Specific energy as a criterion for the use of rapid excavation systems in Turkish mines

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Synopsis

Mechanical miners, such as roadheaders, continuous miners, impact hammers and tunnel-boring machines, allow continuous operation and it is, therefore, to be expected that mechanization of mines by the introduction of such equipment will increase productivity, decrease production costs and improve competitiveness. As part of a research project supported by the Turkish Government, a review of Turkey's mining industry in terms of reserves, production, exports and imports was undertaken and the parameters influencing the applicability of rapid excavation systems were then assessed. Many mine visits were made to gather information. Eleven large samples of rock block, including chromium ores, copper ores, harzburgite, serpentinite, trona, celestite, anhydrite and gypsum, were collected from some of these mines and subjected to full-scale laboratory cutting tests with a conical cutter at Istanbul Technical University; the data from these tests were then used to assess cuttability and estimate performance/production rates. An equation was developed to predict the optimum specific energy and, thus, the production rate. A case study of the potential for mechanical miner application was performed for a chromite mine on the basis of an analysis of the operational conditions and rock mass properties of the orebody, such as geometry, jointing, foliation, cuttability and abrasiveness. The results indicate that the introduction of mechanical miners at some mines in Turkey would be technically viable and efficient.

Global trends over the past decade, such as the dissolution of the Soviet Union in the early 1990s and the Asian financial crisis of the late 1990s, oversupply conditions, the finding of new deposits, environmental restrictions on some minerals and long-term contracting practices have combined to push down commodity prices, especially those of metallic minerals, and have added to the challenges facing the mining industry.

To stay competitive in these market conditions requires that productivity be improved. One of the solutions is to use mechanical miners, such as roadheaders, continuous miners, impact hammers or hydraulic breakers and tunnel-boring machines. Since these machines permit continuous operation, they should increase productivity and reduce production costs where they are able to be applied.

The aim of the work reported here was to investigate the possibility of using rapid excavation systems in some of Turkey's mines. To this end, first, a general review of the Turkish mining industry was conducted. Many mine visits were made and information about the mines was gathered. Eleven large samples of rock block were collected from some of the mines and subjected to full-scale laboratory cutting

Table 1 Data on Turkey's minerals industry[1]

	Total output, t/year	Work-force	Mines operating	Annual output, t/mine	Workers per mine
Hard coal	3 196 000	18 257	1	3 196 000	18 257
Lignite	49 588 000	37 411	235	214 000	159
Copper	3 178 000	2837	5	626 000	543
Chromite	1 262 000	4241	80	17 000	51
Barite	228 000	432	10	22 000	39
Borate	1 887 000	3076	6	391 000	595

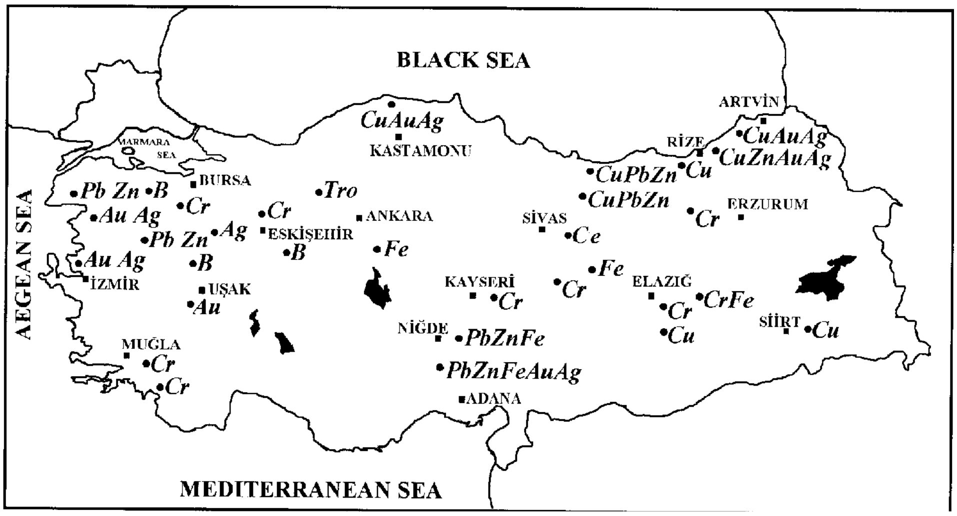

Fig. 1 Distribution of deposits/mines of selected minerals in Turkey (*B*, borate; *Ce*, celestite; *Cr*, chromite; *Tro*, trona)

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Table 2 Summary of Turkey's minerals industry[2–5]

Mineral	Reserve, proven and probable, t	World reserve share, %	Run of mine production, t 1998	1999	2000
Aluminium	48 056 250 (Al_2O_3)	0.17	NA(*)	459 028	NA
Antimony	106 306 (Sb)	2.26	550	12 900	NA
Chromium	30 370 182 (45% Cr_2O_3)	0.40	1 517 908	770 000	545 725
Copper	2 279 210 (Cu)	0.37	4 043 869	3 979 381	4 473 711
Iron	82 458 000 (Fe)	0.07	5 965 942	6 500 000	4 076 257
Lead	860 387 (Pb)	0.72	NA	293 187	NA
Lead–zinc	NA	NA	283 199	NA	345 391
Zinc	2 294 479 (Zn)	0.69	64 535	48 837	NA
Magnesium	50 116 000 (MgO)	1.47	NA	2 703 720	NA
Silver	6 062 (Ag)	1.44	828 603	NA	809 890
Strontium	210 123 (Sr)	1.75	NA	52 500	NA
Hard coal	1127 000 000	0.22	2 865 824	2 601 175	3 196 643
Lignite	7965 000 000	1.52	61 203 154	NA	61 314 974
Baryte	35 001 304	7.00	130 155	60 000	120 893
Borate	150 000 000 (B_2O_3)	36.00	2 754 082	1 400 000	2 398 220
Trona	130 658 000	0.32	NA	NA	NA

NA = not available.

tests for cuttability assesment and production rate estimation. A chromite mine was chosen for a case study of the potential for application of a mechanical miner on the basis of the information gathered.

Review of Turkey's mining industry

Turkey, which has a complex geology and surface area of 775 000 km^2, comprises a wide variety of mineral deposits, including many types of metallic and industrial minerals as well as lignite and hard coal. Today in Turkey six borate, 42 magnesite, 80 chromium and 22 lead–zinc mines are active, individually producing averages of 391 000 t borate, 26 000 t magnesite, 17 000 t chromite and 13 000 t lead–zinc minerals annually. Small-scale, labour-intensive operations and low productivity characterize many of these mines. Production costs at Turkey's mines are usually high owing to low productivity and the high cost of manpower. This exacerbates the negative impact of global trends substantially. Some information about the Turkish mining industry is presented in Table 1 and Fig. 1.

Turkey's mineral reserves, annual production, exports and imports are summarized in Table 2. As can be seen, the metallic mineral reserves are not very significant on the global scale; moreover, the deposits are generally small. Turkey's industrial mineral reserves are more significant. For example, Turkey has more than 50% of the world's borate/boron reserves, supplying almost half of the world demand. Most of Turkey's chromium reserves are of very high-grade metallurgical ore, which commands a high price in the market, although the world reserve share is lower.

Turkey is a significant exporter of ferrochromium and also exports chromite, copper and zinc ores and some refined metals. Ore and mineral exports usually made up around 2–2.5% of total Turkish exports during the past decade.[3] Mining's share of the gross domestic product was around 1–1.4% during this period.[4] If secondary mineral commodities, such as ferrochromium, cement, glass and steel, are included, this figure reaches roughly 10% of the gross domestic product. Turkey's metal imports were generally dominated by ferrous scrap and steel, since the Turkish steel industry depended on imported scrap to feed the electric-arc mini-mills.

Most mineral extraction in Turkey is by conventional underground mining methods based on drilling and blasting. Copper, chromium, lead and zinc are produced entirely by underground methods. Although most of the production comes from state-owned companies, the situation is gradually changing in favour of the private sector as the result of recent privatization attempts. In the cases of chromium and lead and zinc the private sector is already dominant.

Mechanical mining with roadheaders has been introduced only in a few state-owned lignite mines for the excavation of development drives[6] and a few shearers are in use in a private lignite mine.

Parameters influencing applicability of mechanical miners

The decision to introduce a mechanical miner is generally based on the predicted performance of the selected machine in the given geological and operational conditions. Since it is usually not possible to change the geological conditions, a thorough study of the geological and geotechnical parameters (rock mass and intact rock properties) at the feasibility and planning stages should be carried out to match the machine and operational parameters to the geological conditions.

Machine considerations

The general technical requirements of excavation machines, in addition to safety and economy, are selective mining ability, flexibility, mobility and hard and abrasive rock-cutting ability. Selective mining ability is the ability to cut selectively in mixed face conditions so that the mineral can be excavated separately, reducing dilution. Mobility means easy relocation of machines from one face to another, when necessary. Flexibility means easy adaptability to changing operational conditions, such as face cross-section shape (horseshoe, rectangular, circular, etc.), gradient, turning radius and unevenness of the floor. Hard and abrasive rock-cutting ability is the most important limiting factor on the performance of mechanical miners; applications show that disk cutters are the most efficient type of tool in hard and abrasive rock.

Geological and geotechnical considerations

Rock mass features (such as joint sets, bedding planes, foliation, hydrogeological conditions, deposit geometry, etc.) and intact rock properties (such as cuttability, abrasiveness,

Table 2 *(continued from page A150)* Summary of Turkey's minerals industry[2–5]

Mineral	Export, t 1998	1999	2000	Import, t 1998	1999	2000
Aluminium	320	70	136	24 844	25 247	35 758
Antimony	60	164	360	1 108	NA	NA
Chromium	588 910	553 338	471 451	19 497	48 284	69 470
Copper	151 533	206 444	190 565	8 219	18 369	56 968
Iron	6 043	9 900	26 310	3 857 835	2 973 053	4 140 102
Lead	500	1 000	4 089	18	2	NA
Lead–zinc	8 270	9 800	7 535	NA	NA	NA
Zinc	77 893	68 572	73 796	83 377	59 099	332 709
Magnesium	212 250	227 097	235 273	15 164	18 287	79
Silver	NA	NA	NA	NA	NA	NA
Strontium	NA	NA	NA	NA	NA	NA
Hard coal	4 495	5 196	13 766	8 450 734	6 515 725	13 173 182
Lignite	10	146	69	22 580	9 201	10 730
Barite	127 714	54 133	99 008	2 069	515	626
Borate	650 318	665 905	577 175	39	1	1 570
Trona	NA	NA	NA	NA	NA	NA

NA = not available.

strength, texture, etc.) of the geological environment are the basic input parameters for the selection of mechanical miners and performance prediction.

The cuttability of rocks determined from full-scale rock-cutting tests is one of the best guides in selection, design and performance prediction.[7] Full-scale tests measure full-scale cutting forces that act on a cutter while it cuts rock. The force data are used as the input for the design and selection of an excavator, selection of the cutter, definition of optimum cutting geometry and prediction of performance and cost.

Rock abrasiveness affects the cutter consumption rate. If the rock is very abrasive and the wear rate of the cutting tool is very high, the excavation might become uneconomic owing to frequent pick changes, increased machine vibration and maintenance costs. The contents of quartz and hard minerals and other rock textural properties, such as grain size and shape, are the basic parameters that determine abrasiveness.

Increasing frequency of rock weaknesses, such as joint sets, bedding planes and foliation, makes excavation easier as the machine simply pulls or rips out the blocks instead of cutting them. On the other hand, a weak formation requires heavier support and more time for its installation, resulting in reduced machine utilization time.

Operational considerations

Mine layouts and development drivages are planned in accordance with the mining method, which is selected on the basis of orebody shape and dimensions and other deposit characteristics. For reliable, economic operation the characteristics and layout features of a mechanical miner should reflect whether it is to be used for the excavation of drifts or for ore/mineral. The layout might be modified for a particular mechanical miner if necessary. For example, the turning radius of a tunnel-boring machine (TBM) is generally 20–30 m per metre of cutterhead diameter. This means that a TBM cannot make sharp turns and the layout should be modified to accommodate this feature where a TBM is to be used. Such a modification might require longer drivages, but these should be compensated for by the machine's rapid excavation rate, resulting in earlier excavation of the orebody. On the other hand, partial-face machines, such as roadheaders and impact hammers, can make sharp turns and open any required shape of opening, including horseshoe, rectangular and circular. The back-up equipment (such as muck transportation, support, etc.) selected for a new mine must be chosen to be compatible with the mechanical miner. In an existing mining operation, however, the machine might be selected on the basis of the equipment already in use.

Advantages to be borne in mind are that mechanical excavation is usually safer since it does not include any explosive handling. It is usually much less labour-intensive, resulting in reduced accident rates and a significant saving in labour costs. It causes minimal or no ground disturbance, which means less overbreak and reduced support and ventilation requirements. It produces a uniform muck size, allowing for the use of continuous haulage systems, such as conveyor belts. Its continuous (rather than cyclic) operation can facilitate automation under favourable conditions.

Performance prediction methods for mechanical miners

The predicted cutting performance of a mechanical excavator (continuous miner, roadheader, impact hammer, etc.) in the mineral or rock formation to which it will be applied is one of the main factors determining the economics of a mechanized mining operation. There are several methods of prediction and it is advisable to use more than one of these to obtain realistic results. The principal methods are a full-scale linear cutting test, a small-scale cutting test (core cutting), an empirical approach, recourse to a semi-theoretical approach or an *in-situ* machine test.

Full-scale linear cutting test

The full-scale linear cutting test is a precise approach, since a rock block, 70 cm · 50 cm · 50 cm in size, is cut in the laboratory with a full-size cutter (point attack/conical tool, chisel picks, disk cutter, etc.). The cutting force, normal force, sideways force and specific energy values are obtained for different depths of cut and tool spacing values and the production rate of a given mechanical miner is calculated from the formula[7]

$$ICR = 0.8\frac{P}{SE_{opt}} \qquad (1)$$

where ICR is instantaneous production rate, m^3/h, P is cutting power of the mechanical miner, kW, and SE_{opt} is optimum specific energy, kWh/m^3.

Small-scale cutting test (core cutting)

The small-scale cutting test has been discussed in detail by McFeat and Fowell.[8,9] A core of 7.6-cm diameter or a small rock sample of 20 cm · 10 cm · 10 cm is fixed in the table of a shaping machine and cut by a chisel pick that has a rake angle of –5°, a clearance angle of 5°, a tool width of 12.7 mm and a cutting depth of 5 mm. The tool forces in three orthogonal directions are recorded with a force dynamometer and the specific energy, MJ/m^3 or kWh/m^3, is calculated by dividing the mean cutting force by the yield (the volume of rock or mineral obtained by unit distance of cut). The test results, which may be classified as index values, are evaluated by reference to previously accumulated field performance data.

Empirical approach

Empirical performance prediction models are based mainly on past experience and the statistical interpretation of previously recorded case histories. The collection of field data is, therefore, very important for the development of empirical performance prediction models. The accuracy and reliability of these models depend on the quality and extent of the available data. The most widely used empirical approach, described by Bilgin and his colleagues, predicts the instantaneous production rates of axial- and transverse-type roadheaders and impact hammers and is based on the *in-situ* observation of many tunnelling and mining projects.[10–14] The cutting performance is formulated thus:

For roadheaders

$$ICR = 0.28 \cdot HP \cdot (0.974)^{RMCI} \quad (2)$$

For impact hammers

$$IBR = 4.26 \cdot HP \cdot (RMCI)^{-0.567} \quad (3)$$

$$RMCI = UCS \cdot \left(\frac{RQD}{100}\right)^{\frac{2}{3}} \quad (4)$$

where ICR is instantaneous cutting rate, m^3/h, IBR is instantaneous breaking rate, m^3/h, HP is cutting or breaking power, hp, RMCI is rock mass cuttability index, UCS is uniaxial compressive strength, MPa, and RQD is rock quality designation, per cent.

Semi-theoretical approach

Deterministic computer modelling is used in the semi-theoretical approach. Performance prediction and machine and cutterhead design are possible with this method, which has been proven to be precise and reliable. Many machine manufacturers, research institutes and consultants have their own computer models for this purpose.[15–17]

In-situ machine testing

A used or new machine may be hired and tested in the mine. This is a very expensive and time-consuming approach, but is the most precise.

Full-scale linear cutting tests on different rocks and minerals

Linear cutting tests measure the full-scale cutting forces that act on a cutter. Full-scale testing minimizes the uncertainties of scaling and any unusual rock-cutting behaviour.

Many mine visits were performed within the scope of the present study and 11 large block samples of ore and the enclosing rock were collected from some of the operating mines and subjected to full-scale cuttability tests with a type of conical cutter. The tests were performed in laboratories at Istanbul Technical University. The programme included full-scale rock-cutting tests and physical and mechanical property tests. The full-scale linear cutting equipment, procedures, testing parameters and results are introduced and discussed here.

Linear cutting test equipment

The linear cutting machine used in the study was built recently as an outcome of a NATO-supported project.[18] It includes a stiff reaction frame on which the cutter and dynamometer (load cell) are mounted. The triaxial pillar-type dynamometer with 50 t of thrust capacity monitors orthogonal forces acting on the cutter. The cutter has to be calibrated with the dynamometer prior to testing by applying certain loads with a hydraulic jack. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing, and it can be set in the concrete at a desired dip angle or parallel or perpendicular to the bedding planes to simulate the actual cutting conditions of the deposit. A schematic drawing of the linear cutting machine used is presented in Fig. 2.

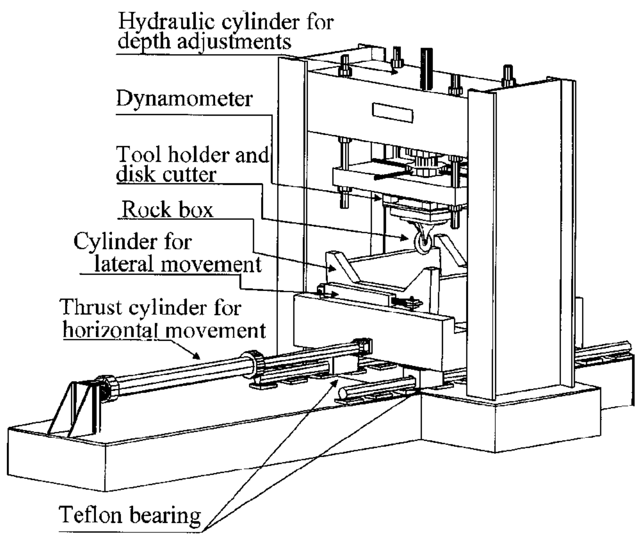

Fig. 2 Schematic drawing of linear cutting machine[18]

A servo-controlled hydraulic actuator forces the sample through the cutter at a preset depth of cut, width of spacing and constant velocity. The dynamometer measures the normal, drag and sideways forces acting on the cutter during the cut. The rock box is moved sideways after each cut by a preset spacing to duplicate the action of the multiple cutters on a mechanical excavator.

The data-acquisition system includes the dynamometer, an amplifier and a personal computer. The data are handled by commercial software. The data-acquisition card includes eight independent channels and monitors and collects data from the dynamometer. The excitation voltage ranges between 0 and 10 V. The data sampling and recording rate is adjustable up to 50 000 Hz. The recorded data are evaluated by a custom-written macro program.

Parameters and procedures

The three major variables in the independent linear cutting test were rock type, depth of cut and line spacing. The dependent variables were average and maximum cutter forces (cutting and normal force), specific energy values and size distribution of the rock cuttings. The constant conditions throughout the testing programme were cutting sequence (single-start), attack angle (55°), cutting speed (12.7 cm/s),

Table 3 Physical and mechanical properties of rock samples tested

Rock	, g/cm³	UCS, MPa	BTS, MPa	E_{sta}, GPa	E_{dyn}, GPa	SHRV	CAI
High-grade chromite (46–50% Cr_2O_3)	4.03	32	3.7	3.5	31.2	28–37	2.12
Medium–grade chromite (42–46% Cr_2O_3)	3.39	47	4.5	–	76.4	43	1.60
Low–grade chromite (20–25% Cr_2O_3)	2.88	46	3.7	2.9	35.2	42	2.40
Copper ore, yellow	4.13	33	3.4	–	42.0	–	2.80
Copper ore, black	4.07	41	5.7	–	49.6	–	3.00
Harzburgite	2.65	58	5.5	2.1	16.1	35–59	0.80
Serpentinite	2.49	38	5.7	2.3	13.9	39–58	1.00
Trona	2.13	30	2.2	3.4	3.7	39	–
Anhydrite	2.90	82	5.5	–	–	–	–
Celestite	3.97	29	4.0	–	–	–	–
Gypsum	2.32	33	3.0	–	–	–	–

, density; UCS, uniaxial compressive strength; BTS, Brazilian tensile strength; E_{sta}, static elasticity modulus; E_{dyn}, dynamic elasticity modulus; SHRV, Schmidt hammer rebound value (N-type); CAI, Cerchar abrasivity index.

skew angle (0°), tilt angle (0°) and a conical cutter. The data sampling rate was 2000 Hz.

The 11 samples consisted of three different chromite ores, harzburgite, serpentinite, two different copper ores, trona, anhydrite, gypsum and celestite. The physical and mechanical properties of the samples are summarized in Table 3. All the tests were carried out with an S-35/80H conical cutter manufactured by Sandvik. It had a gauge of 80 mm, flange diameter of 64 mm, shank diameter of 35 mm, tip diameter of 22 mm and primary tip angle of 80°.

The initial linear cutting tests are carried out in unrelieved cutting mode to determine the variation of specific energy with the depth of cut, as shown in Fig. 3. This helps to find the optimum depth of cut value (d_{opt}) at which the relieved cutting tests will be carried out for determination of the optimum specific energy and line spacing and production rate estimations.

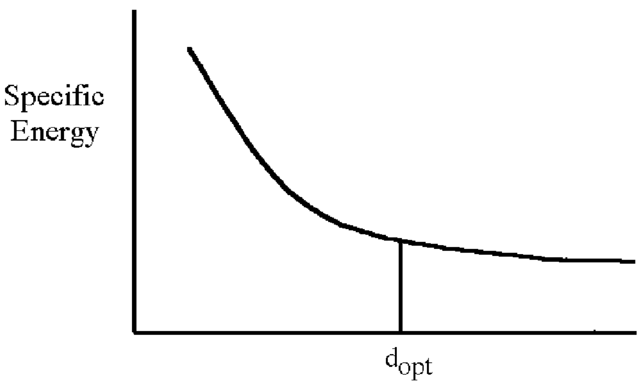

Fig. 3 General variation of specific energy with depth of cut

Unrelieved and relieved cutting modes are explained in Fig. 4. There is no interaction between cutting grooves in the case of unrelieved cutting; there should be interaction between grooves in the relieved cutting mode. The variation of specific energy with the ratio of cutter spacing to depth of cut is plotted from the relieved cutting test results and the graph is used to find the cutting conditions in which the machine excavates the rock in the most energy-efficient manner.

Specific energy is a measure of the cutting efficiency and is defined as the energy to excavate a unit volume of rock. The effect of the spacing between the cuts and depth of cut (or penetration) on cutting efficiency is also explained in Fig. 4. If the line spacing is too close (*a*), the cutting is not efficient because the rock is overcrushed. If the line spacing is too wide (*c*), the cutting is not efficient since the cuts cannot generate relieved cuts (tensile fractures from adjacent cuts cannot reach each other to form a chip), creating a groove-deepening situation or forming a bridge or rib between the cuts. The minimum specific energy is obtained with an optimum spacing to depth of cut ratio (*b*). The optimum ratio of cutter spacing to depth of cut generally varies between 1 and 5 for pick cutters.

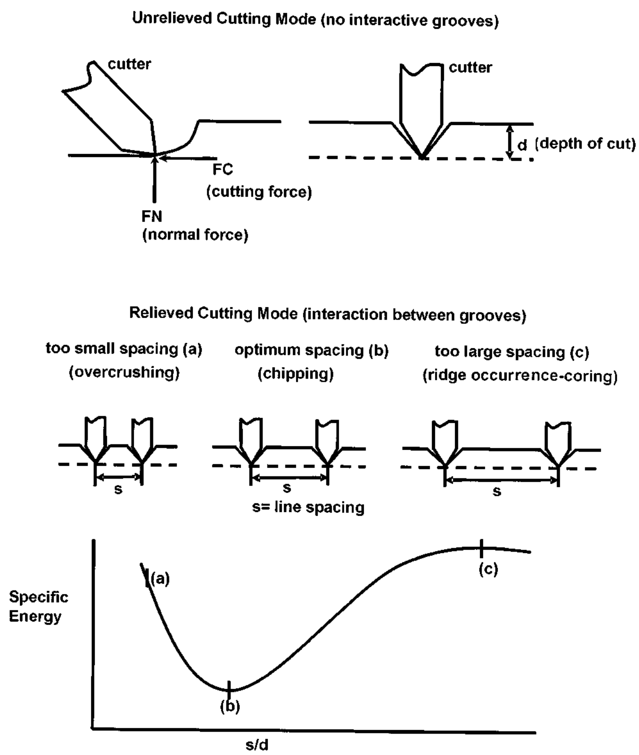

Fig. 4 Unrelieved and relieved cutting modes and effect of spacing on cutting efficiency and specific energy

Results and discussion

Some of the linear cutting test results are summarized for the unrelieved mode in Table 4. These tests defined the optimum

Table 4 Examples of linear cutting test results for unrelieved cutting mode

Rock	d, mm	FC, kgf	F C / FC	FN, kgf	F N / FN	SE, kWh/m^3
High-grade chromite	5	279	2.57	231	2.39	11.1
	10	530	2.80	354	2.60	5.8
Medium-grade chromite	5	347	2.94	302	2.60	14.8
	10	931	2.85	666	2.48	12.0
Low-grade chromite	5	319	2.73	285	2.51	11.7
	9	663	2.45	572	2.07	11.0
Copper ore, yellow	5	170	2.59	131	2.46	7.7
	10	515	2.88	333	2.79	5.9
Copper ore, black	5	270	2.72	323	2.54	19.4
	10	908	2.84	894	2.70	14.9
Harzburgite	5	531	2.82	621	2.33	18.6
	9	922	2.92	952	2.30	9.4
Serpentinite	5	295	2.66	326	2.70	9.5
	9	710	2.84	823	2.14	8.1
Trona	5	139	2.80	215	2.28	8.7
	9	420	2.92	639	2.16	6.7
Anhydrite	4	340	1.77	401	1.56	6.4
	8	518	1.96	553	1.82	7.2
Celestite	4	150	3.17	126	2.94	8.1
	8	343	2.64	256	2.49	5.5
	12	588	2.74	434	2.52	4.7
Gypsum	4	122	2.23	76	2.72	–
	8	338	2.26	222	1.98	6.7

d, depth of cut; FC, average cutting force; F C, maximum cutting force; FN, average normal force; F N, maximum normal force; SE, specific energy.

depth of cut values to be used in the relieved cutting tests. The linear cutting test results for relieved mode and the predicted instantaneous cutting rates and cutter consumption rates are summarized in Table 5.

It is generally accepted that a 4–5 t cutter force is a strength limit for conical cutters. It can be seen in Table 5 that the cutter forces were at acceptable levels in terms of cutter durability. The highest cutter forces, among the rocks tested, were obtained with harzburgite (average cutting force, 911 kgf; maximum cutting force, 2615 kgf; average normal force, 944 kgf; maximum normal force, 2275 kgf) and black copper ore (average cutting force, 810 kgf; maximum cutting force, 2460 kgf; average normal force, 773 kgf; maximum normal force, 2335 kgf), which were well below the cutter strength limit.

Consideration should also be given to cutterhead design issues. The design of the cutterhead is based on average cutter forces. If the cutter forces are too high, there might be a possibility of torque or thrust limitation for the excavator. This situation could be analysed with a cutterhead simulation program for any selected excavator, but is outside the scope of the present contribution.

The ICR predictions in Table 5 were based on the specific energy method and were obtained by the use of equation 1 for machines of 100 kW cutting power employing conical cutters, such as roadheaders and continuous miners—on the assumption that no torque or thrust limitation is faced during excavation. The IBR predictions were estimated from equation 3 and were performed for impact hammers of 33 kW breaking power, with the assumption of a RQD of 100%. These production values should be corrected linearly for the actual cutting power of the machine. For example, the ICR value should be multiplied by two if the cutting power is in fact 200 kW. The predictions did not include any machine

Table 5 Summary of cutting tests for relieved mode and performance predictions

Rock	s/d, optimum ratio	d_{opt}, mm	FC, kgf	F C / FC	FN, kgf	F N / FN	SE_{opt}, kWh/m^3	ICR for 100 kW cutting power, m^3/h	ICR t/h	IBR for 33 kW breaking power, m^3/h	IBR t/h	Cutter consumption, picks/m^3	picks/t
High-grade chromite	3	10	395	3.60	272	3.26	3.9	20.7	83	19.7	79	0.53	0.132
Medium-grade chromite	2	10	516	2.78	379	2.51	6.4	12.6	43	15.8	54	0.40	0.118
Low-grade chromite	3	9	455	3.08	363	2.83	5.0	16.2	47	16.0	46	0.60	0.208
Copper ore (yellow)	4	10	403	3.13	257	3.12	3.7	21.8	90	19.4	80	0.70	0.169
Copper ore (black)	4	10	810	3.04	773	3.02	9.2	8.7	35	17.1	70	0.75	0.184
Harzburgite	5	9	911	2.87	944	2.41	8.4	9.5	25	14.1	37	0.20	0.075
Serpentinite	3	9	444	3.17	484	2.65	6.2	12.9	32	17.9	45	0.25	0.100
Trona	3	9	222	4.09	294	2.93	2.7	29.6	63	20.4	44	–	–
Anhydrite	5	8	451	2.44	452	2.04	3.8	23.5	68	11.6	34	–	–
Celestite	3	12	390	3.06	301	2.76	3.0	26.7	106	19.4	45	–	–
Gypsum	3	8	185	2.28	117	2.28	3.4	21.1	49	20.8	83	–	–

s, line spacing; *d*, depth of cut; d_{opt}, depth of cut for optimum cutting conditions; FC, average cutting force; F C, maximum cutting force; FN, average normal force; F N, maximum normal force; SE_{opt}, specific energy for optimum cutting conditions; ICR, instantaneous cutting rate for 100 kW roadheader cutting power, t/h; IBR, instantaneous breaking rate for 33 kW impact hammer breaking power, t/h.

utilization factor, which is defined as the percentage of shift time used for excavation. If the daily production rate is to be estimated, the instantaneous cutting rate should be multiplied by the machine utilization factor, which varies usually between 25% and 50% (0.25 and 0.50) for roadheaders and impact hammers working in typical mining conditions. In addition, most of the deposits visited exhibited some joint sets and foliation, which indicated that the machine performance might be higher than that predicted in this study. The ICR and IBR predictions indicate that roadheaders and impact hammers might be used with acceptable production rates in the mines mentioned. A problem of low production rate might be faced with the massive portions of black copper ore and harzburgite.

Cutter consumption rates in Table 5 were predicted on the basis of field data given elsewhere.[19] The cutter consumption rate, cutters/m^3, due to abrasive wear might be predicted to be 0.25 · Cerchar abrasivity index. The predictions indicate that moderately high conical cutter consumption rates would be expected for copper ores (0.184–0.169 cutters/t excavated material) and low-grade chromite (0.208 cutters/t). However, cutter consumption rates for the other rocks are considered to be low.

The test results were used to develop a simpler performance predictor equation for mechanical miners using conical cutters, which could be used by decision-makers in industry. The relationships of uniaxial compressive strength and of Brazilian tensile strength to the optimum specific energy values of the rocks were analysed by simple regression analysis and are presented in Figs. 5 and 6, respectively.

Some studies carried out in the past on brittleness in rock cutting have indicated that a combination of uniaxial compressive strength and Brazilian tensile strength obtained by multiplying these two improved the correlation factors.[15,20] The correlation between optimum specific energy and the product of uniaxial compressive strength and Brazilian tensile strength was, therefore, analysed. Fig. 7 shows that the correlation was improved. On this basis the optimum specific energy can be predicted from equation 5:

$$SE_{opt} = 0.027(UCS \cdot BTS) + 0.675 \quad (5)$$

where SE_{opt} is optimum specific energy, kWh/m^3, UCS is uniaxial compressive strength, MPa, and BTS is Brazilian tensile strength, MPa. The outlier (anhydrite) shown in Fig. 7 might be due to the coarse grains of anhydrite. It is known that coarse grains influence the cuttability of rocks.[21]

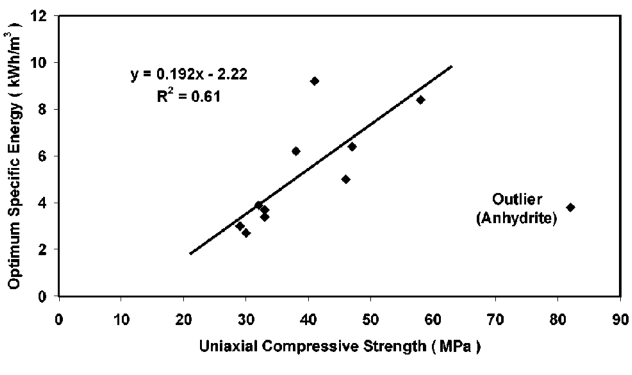

Fig. 5 Relationship between optimum specific energy and uniaxial compressive strength

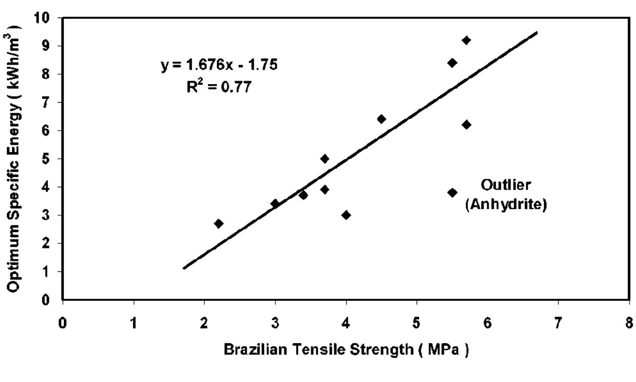

Fig. 6 Relationship between optimum specific energy and Brazilian tensile strength

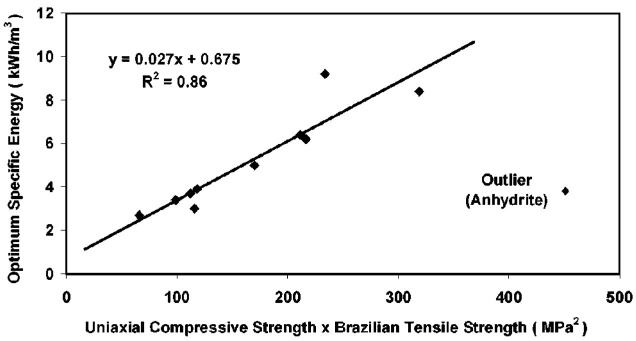

Fig. 7 Relationship between optimum specific energy and (uniaxial compressive strength · Brazilian tensile strength)

This relationship gives a rough idea of the production rates of a machine that employs conical cutters. The database on this subject should be enlarged and a multivariate regression analysis then run to obtain a more precise predictor equation. It should also be noted that this type of prediction cannot be more precise than a set of full-scale linear cutting tests. In addition, cutting tests also yield values for cutter forces, which are used for cutterhead and machine design.

The ratio of maximum cutting (drag) forces to average cutting forces varied between 2.28 and 4.09 for the optimum specific energy values and all types of rocks tested. The ratio of maximum normal forces to average normal forces varied between 2.04 and 3.26 for the optimum specific energy values and all types of rocks tested. This ratio can be related to machine vibrations; a lower ratio indicates less vibration. A regression analysis performed on the data showed that there was no meaningful relationship between these ratios and rock properties.

Assessment of potential of a chromite mine to make use of mechanical miners

A typical chromite mine was analysed to assess the applicability of mechanical miners with reference to the properties of the deposit (rock mass and cuttability) and operational characteristics. Two podiform types of ore deposits (locally named Rifat and Banu) sited about 500 m from each other are exploited by a private company, Dedeman AS, in Kayseri. The Banu deposit is of lens type, dipping around 60° and with ore delineated below a surface area of 30 m · 130 m. The Rifat deposit is of vein type, dipping 70–80° and comprised within a 50 m · 50 m boundary on the surface. The chromite mineralization is within dunite zones. The hangingwall and footwall are harzburgite. The deposits are highly fractured and faulted.

The current mining method is top-slicing with an artificial roof. Access to the deposits is via a shaft (Rifat shaft) located between the two orebodies. There are ventilation raises from each deposit. The orebody is divided into individual panels every 30 m of vertical distance by main roadways. The main roadways, having a horseshoe profile of 8 m^2, are located in the footwall. The main roadways are connected to each other by two raises, one for transportation of backfill material and other as an ore pass. Excavation is by drill and blast. The total average production from the two deposits is around 110 000 t/year. Thirteen labourers work on each shift (three shifts/day) to achieve the required production rate.

The rock samples used in the laboratory tests for cuttability determination included high-grade chromite (46–50% Cr_2O_3) from Rifat deposit and medium-grade chromite (42–46% Cr_2O_3) from Banu deposit, plus a sample of the surrounding harzburgite from Banu. Some physical and mechanical properties of the samples from the Banu and Rifat orebodies are presented in Table 3.

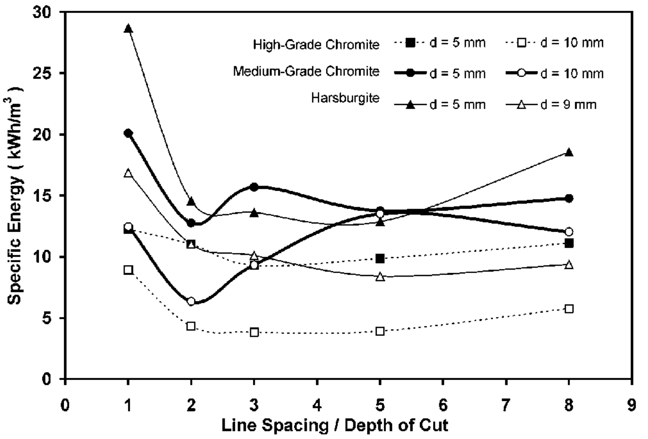

Fig. 8 Specific energy versus line spacing to depth of cut ratio for high-grade chromite, medium-grade chromite and harzburgite

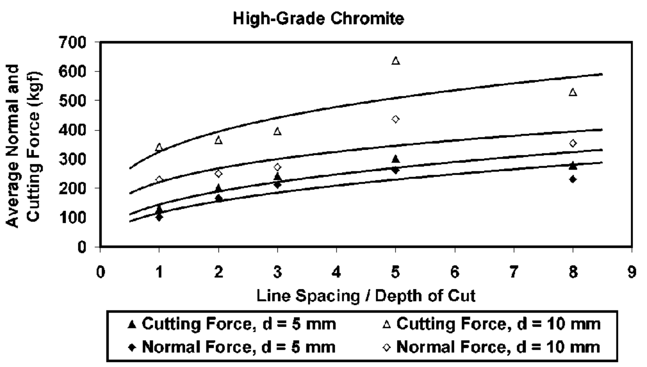

Fig. 9 Average normal and cutting forces versus line spacing to depth of cut ratio for high-grade chromite

The results of the linear cutting tests on these rocks are presented in Table 5 and summarized in graphical form in Figs. 8–11. These results are for relieved and unrelieved (s/d = 8) cutting modes. The force levels are acceptable in terms of conical cutter durability. These cutter forces might also be used to design a roadheader cutterhead.

The rock mass and cuttability characteristics of the Banu and Rifat orebodies indicate that a partial-face mechanical miner, such as a medium-duty roadheader or an impact hammer, could be used for excavation of both the chromite ores and the enclosing harzburgite. The instantaneous cutting rates of a roadheader were predicted to be 83, 43 and 25 t/h/100 kW cutting power for high-grade chromite, medium-grade chromite and harzburgite, respectively. The instantaneous breaking rates of an impact hammer were predicted to be 79, 54 and 37 t/h/33 kW breaking power for high-grade chromite, medium-grade chromite and harzburgite, respectively. The conical cutter consumption rates were predicted to be 0.132, 0.118 and 0.075 cutters/t of excavated material for high-grade chromite, medium-grade chromite and harzburgite, respectively. The fractured nature of the orebodies and enclosing rock would facilitate excavation, increasing the predicted excavation rates and reducing the cutter consumption rates.

Use of a multi-purpose, medium-duty excavator boom with an interchangeable roadheader cutterhead and impact hammer might improve the excavation performance in chromite and harzburgite, if the impact hammer were applied in fractured zones and the roadheader cutterhead in more massive and stronger zones. The high-grade chromite is ideally removed as lumps of up to 30 cm. Since the high-grade

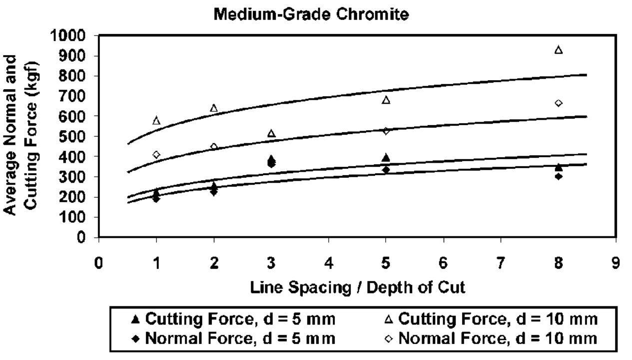

Fig. 10 Average normal and cutting forces versus line spacing to depth of cut ratio for medium-grade chromite

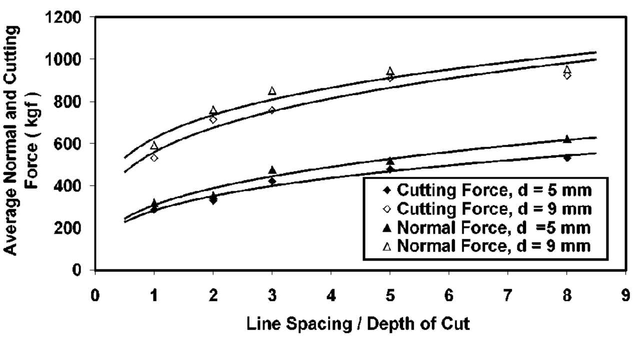

Fig. 11 Average normal and cutting forces versus line spacing to depth of cut ratio for harzburgite

chromite is not strong and has some planes of weakness it would be possible to obtain lump chromite with an impact hammer. Moreover, using a roadheader cutterhead for the lower-grade ores might reduce the primary crushing costs of processing by generating a uniform, small size of muck. An increased production rate would result in fewer shifts per day and reduced production costs.

The excavated material might be loaded by a loading apron of the miner on to a tail conveyor. Transportation to the ore passes might not requuire modification of the mine layout. However, it should be considered that if the production capacity of the mine increased or the production levels went deeper, the current shaft capacity might not suffice to hoist all the production.

Conclusions

The results of full-scale rock-cutting tests conducted with a conical cutter in the laboratory combined with geological and geotechnical information gathered during mine visits have indicated that many mines in Turkey could be operated with partial-face excavation machines, such as roadheaders and impact hammers/breakers, and that acceptable production rates could be achieved. Moderately high conical cutter consumption rates would be expected in the case of copper ores and low-grade chromite. Analysis of the data obtained from the testing programme led to the development of a predictor equation for the optimum specific energy and thus, production rate. It was seen that the optimum specific energy could be predicted acceptably on the basis of a correlation with the uniaxial compressive and Brazilian tensile strength values of rocks. However, it should be noted that this prediction cannot be more precise than a set of full-scale cutting tests.

A chromite deposit located in Turkey was studied in detail. Analysis of the rock mass and intact rock properties, such as joint sets, foliation, cuttability and abrasiveness, indicated that a medium-duty excavator boom with an interchangeable roadheader cutterhead and impact breaker would be technically and efficiently applicable to the production of ore and excavation of roadways at this mine and other similar mines. Faster and continuous excavation has the potential to reduce the number of working shifts per day and, thus, the labour cost.

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