Mechanical excavation of hard rocks

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ABSTRACT: In the case of hard rocks the problems arising 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 presently available technology two possible ways can be followed:
- using special tips made of polycrystalline diamond for longer duration;
- availing of the assistance of waterjet for better performance.

Both solutions are being developed in the case of picks or disks applied to roadheaders and full-facers. The paper illustrates the results obtained at the DIGITA laboratories of the University of Cagliari on a medium-hard rock using a carrousel-type testing machine capable of reproducing the conditions of rock-tool interaction encountered in the industrial practice and discusses the prospects of the technological advances under development.

1 FOREWORD

Interest is growing today regarding the development of a suitable technology for the excavation of hard rocks as an alternative to the use of explosive. In fact, although blasting can be applied successfully for winning a great variety of rocks and geologic situations, a number of drawbacks are often encountered such as overbreak, noise, airblast, flyrock and vibration.

Moreover, the lack of accuracy in tunnelling may render the support and concrete finishing 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.

Aiming at a better understanding of the rock-tool interactions in hard rock cutting a research programme has been started at the DIGITA laboratories under a co-operation agreement with the Czech Academy of Sciences.

Experiments are being carried on using a special testing apparatus designed and built for studying the excavation mechanism of a variety of tools (picks of different shape, disks and rollers) on circular rocks samples. A waterjet can be added in a suitable position for assisting the work of the mechanical instrument.

The experimental apparatus is characterised by a high degree of flexibility allowing to investigate the influence on the technical results of the chief operational variables (radius of the circular path, vertical load and rotation speed) according to a plan of systematic tests.

This paper deals with the results so far obtanined on a hard volcanic rock using flat picks with polycrystalline diamond tip.

Results have been expressed in terms of:

- Depth of grooves
- Size distribution of cuttings
- Drag force on the tool
- Wear rate
- Volume removed per metre of groove length;
- Volume removed per unit time;
- Specific energy.

Correlations linking these parameters to the operational variables have also been sought, aiming at finding the optimum conditions.

2 EQUIPMENT

The concept followed in the design and the development of the testing apparatus installed at the DIGITA laboratories was that of reproducing 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 vertcal load is provided by a hydraulic piston actuated by a pump through an accurate control system (oil pressure and flowrate).

2.1. *Testing apparatus*

The main components of the apparatus are shown in figure 1.

The electric motor (2), with a nominal power of 7.5 kW, rotates the vertical shaft (3) rigidly connected at its top end to a 80 cm diameter platform (4) sopported at the bottom by a set of spherical bearers (5). The maximum speed is about 60 rpm.

The cylindrical sample of rock (see figure 5) is fastened onto the holder 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 that drives the cutting head, guided by horizonlal rods and axial bearings (12), by means of snail/thread couplings .

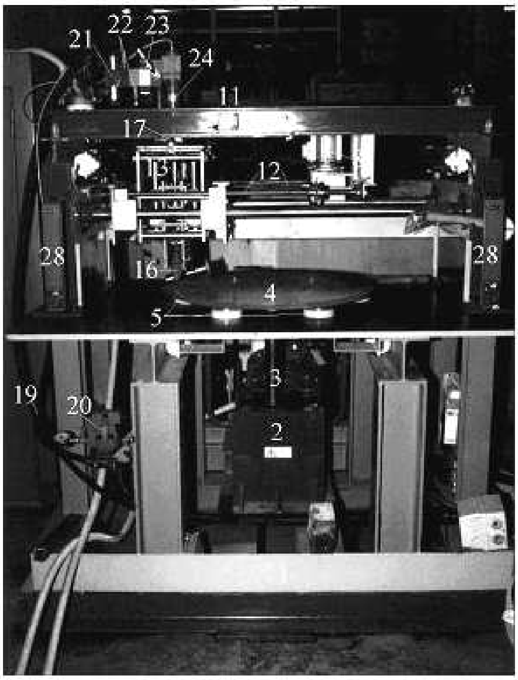


Figure 1. The experimental apparatus

The cutting head (figure 2) consists of an inner fixture (10) inside which the tool (16) is fastened, pushed downwards by the hydraulic piston (24) and guided by a pair of vertical rods (13) through sets of axial bearings.

These rods are rigidly connected to an intermediate box (12), to the vertical walls of which two rods are applied at each sides, allowing the horizontal backwards movement of the fixture again through sets of axial bearings (not visibile in the figure). All the above devices are hosted inside an outer box (9) that is moved sideways for positioning the tool on the selected trajectory, as already described.

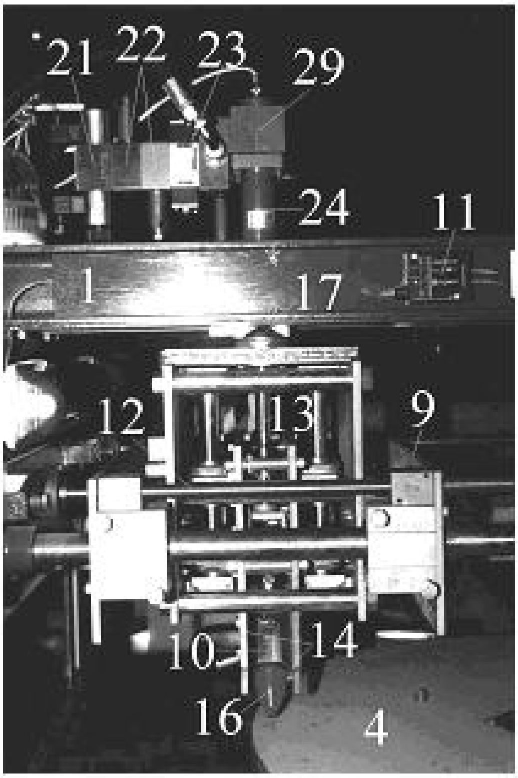


Figure 2. Datailed view of the cutting head

The reaction force transmitted to the piston is discharged on a pair of horizontal beams (11) at the top of the frame through spherical bearings allowing the lateral displacement of the tool under load.

During a test, the free motion of the tool in the vertical direction is controlled by the resistance of the rock to penetration under the load applied by the hydraulic piston, while in the horizontal direction the backward displacement is limited by a traverse beam rigidly connected to the main frame, against which the drag force is discharged through a spherical bearing.

The variation of the vertical load and of the drag force around the average values set by the oil pressure through an arrangement of electronically controlled valves (21, 22 and 23) and by the torque applied to the rotating platform are directly measured by means of 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.

The cutting head has been designed for mounting different tools including conical and PCD picks hosted inside a sleeve in the tool holder. The angle of the pick can be adjusted continuously from 30 to 60° with respect to the horizontal plane .

2.2 *Control and data acquisition system*

The control system includes four inverters for the independent driving of the different motors, the console with the timers and the computer setting of electric parameters (torque, speed, power) and other auxiliary devices.

The data acquisition system consists of a set of transducers (two for the horizontal and vertical displacements and two for the horizontal and vertical forces), a signal amplifier, a “WorkMate” data acquisition board, the WorkBench PC software and an infrared Flir Systems thermocamera.

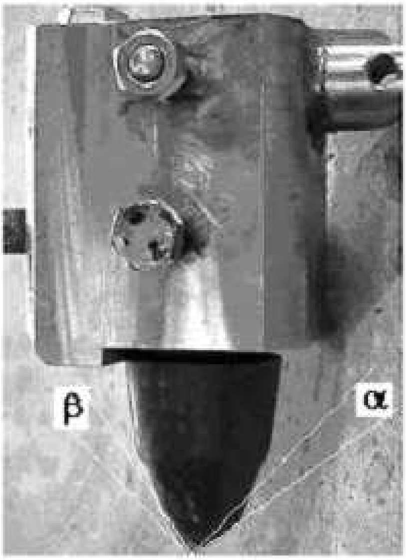


Figure 3. The diamond tipped tool used for the experiments.
α = attack angle
β = clearance angle

2.3 *Cutting tool*

The pick is mounted into a cylindrical sleeve inside the holder body, as shown in figure 3 where the attack angle α and the clearance angle β are indicated. Rotation is hindered by means of a tooth-notch coupling and axial movement is controlled by a multiple-disk spring located at the bottom of the sleeve in order to absorb the dynamic impacts transmitted by the rock.

The position of the pick holder can be adjusted in order to modify the angle of attack.

The pick has the shape of conventional conical tools but the tip is cut flat 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.

3 EXPERIMENTS

3.1 *Factorial plan*

In this first stage of the research, 27 single groove tests have been carried out according to a factorial plan resulting from the combination of:

- three vertical loads: 2000, 3000 and 4200 N;
- three rotation speeds: 30.30, 42.42, and 60.60 rpm (corresponding to 50, 70 and 100% of the maximum speed provided by the gearbox);
- three values of the trajectory radius: 0.15, 0.25 and 0.35 m.

The testing plan is summarized in Table 1.

Table 1. Test plan

LOAD [N]	TEST	RADIUS [m]	SPEED [rpm]
2000	P1	0.35	30.30
	P2	0.25	30.30
	P3	0.15	30.30
	P4	0.35	42.42
	P5	0.25	42.42
	P6	0.15	42.42
	P7	0.35	60.60
	P8	0.25	60.60
	P9	0.15	60.60
4200	P10	0.35	30.30
	P11	0.25	30.30
	P12	0.15	30.30
	P13	0.35	42.42
	P14	0.25	42.42
	P15	0.15	42.42
	P16	0.35	60.60
	P17	0.25	60.60
	P18	0.15	60.60
3000	P22	0.35	30.30
	P23	0.25	30.30
	P24	0.15	30.30
	P25	0.35	42.42
	P26	0.25	42.42
	P27	0.15	42.42
	P28	0.35	60.60
	P29	0.25	60.60
	P30	0.15	60.60

In addition to this, some tests have been done under a 5000 N load at convenient radius and rotation speed, in order to get further data enabling to compare the results at equal peripheral velocity.

3.2 Rock tested

The material used for the experiments is 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 (σ_c variable from 37 MPa to 80 MPa according to source), the microscope analysis of which evidences the presence of plagioclase phenocrysts into a microcrystalline seldom vitreous matrix. Secondary components are biotite and horneblende. Some opaque minerals identified as metal sulphides are also found (figure 4).

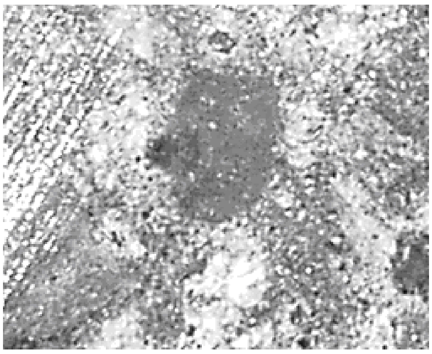


Figure 4. Fabric features of the “Serrenti stone”

The fabric is very tight maybe due to the high temperature of the erupting lava. The volumic mass is 2,277 kg/m^3.

Table 2 Characteristics of the rock samples used for the grooving tests.

CHARACTERISTICS	Serrenti stone
- Bulk specific gravity [kg/m^3]	2,277
- Compressive strength [MPa]	78.4
- After 20 freezing cycles [MPa]	64.6

3.3 *Experimental procedure*

The tool is positioned at the starting point of the selected trajectory about 10 mm above the rock sample placed onto the rotating platform and the setting parameters are carefully controlled. After a convenient number of revolutions of the sample until reaching the final velocity, the pick is pushed against the target by the automatic opening of the pressure valve and the full load is applied. On completion of a revolution the tool is automatically raised and the rotation speed reduced to zero.

During the test both the drag and the normal forces and the rotation speed are recorded in real time and the data stored in a computer file for further statistical processing. The electric data of the driving motor are also measured for a crossed checking of the drag force.

All the cuttings are collected and sieved for obtaining the particle size distribution and the larger chips are examined for assessing the shape features (length, width and thickness).

The depth of cut is measured at intervals by means of a high accuracy digital comparator, whereas the removed quantity of rock is determined by pouring a classified dry sand of known specific gravity into the groove and weighting the material filling the excavated volume (figure 5).

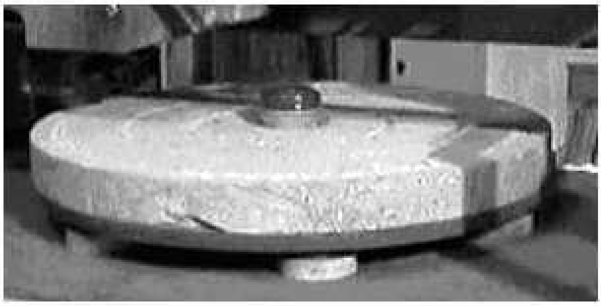


Figure 5. The rock sample plaved onto the rotating platform

4 RESULTS AND DISCUSSION

4.1 *Technical performance*

A first analysis of the experimental data is made on the basis of the removed volume of rock per unit lenght of groove V_u [cm^3/m].

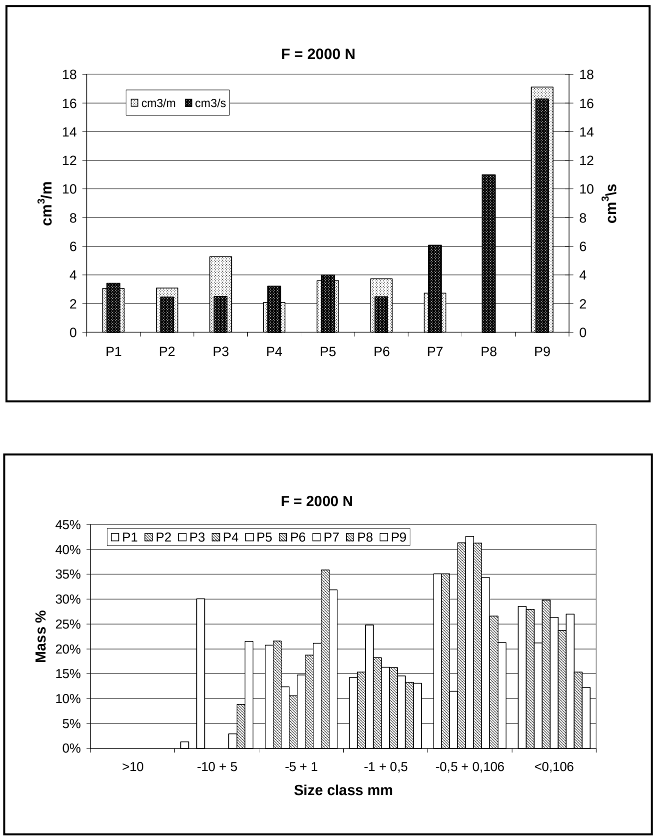
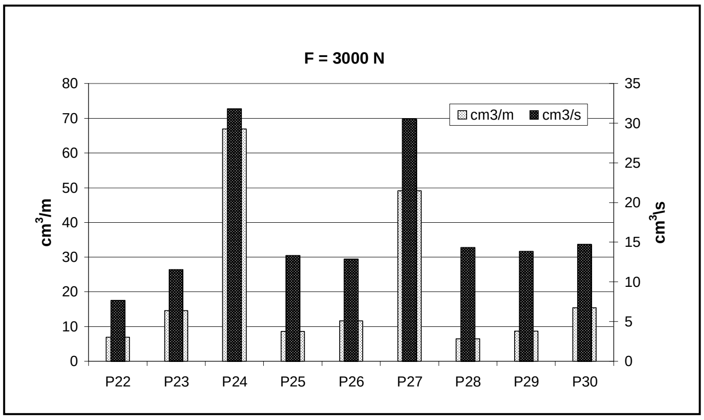


Figure 6. Results of excavation tests at 2.0 kN applied load (top) and corresponding size analysis of the cuttings.



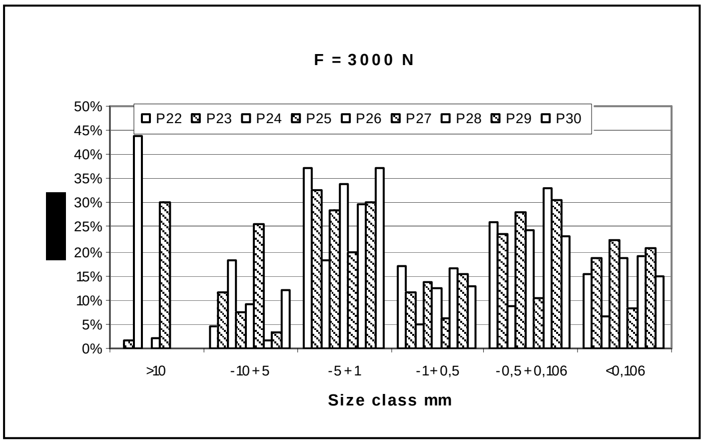
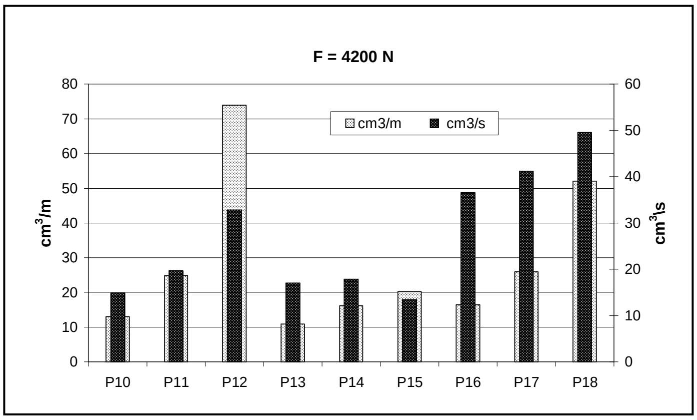


Figure 7. Results of excavation tests at 3.0 kN applied load (top) and corresponding size analysis of the cuttings.



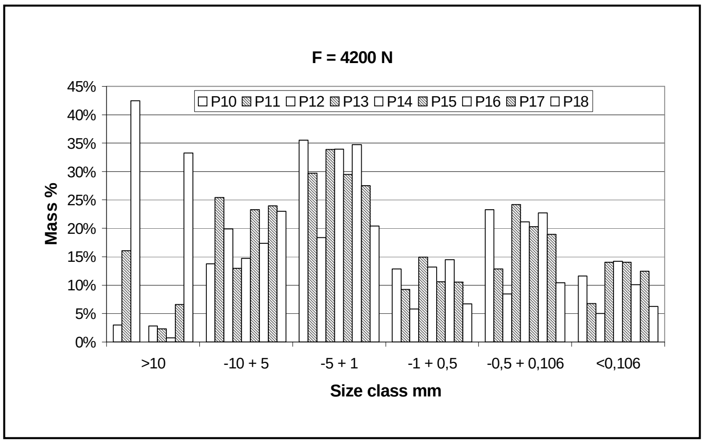


Figure 8. Results of excavation tests at 4.2 kN applied load (top) and corresponding size analysis of the cuttings.

The results at 2 kN applied normal load (tests 1 to 9) are reported in figure 6. It appears that V_u increases as the radius of the circular trajectory decreases, the more at higher rotation speed (except for tests P4 and P6).

Sieve analysis for each test shows that under a small load the top size of the cuttings is always below 10 mm, the predominant size classes being those between 0.50 mm and 0.106 mm.

The subsequent series of tests at 3 kN applied normal load (tests 22 to 30, figure 7) confirms with even more evidence the fact that the excavated volume per metre increases as the radius decreases. However the influence of rotation speed is here different since V_u decreases as speed increases at equal radius, as expected.

Size distribution shows the presence of cuttings larger than 10 mm for the tests at the shortest radius of curvature especially those at low speed (tests 24 and 27) for which the proportion of coarse fragments is quite high (more that 30%).

Finally for the tests at 4.2 kN applied load (tests 10 to 18 figure 8) the influence of the curvature is again confirmed.

However the rotation speed is not in full agreement with the expected trend since V_u first decreases at increasing speed as before and then it recovers for the highest speed, like in the case of the 2.0 kN load. The central values appear too low.

Concerning the size analysis, a further shifting of the distribution towards the coarser sizes is evident, confirming what could have been predicted on theoterical grounds: larger load means deeper penetration and thence coarser fragment sizes.

Comparing the values of V_u obtained in all the 27 tests, it ensues that:

- At a given rotation speed and applied load, the volume excavated per metre of groove always decreases as the radius increases. This outcome can be explained by considering the fact that the peripheral velocity increases with the radius, thus reducing the penetration depth, especially if the pick works with a negative attack angle like in the case at hand. Moreover the curvature of the trajectory affects the scaling mechanism, due to the increase of stress at the inner side of the groove, as confirmed by the study of its contour.

- At a given radius and applied load, the effect of the rotation speed appears controversial because of some semingly anomalous outcomes like those of tests 13, 14 and 15 (the values of V_u are too small with respect to the general trend) maybe due to some local increase in the rock strength (the three tests are done on the same sample). However the predominant trend observed suggests that the removed volume V_u decreases as velocity increases especially in the field of higher loads (> 3 kN) where the cutting process is fully developed. Also the tests at higher speed and 2.0 kN load (tests 7, 8 and 9) show higher values of Vu than expected but in this case the results can be explained assuming that a contribution to the excavation process might have been produced by some dynamic action of the pick.

- For the 2 kN load the excavated volume per metre V_u is very small: this fact, associated with the result of the size analysis of cuttings, characterised by abundant fine classes, seems to indicate that the removal process is dominated by a plasticization effect. This conclusion is corroborated by the smooth features of the groove, the section of which matches closely the contour of the pick's tip.

- Compared to the results at 2 kN, a considerable increase of V_u is achieved if the load is increased to 3.0 kN, whereas a further increase to 4.2 kN does not produce a consistent effect except for the highest speed. This suggests that the cutting mechanism changes considerably between 2 and 3 kN passing through a critical point beyond which the chipping mode becomes predominant over the plasticization mode. This is confirmed by the size distribution of fragments as well as by the appearance of the groove, the cross section of which is very irregular and much larger than the pick's tip.

The experimental results have been compared also on the basis of the excavated volume per unit time V_s [cm^3/s] the values of which are shown superimposed to the values of V_u in Figures 6 to 8. .

This is a more interesting parameter to evaluate since it gives a better idea of the excavation rate achievable with the tunneling machine, in which all the tools work with the same penetration depth and with the same rotation speed.

The following points are worth noting:

- The effect of the radius is somewhat smoothened since the lower volume excavated per metre is compensated by a higher velocity.

- The least favoured picks are those at the periphery of the cutting head of the tunneling machine and therefore they would need either an assistance (for instance by applying a water jet to each of them) and/or by increasing the number of picks, i.e. by decreasing the radial spacing of trajectories, so as to promote a form of co-operation among the tools.

The above considerations are reflected also in the curves of figure 9 where the values of V_u are given

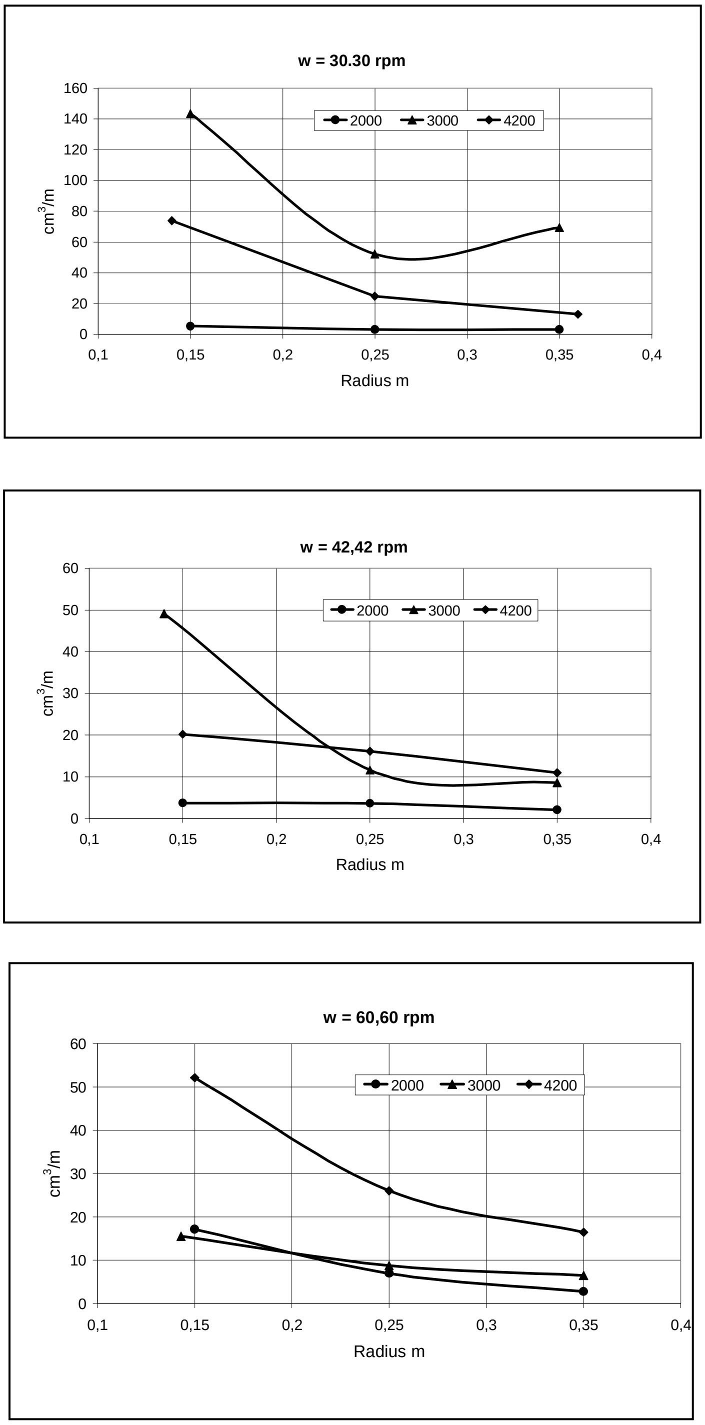


Figure 9. Excavation results at equal rotation speed.

as a function of the radius of the circular grooves for each load at different rotation speed.

It is interesting to note that, as the radius increases, all the curves converge on a common asymptote the level of which progressively rises with the applied load after a jump at the critical point between 2 and 3 kN.

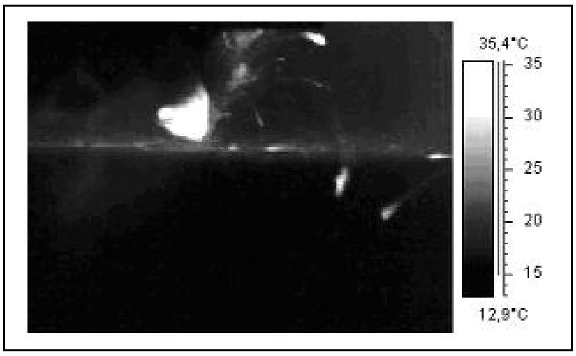
Some further series of tests have been carried out enabling to explore the influence of the variables at constant peripheral velocity.

It can be observed that, for a given peripheral velocity (the highest velocity of 1.1 m/s is only reached for the larger radius), the removed volume per metre V_u increases almost linearly with the applied load. If the results are compared at equal load and radius (for instance 4.2 kN and 0.25 m), after a sharp drop when passing from 0.47 to 0.79 m/s, V_u tends towards a more stable value around 15 cm^3/m.

4.2 Heat transfer

Immediately after the end of each test (one full revolution), the temperature at the tip of the pick was measured by taking a series of pictures at a frequency of 7 frames per second, using an infrared photocamera (see figure 10).

For the sake of a correct comparison among all the tests, the duration of which varies according to speed and trajectory, the average temperature gradient has been considered (final temperature divided by the duration time).



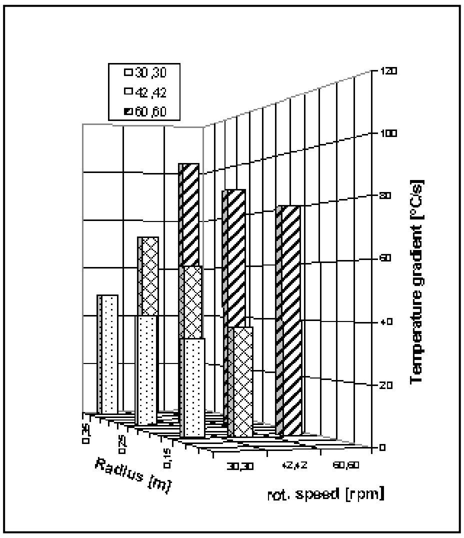


Figure 10. Tool's temperature raise measured with the thermocamera (top) at different experimental conditions.

Results are given in figure 10 showing the outstanding effect of peripheral velocity on heat generation at constant load of 3.0 kN.

Since the temperature affects the toughness of the material (especially the polycrystalline diamond) the problem of heat accumulation at the tool's end is very important. It can be solved through an efficient cooling, using a water jet, for instance.

5 CONCLUSIONS

The results of 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;
- regarding the influence of process variables, interesting relationships have been found between some relevant performance parameters (excavated volume per metre of groove and excavated volume per second) and the applied load to the pick. The effect of the radius of the circular path and of the rotation speed is also highlighted.

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