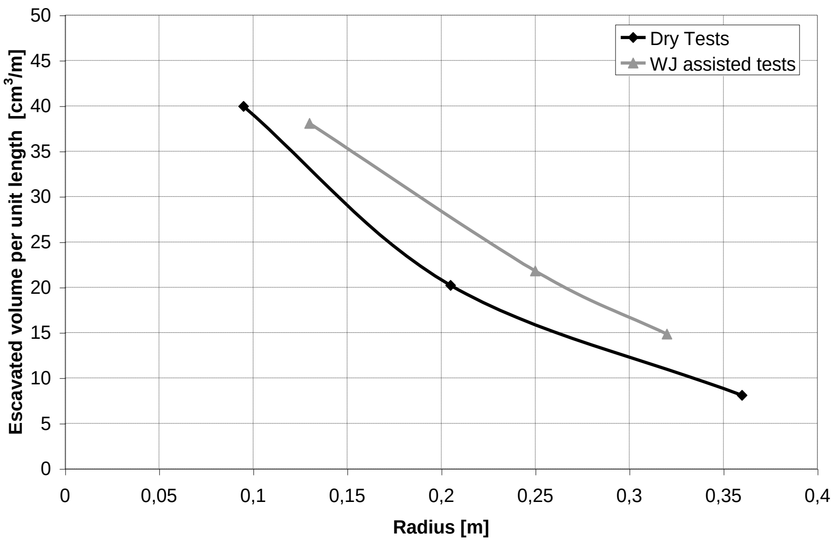

Figure 8. Excavated volume per unit length for dry and waterjet assisted tests as a function of the path radius. (Normal load: 3.2 kN - Rotation speed:42.42 rpm)

7.2. Rolling tools

The effect of the waterjet assistance on the tool performance was explored for different trajectories and rotation velocities. The tests were performed for:

- Radius of the circular path of the tool on the rock: 0.34 m, 0.26 m and 0.15 m for dry tests and 0.29 m, 0.22 m and 0.11 m for waterjet-assisted tests.

- Rotation speed: 30.30 rpm and 60.60 rpm corresponding to 50% and 100% of the maximum value allowed by the gear device.

The experimental plan consisted of 24 tests (12 dry and 12 with waterjet assistance) divided into two series at different rotation speed (6+6 tests at ω = 30.30 rpm and 6+6 tests at ω = 60.60 rpm). In each series the radius of curvature was changed and each test was repeated on a different sample for confirmation (the average value was eventually taken after excluding few anomalous results).

The grooves showed irregular borders due to the variable size of the scales arising from the discontinuous process of cutting. Especially in the case of smaller trajectory radius the detachment of scales occurred more frequently at the inner side of the circular groove. In most tests the waterjet kerfs did not overlap completely with the groove produced by the disk, as it appears in figure 9.

Figure 9. Geometry of the grooves in waterjet-assisted tests

The experimental results are expressed in terms of specific excavated volume (figure 10) and excavation rate (figure 11).

The analysis of the figure 10 highlights that:

- the advantage of waterjet assistance, substantiated by an almost threefold increase of specific volume for all the trajectories, is clearly evident. Therefore, it is still relevant at the highest traverse velocity within the explored range (0.30 m radius at 60.6 rpm) suggesting that the contribution to stress due to the jet impact plays an important role in addition to the weakening of the rock. A flushing action on the plasticized material can also be alleged. Further research is needed in order to confirm this assumption.
- on doubling the rotation speed (from 30.3 to 60.6 rpm) specific volume is somewhat reduced, as expected;

Excavation rate (figure 11) is less affected then specific volume by the radius of curvature, owing to the higher peripheral velocity that compensates the fall in specific volume as the radius increases. In the case of waterjet assistance there is even a gain in excavation rate for the larger radius especially for the higher rotation speed.

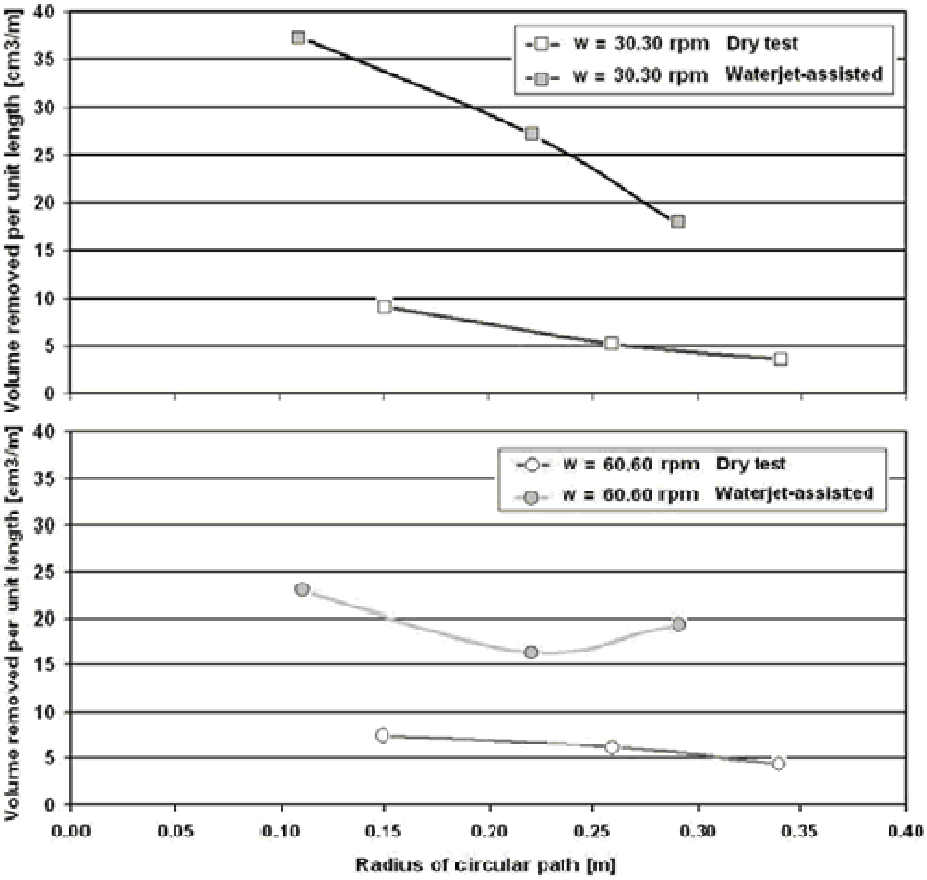

Figure 10.Curves of the specific excavated volume

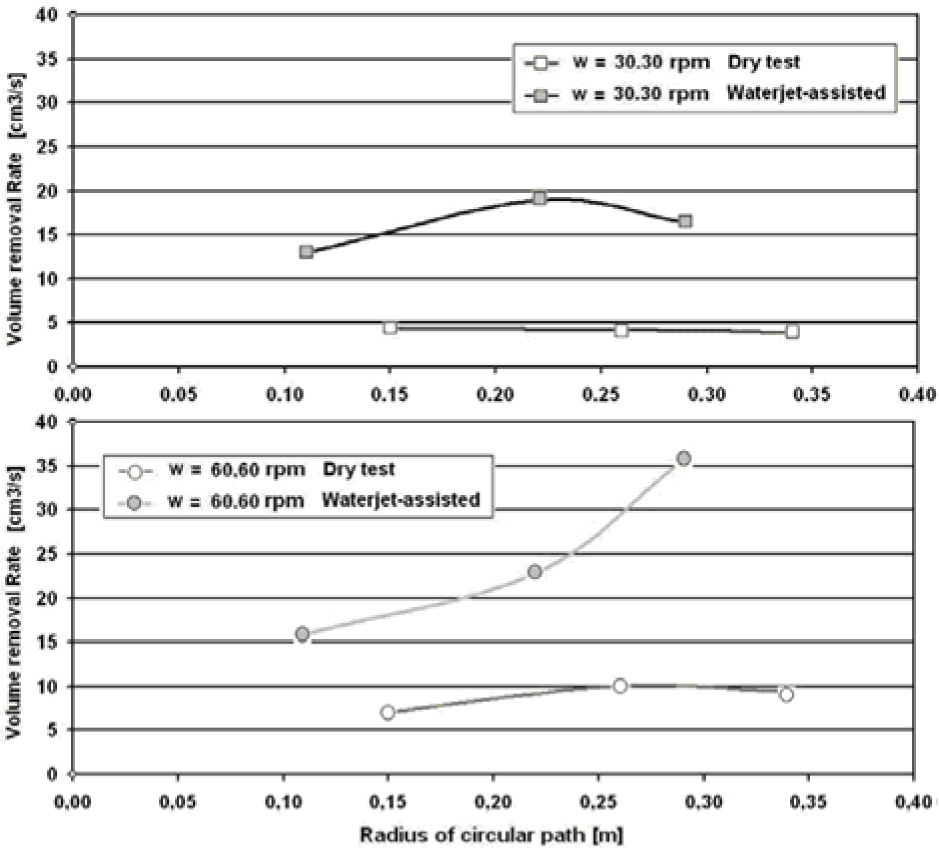

Figure 11.Curves of excavation rate

8. CONCLUSIONS

The results of the experimental tests show that:

- the performance of the testing apparatus is satisfactory, since it allows to reproduce the operating conditions (forces, velocity) typical of commercial machines for small tunnels;
- considerable benefits can be obtained with the synergetic action of the high velocity water jet both in terms of excavated volume and excavation rate. This benefit results around 20 – 25% in the case of the drag tool while it reaches 300% for the rolling tool.
- The result that waterjet assistance seems to be more efficient for disks than for drag tools is quite intriguing. This may depend on the fact that a jet placed ahead of the pick along the trajectory lays on the same vertical plane as the peripheral velocity and it impinges the rock just at the midpoint of the scale's front border contributing to the scale formation only at the very moment of detachment. On the other hand a jet placed at one or both sides of a disk cutter at a distance corresponding to the length of the scale moves along the border of the scale under formation thus contributing to the excavation process almost continuously. Therefore energy is much better exploited in this case.

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