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ORIGINAL ARTICLE

An experimental study on the cutting depth produced by abrasive waterjet: how do abrasive and rock properties affect the cutting process?

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Abstract
The abrasive and rock properties have a significant impact on the performance and profitability of abrasive water jet (AWJ) cutting. In the relevant literature, there is no comprehensive study that investigates the effects of abrasive type on the AWJ cutting of rocks. As a result, in the current study, various abrasives (garnet, white fused alumina, brown fused alumina, glass beads, emery powder, olivine, steel shot, and plastic granule) were used in tests where workpieces prepared from various rock types (igneous, metamorphic, and sedimentary) were cut with AWJ. The cutting parameters were kept constant during the cutting operations. The cutting depth was taken into account when evaluating the AWJ performance. It was revealed that garnet, steel shot, and fused alumina (brown and white) have higher cutting abilities (cutting depth: 39.23–125.94 mm by the rock type). Compared to them, olivine, emery powder, and glass bead produced shallower cuts (21.11–80.00 mm by the rock type). Despite this, effective cutting did not occur with plastic granules. It was demonstrated that there are strong correlations between the cutting depth-abrasive hardness (up to *r*: 0.82 by rock type) and cutting depth-abrasive density (up to *r*: 0.87 by rock type). It was determined that the cutting depth increases as the Bohme abrasion loss, effective porosity, and water absorption capacity of the rocks increase. It was also found that the cutting depth decreases as the strength, Schmidt hardness, unit volume weight, and ultrasonic wave velocity of the rocks increase. The most essential rock properties influencing cutting depth were determined as the Bohme abrasion loss, uniaxial compressive strength, and point load strength.

Keywords Abrasive waterjet · Abrasives · Rock cutting · Cutting depth · Abrasive properties · Rock properties

1 Introduction

Abrasive waterjet machining (AWJ) has distinct advantages over other traditional and advanced cutting technologies (no thermal damages, minimal wear problems, and others). Hard materials such as rocks can be effectively cut with this technology. In AWJ cutting, the high-pressure jet (mixture of water and abrasive) leaving from a narrow focusing tube hits the workpiece surface and removes the particles [1]. Many factors influence this process, including operating parameters [2–5], workpiece properties [2, 6–11], and abrasive type. Although the studies focused on the performance of the AWJ including garnet have been well documented, there are only a few studies (except for non-rock materials [12, 13]) examining the effect of abrasive type on cutting performance in rock cutting with AWJ (see Table 1). In research where various rocks were cut with AWJ, a single abrasive type (garnet) was used. In AWJ cutting processes, garnet is commonly used as an abrasive. However, many abrasive types can be considered an alternative to garnet in cutting applications with AWJ in various sectors. As previously stated, no comprehensive study of the performance of abrasives other than garnet in rock cutting with AWJ is available in the relevant literature (see Table 1). The majority of research that used various abrasives in rock cutting with AWJ utilized one type of rock. There are no generalizable trends for various abrasives in various rocks of different origins. Furthermore, it is unclear how the rock properties will manage the cutting process for various abrasives. This study attempted to fill the aforementioned lack of research. As a result, the study's goal is to determine the natural stone-cutting performance of various abrasives that can be used as a substitute for garnet.

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Table 1 The studies focus on the abrasives that can be used as alternatives to garnet in rock cutting with the AWJ

Authors	Alternative abrasives	Materials
Agus et al. [7]	Silica sand and copper slag wastes	Granite and marble
Axinte et al. [39]	Silicon carbide, aluminum oxide, and diamond powder	Polycrystalline diamonds
Engin et al. [40]	Various types of garnet from different regions	Granite and marble
Cosansu and Cogun [41]	Colemanite powder	Marble, glass, alloys
Aydin et al. [17]	Solid-cutting waste of granite	Marble
Aydin et al. [18]	Alumina, silicon carbide, glass beads, and emery powder	Marble
Cha et al. [42]	Steel shot	Granite

The study's objectives are to determine the effects of various abrasive and rock properties on cutting performance and to identify better-performing abrasive types. It is expected that the study will raise awareness about the use of various abrasives in AWJ rock cutting.

Following Section 1, the rest of the paper is organized as follows: Section 2 includes detailed information on the materials, equipment, experiments, and methodology. In Section 3, the results of tests are presented and discussed. Finally, the main findings of the study and some recommendations for future research are presented in Section 4.

2 Materials and method

In the cutting tests, workpieces prepared from various rocks (basalt, lamprophyre, tuffs, limestones, andesite, marble, and travertine) were cut with the AWJ. Small-grained and homogeneous rocks were selected to minimize the effect of mineralogical properties (content, shape, etc.) on the cutting performance. This structure enables determining the performances of the abrasives effectively. The workpieces (14 in total for each rock) were prepared with a circular saw with a 5 cm thickness, 20 cm length, and 15 cm width. It was planned to use the extra workpieces (4 pieces) if any problems (such as breakage during transportation or cutting) occurred with the workpieces (10 pieces) to be used in the experiments (see Fig. 1).

The characterization of the rocks (Bohme abrasion loss, Schmidt hardness, uniaxial compressive strength, point load strength, Brazilian tensile strength, ultrasonic sound velocity, and some physical properties (such as density, porosity, and water absorption)) was performed in accordance with the relevant standards [14, 15] (see Fig. 2). For the hardness tests, block samples with a 20 cm thickness, 40 cm length, and 10 cm width were used. The Schmidt hammer rebound hardness test [15] was performed using an L-type digital Schmidt hammer device. The rebound of the steel tip of the device, which weighs approximately 1 kg and is pressed to the surface, yields a hardness value. This value is displayed on the electronic screen of the device. Schmidt hardness values provide a data scale for comparing material hardness. Before the test, the upper surfaces of the natural stone blocks were cleaned and smoothed with hand sandpaper. Natural stone blocks were placed on hard and smooth ground, and necessary controls with a spirit level were performed. The test was carried out on the blocks' 10×20 cm surfaces. Schmidt hardness values were obtained by reading the rebound values after applying the Schmidt hammer to 20 different points determined on the surface.

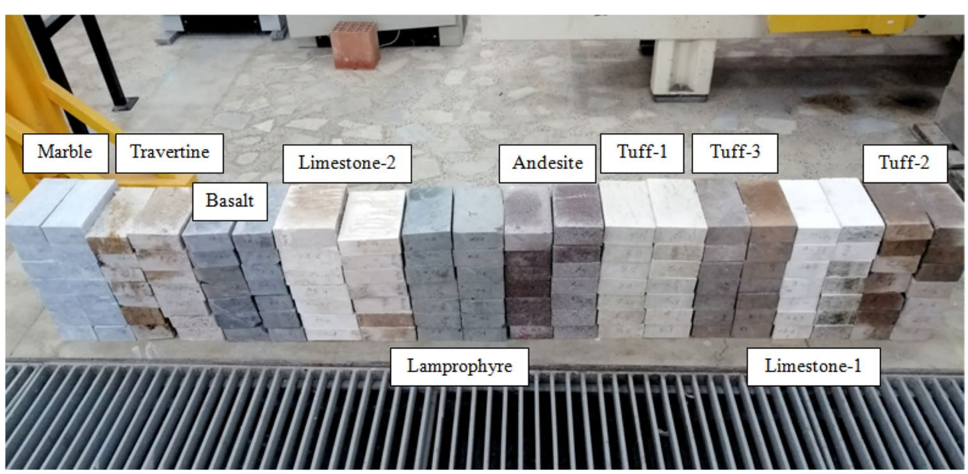

Fig. 1 Workpieces used in the study

Fig. 2 Processes for determination of rock properties

For the Bohme abrasion resistance test [14], cubic samples with a side length of 71 mm were used. A circular cutting saw was used to cut cube samples from block samples. A horizontally placed abrasion disc with a diameter of 75 cm and a speed of 30 rpm was used in the test. One side of each sample was fixed to the disc, the disc was rotated, and the sample surface was abraded. The disc rotates 22 times in one cycle. Each sample received 16 cycles. A total of 20 gr of emery powder (abrasive agent) was sprinkled on the disc in each cycle. The volume loss at the end of the test was recorded as the Bohme abrasion loss value for each sample. For use in the other tests, core samples were taken from the block samples using a core drilling machine (see Fig. 3). The samples were extracted from the blocks using a cold-drawn steel core barrel (50 cm long, NX (54.7 mm) diameter) attached to an electric motor core drilling machine (immobile type, running at 600 rpm). Core and disc samples were processed/produced using a core cutting saw. The surfaces of the samples were then sanded and stored at room temperature for 2 weeks. Three disc samples from each natural stone type were used to determine the physical properties of natural stones with caliper techniques (suggested methods for determining water content, porosity, density, absorption, and related properties [15]). First, the samples' dimensions were determined using a digital caliper with 0.01 mm precision, and then samples were weighed with a digital scale with 0.01 g precision, and their natural densities were determined. Following that, samples were dried in a 105 °C oven for 24 h, then cooled in a desiccator, and weighed. Finally, the samples were weighed again after being kept in 20 °C water for 24 h. As a result, dry and saturated densities were found, as well as other physical properties, using the calculations specified in the relevant standard. For the compressive strength test (suggested methods for determining the uniaxial compressive strength of rock materials [15]), 5 core samples of each natural stone type with length/diameter ratios ranging between 2.5 and 3.0 were prepared. The samples were broken using a hydraulic press at a constant stress

Fig. 3 Block samples and obtaining a core sample

rate of 0.5 MPa/s, and the breaking loads were recorded. Uniaxial strength values were calculated using the formulas specified in the relevant standard. To determine tensile strength (suggested method for determining indirect tensile strength by the Brazil test [15]) and point load strength (suggested method for determining point load strength [15]), ten disc samples with 0.5 length/diameter ratios were prepared. The samples' diameter was NX (54.7 mm). For the tensile strength test, the samples were placed in the steel loading jaw and then broken under the hydraulic press, and for the point load strength test, the samples were broken in the point load strength device under the conditions specified in the relevant standards, and strength values were obtained using the calculations specified in those standards. Furthermore, the ultrasonic velocity test (suggested method for determining sound velocity by ultrasonic pulse transmission technique [15]) was performed on 1 core sample from each natural stone type to determine *p*-wave transmission velocity. An ultrasonic speed tester and signal receiver geophones were used in the test. The chemical composition of the rocks was also determined using the X-ray fluorescence technique (see Table 2).

In the current study, various abrasives (80 mesh size) such as white fused alumina, brown fused alumina, glass bead, emery powder, olivine, steel shot, and plastic granules were considered alternatives to garnet, which is commonly used as abrasive in AWJ cutting operations. The abrasives were chemically investigated using the X-ray fluorescence technique (see Table 3). A scanning electron microscope was also used to evaluate the abrasive shapes (see Fig. 4). The hardness (Mohs) of the abrasives was obtained from the companies that supplied the products. The abrasive densities were also determined using a water pycnometer [16].

The cutting tests were carried out on an S-HP model, bridge-structured AWJ cutting machine equipped with a high output pump (see Fig. 5). The machine's cutting head can move in three axes. The machine consumes 40 kWh of energy, has a maximum pump pressure of 400 MPa, and a maximum traverse speed of 12,000 mm/min. The diameter and length of the AWJ focusing tube are 1.1 mm and 75 mm, respectively. The orifice diameter is 0.33 mm. The focusing tube is made of tungsten carbide, while the orifice is produced of sapphire. Under the ASJ cutting head, the workpieces were positioned vertically (at a height of 15 cm) on the 5 × 20-cm-sided surfaces. The cutting angle is 90°. The workpieces were cut along their lengths (20 cm). The cutting plan was designed using a computer in a control room, and

Table 2 Chemical composition (%) of the rocks

Rock type	Loss of ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	MnO	TiO_2
Limestone-1	43.15	0.20	< 0.10	< 0.10	55.40	0.30	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Limestone-2	43.00	0.30	0.10	< 0.10	55.60	0.30	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Travertine	41.55	3.20	1.10	0.50	52.30	0.80	< 0.10	0.10	< 0.10	< 0.10	0.10
Marble	43.25	0.40	0.20	0.10	55.00	0.40	< 0.10	0.10	< 0.10	< 0.10	0.10
Tuff-1	7.45	70.10	12.30	1.20	3.10	0.80	0.60	3.80	< 0.10	< 0.10	0.20
Tuff-2	0.40	71.10	14.00	2.60	1.30	0.50	4.10	4.80	0.10	0.10	0.50
Tuff-3	8.75	42.20	16.90	10.50	3.30	8.50	3.50	4.00	0.30	0.20	0.90
Lamprophyre	7.50	38.70	14.00	9.70	16.00	4.60	3.60	2.60	1.30	0.20	1.10
Basalt	6.55	52.80	15.00	8.50	5.50	3.20	1.70	4.90	0.30	0.20	1.00
Andesite	0.80	64.40	16.50	4.70	4.60	0.90	3.70	3.00	0.30	0.10	0.70

Table 3 Chemical composition (%) of the abrasives

Abrasive type	Al_2O_3	SiO_2	CaO	Na_2O	MgO	Fe_2O_3	Other
Garnet	23.00	35.00	1.00	–	7.00	33.00	MnO: 1.00
White fused alumina	99.73	0.01	0.02	0.14	0.01	0.03	TiO_2: 0.02
Brown fused alumina	95.65	0.92	0.32	–	0.22	0.12	TiO_2: 2.42
Olivine	0.80	40.00	1.90	–	49.00	7.80	MnO: 0.10
Glass bead	2.50	71.50	8.85	11.15	5.00	0.50	K_2O: 1.50
Emery powder	62.30	8.40	1.20	–	0.20	25.60	–
Steel shot	–	-	–	–	–	-	C: 1.20, Si: 1.5, Fe: 96, Mn:1

Plastic granules: urea, melamine, and acrylic

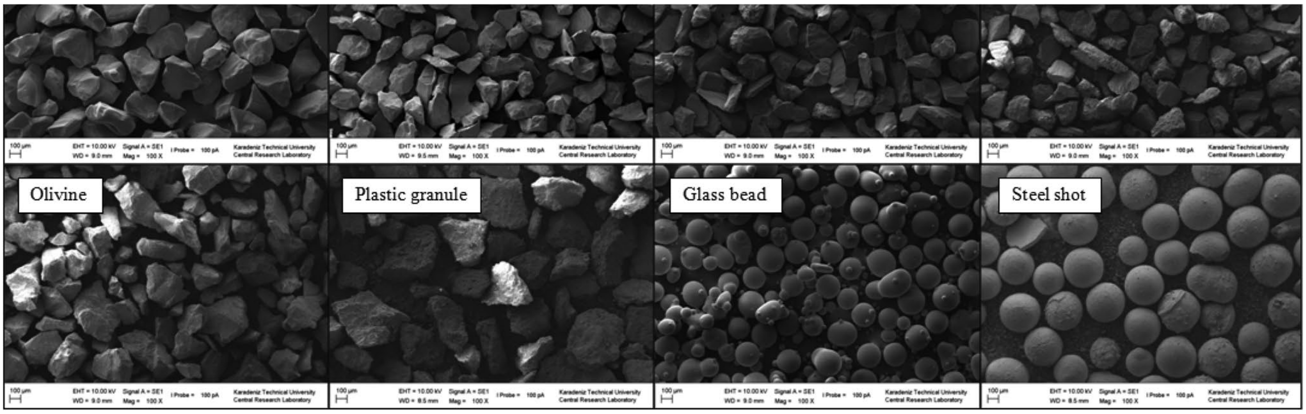

Fig. 4 Scanning electron microscope images of the abrasives (100×)

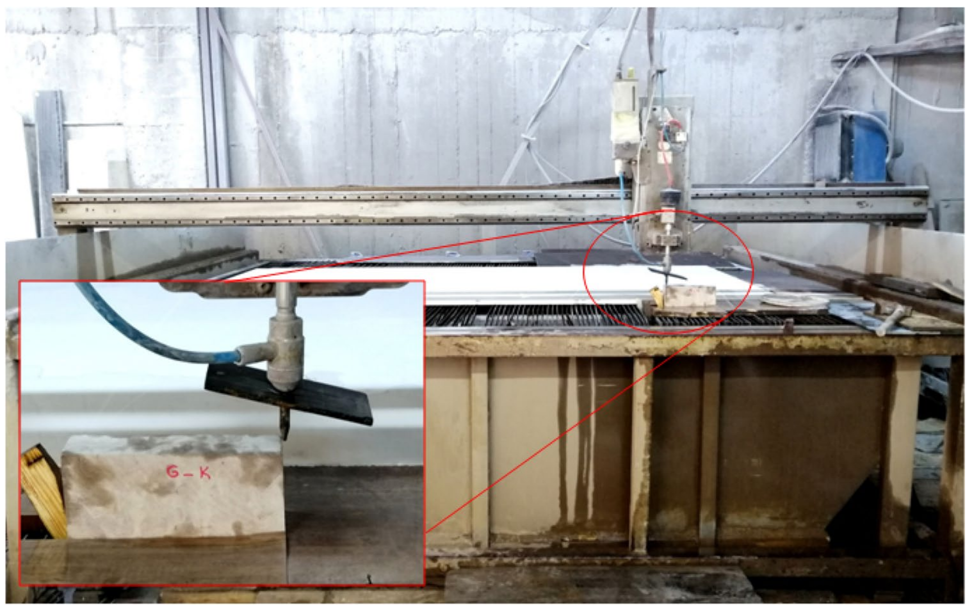

Fig. 5 The AWJ cutting machine used in the study

the cutting operations were monitored by the control panel. After cutting a workpiece, system components automatically adjust and take the position for the next cut. A total of 80 cutting tests (10 tests for each abrasive) were performed. To evaluate the cutting performance of material (abrasives and rocks) types and properties, all cutting parameters (water pressure, traverse speed, abrasive mass flow rate, and standoff distance) were kept constant (see Table 4). These values were selected based on previous studies [11, 17–24], preliminary experiments, and the technical properties of the AWJ machine used. After completing the cutting tests on all workpieces (10 types) for an abrasive, the abrasive tank was emptied and refilled with another abrasive to cut the next 10 workpieces. Finally, the cut workpieces were transported to laboratories to evaluate the cutting performance of the AWJ with various abrasives.

Table 4 Levels of the operating parameters

Parameter	Value
Water pressure (MPa)	380
Traverse speed (mm/min)	300
Standoff distance (mm)	4
Abrasive mass flow rate (g/min)	400
Water flow rate (L/min)	3.8

The cutting depth, which represents the vertical distance from the surface to the deepest point of the cut, was used as the performance output [3, 4, 24, 25]. In Fig. 6, the profile (from where the jet enters the workpieces) views of some of the kerfs with different cutting depths are shown. Each workpiece was divided into two parts along the cutting line to measure the cutting depth. Before the separation, pieces of soft cardboards were placed in the kerfs to prevent friction between the kerf walls. Most of the workpieces were easily separated because a large portion

Fig. 6 Profile views of some kerfs with different cutting depths

of them had already been cut. The rest (with lower cutting depths) were turned down and cut with a circular saw in line with the cuts obtained with the AWJ. A safe distance was left between the AWJ and circular saw cuts because the cutting lines did not overlap (see Fig. 7). Finally, the cutting depth was precisely measured at 2 cm intervals along the cutting line with a digital caliper (precision 0.01 mm) (see Fig. 8). For each test, 9 measurements were taken (720 measurements in total for 80 workpieces). The arithmetic mean of these values was recorded as the cutting depth. The precision of the measurements was assessed using the standard deviation.

The Pearson correlation coefficient (*r*), which measures the strength and direction of a linear relationship between two variables, was used to assess relationships between material (abrasive and rock properties) and cutting depth values. Pearson's correlation coefficient is the covariance of the two variables divided by the product of their standard deviations. The scale in Table 5 was used in the interpretation of *r* [26].

3 Results and discussion

A summary of measurements for the cutting depth results is presented in Table 6 and Fig. 9. Table 7 displays the standard deviations obtained for the measurements. The low standard deviations indicate a high level of precision. The cutting depths generated by the abrasives widely range from 5.00 to 125.94 mm. The best results were obtained with steel shot, fused alumina (brown and white), and garnet (cutting depth: 48.78–125.94 mm, 40.40–117.80 mm, and 31.73–105.23 mm by the rock type, respectively). Compared to them, glass beads, olivine, and emery powder produced shallower cuts (27.18–80.00 mm, 21.11–71.05 mm, and 28.08–69.33 mm by the rock type, respectively). On the other hand, plastic granules, which have the lowest hardness and density among the abrasives, achieved very low cutting depths (5.00–31.53 mm by the rock type). Figures 10 and 11 show the cutting depth values obtained for each type of rock cut with different abrasives, listed from left to right based on the abrasive's

Fig. 7 Separation of the workpieces with a circular diamond saw

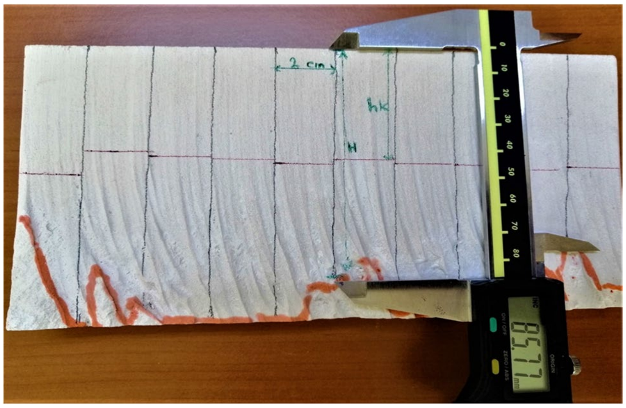

Fig. 8 Measurement of cutting depths from a cutting surface

related property (hardness and density, ascending sort). Higher cutting depths were obtained in general with abrasives of higher densities and hardness (see Figs. 10 and 11). Cutting depth and abrasive hardness (*r*: 0.59–0.82 by rock type) and abrasive density (*r*: 0.63–0.87 by rock type) were found to have very high correlations (see Table 8).

The basic mechanism of cutting with the AWJ is the removal of material from the surface of the workpiece by the erosion of the jet (water-abrasive mixture) at high pressure and high speed. Each abrasive grain performs a micro-cutting action. This process is explained by different mechanisms in ductile and brittle workpieces. The materials are removed from the workpiece by different mechanisms such as plastic flow, cracking (creating micro-fractures), breaking into fragments, scraping, and notching. For ductile workpieces, cutting is accomplished by the impact of abrasive grains, which provide scraping and micro-cutting, at a low angle to the surface of the workpiece. At higher impact angles, the material removed from the workpiece takes on a plastic flowing form. In the case of brittle workpieces (e.g., rocks), the material is removed by the fracture mechanism created by crack formation and propagation. In removal mechanisms, water serves as a carrier and accelerating medium for the entrained abrasive grains. In addition, Momber and Kovacevic (1998) stated that water flow also contributes directly to material removal. While the abrasive grains impinging on the surface of the workpiece create micro cracks, water penetrates these cracks at high velocity and enlarges them by the action of hydrostatic force. In this way, fragmentation and the amount of material removed increase [27].

Although the variety of materials (abrasive type x rock type) used in AWJ rock cutting is limited in the literature, some studies have look into the relationship between abrasive and workpiece material properties and cutting performance. Hlavac [28, 29] explained the reasons for changes in the AWJ's effectiveness due to the influence of some physical phenomena present in the cutting process, with physical dependencies derived from water and abrasive water jets. According to Aydin et al. (2019), the main abrasive properties affecting cutting depth are density and hardness [18]. Quiang et al. (2022) found that the density and Young's modulus of abrasives are the main factors affecting the cutting depth. They also observed that the cutting depth increases with the increase in the relative Young's modulus (ratio of abrasive to workpiece) [30]. Furthermore, Fowler et al. (2009) indicated when workpiece hardness is similar to or higher than abrasive hardness, cutting performance

Table 5 Pearson's correlation coefficient (*r*) scale [26]

The absolute value of *r*	Intensity of correlation
$0.00 < r \leq 0.19$	Very low correlation
$0.20 \leq r \leq 0.39$	Low correlation
$0.40 \leq r \leq 0.59$	Moderate correlation
$0.60 \leq r \leq 0.79$	High correlation
$0.80 \leq r \leq 1.00$	Very high correlation

Table 6 Summary of the cutting depths by different abrasives for the rocks (mm)

Rock type	Garnet	White fused alumina	Brown fused alumina	Olivine	Glass bead	Emery powder	Steel shot	Plastic granule
Limestone-1	71.27	92.66	78.05	52.18	60.23	49.72	98.29	16.34
Limestone-2	93.15	95.68	88.33	58.57	74.29	49.68	125.94	19.21
Travertine	31.73	59.49	53.21	28.49	35.78	28.45	48.78	7.61
Marble	43.58	48.76	45.35	23.81	32.21	28.08	57.29	5.26
Tuff-1	105.23	117.80	106.50	71.05	80.00	69.33	121.20	31.53
Tuff-2	81.77	97.29	90.70	58.55	60.56	54.92	92.57	17.85
Tuff-3	81.70	101.82	98.85	61.04	64.97	56.86	99.64	22.21
Lamprophyre	39.23	40.40	50.70	21.11	27.18	29.86	57.00	5.00
Basalt	50.13	48.79	50.78	26.98	30.30	31.69	57.55	5.56
Andesite	37.96	50.47	49.38	23.01	33.74	28.81	56.00	5.84

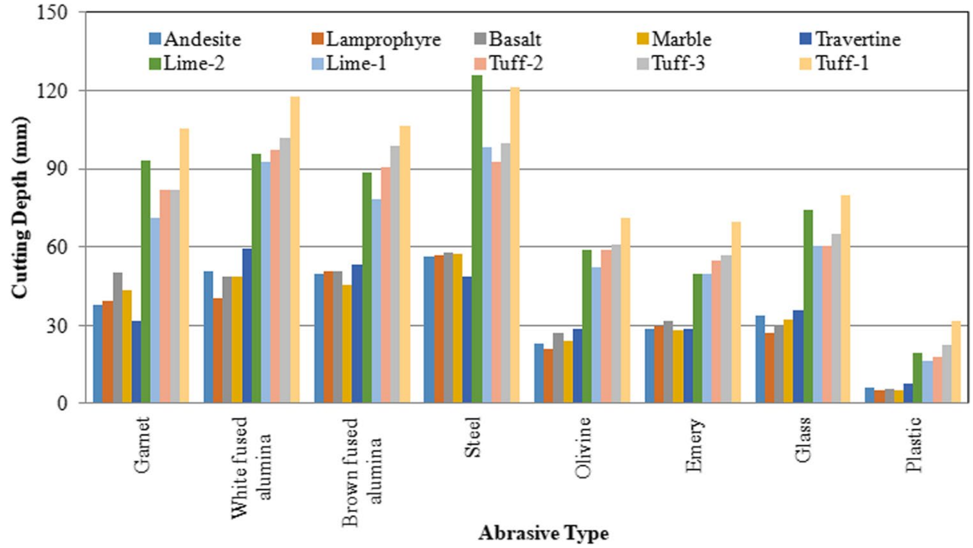

Fig. 9 Cutting depths obtained for the abrasives by rock type

decreases [31]. Moreover, Long et al. (2017) stated that heavier abrasive particles have higher impact capability [32]. As a result, it has been stated that a low-density abrasive particle cannot effectively hit the workpiece due to its low kinetic energy, which can result in a reduction in cutting depth [2, 3, 6, 32]. At a constant abrasive feed rate (mass flow), the proportions of abrasive (by weight) of different densities in the jet are equal. As a result, the initial kinetic energies of the jets produced by the various abrasives (in the mixing chamber) are expected to be equal. In addition, lower-density abrasives will have a higher volume ratio in the jet. In other words, more abrasive particles will be existent per unit volume (for similar size distribution). As is well known, the abrasive particles in the AWJ disperse/break down in the focusing tube (abrasive–abrasive impact and the abrasive hitting the inner surfaces of the focusing tube) and inside the workpiece (abrasive–abrasive impact and the abrasive hitting the inner surface of the workpiece). Abrasives with higher volumetric concentrations are more likely to collide with each other and surfaces, especially at high abrasive feed rates. This phenomenon may result in more fragmentation of the abrasive particles. It is conceivable that the abrasive particles reduced in size cannot perform effective micro-cutting due to the reduced impact effects. Besides that, as the velocities of the frequently colliding abrasive particles decrease, the kinetic energy of the AWJ may decrease. Moreover, as the volumetric abrasive particle ratio increases, the velocity of the water moving through the focusing tube decreases, as does the kinetic energy of the AWJ. Consequently, as stated in some studies [33–35], it can be predicted that the kinetic energy of the jet will be depleted faster, and lower cutting depths will be obtained in cuttings using lower-density abrasives (especially at high abrasive feed rates).

Table 9 summarizes the physicomechanical properties of the rocks. Additionally, the effects of rock type on the cutting

Table 7 The standard deviation of the measurements (mm)

Rock type	Garnet	White fused alumina	Brown fused alumina	Olivine	Glass bead	Emery powder	Steel shot	Plastic granule
Limestone-1	1.66	4.26	1.85	0.55	0.67	2.91	1.34	0.26
Limestone-2	3.14	5.25	3.54	3.07	3.83	0.49	5.56	1.27
Travertine	0.77	2.17	1.23	1.76	0.69	2.42	1.27	0.34
Marble	1.18	3.45	0.35	1.35	1.51	1.13	1.12	0.27
Tuff-1	5.05	3.07	4.73	0.76	1.30	1.81	0.40	1.29
Tuff-2	3.22	2.27	0.92	2.82	0.74	3.37	0.93	0.49
Tuff-3	1.09	0.69	0.68	1.12	0.64	0.41	3.31	1.42
Lamprophyre	0.88	1.81	1.90	1.09	0.89	0.74	2.59	0.43
Basalt	2.01	1.91	0.72	0.73	2.22	2.46	2.61	0.26
Andesite	0.38	2.32	1.44	0.33	0.33	0.56	0.77	0.39

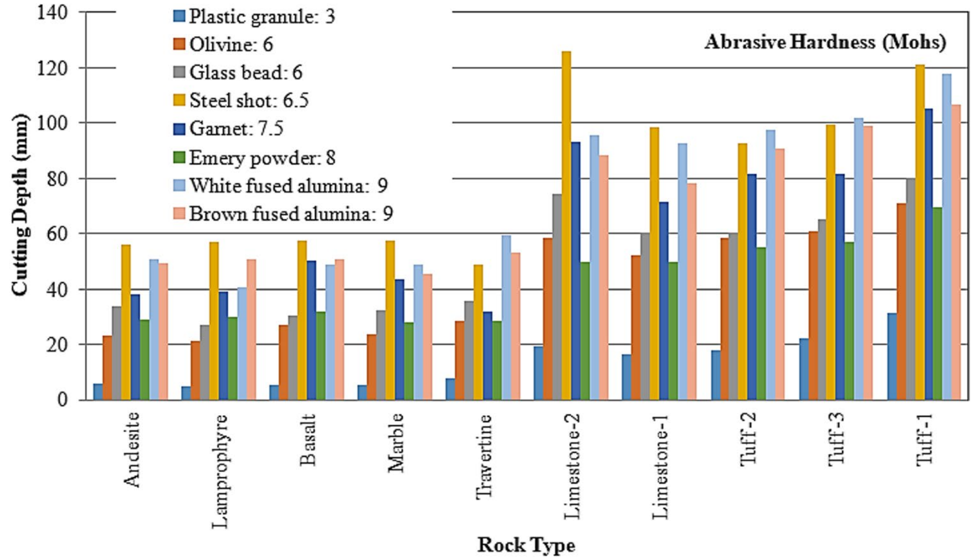

Fig. 10 Effect of abrasive hardness on the cutting depth

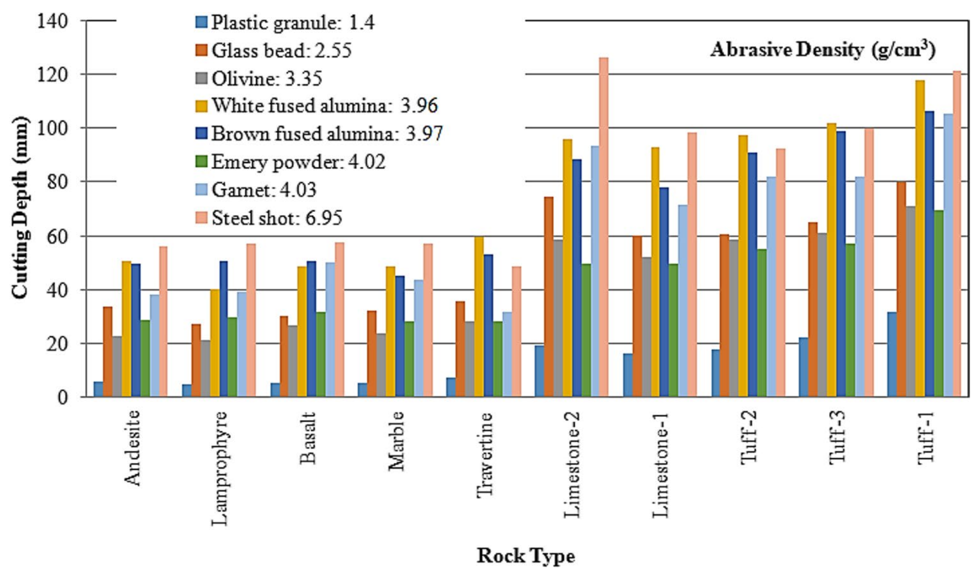

Fig. 11 Effect of abrasive density on the cutting depth

depth for various abrasives are depicted in Fig. 10. As can be seen, the highest cutting depths were obtained for the limestones and tuffs. Table 10 demonstrates the correlations between the cutting depth and some physical properties of the rocks. It can be stated that more material by weight must be removed from the workpiece with a higher unit volume weight to achieve the same cutting depths when compared to workpieces with a lower unit volume weight. As a result, as reported by previous studies [2, 3], lower cutting depths were produced on workpieces with higher unit volume weights (in the current study, r: 0.71–0.88 by abrasive type). On the other hand, the cutting depths tend to increase with increasing water absorption capacity (r: 0.73–0.90 by abrasive type) and effective porosity (r: 0.76–0.91 by

Table 8 Correlations between the cutting depths and some abrasive properties (hardness and density) by rock type

	Andesite	Lamprophyre	Basalt	Marble	Travertine	Limestone-2	Limestone-1	Tuff-2	Tuff-3	Tuff-1
Hardness	0.76	0.73	0.78	0.73	0.81	0.59	0.72	0.82	0.81	0.76
Density	0.80	0.87	0.83	0.84	0.63	0.84	0.81	0.74	0.75	0.78

Table 9 Summary of the physicomechanical properties of the rocks

Rock type/rock property	Limestone-1	Limestone-2	Travertine	Marble	Tuff-1	Tuff-2	Tuff-3	Lamprophyre	Basalt	Andesite
Uniaxial compressive strength (MPa)	48.93	52.39	70.09	65.49	41.85	56.24	52.60	93.71	106.69	67.81
Brazilian tensile strength (MPa)	4.57	6.59	7.28	7.07	4.58	3.85	5.85	9.77	9.58	5.29
Point load strength (MPa)	3.19	3.50	5.45	4.47	2.54	3.71	3.49	7.84	7.66	4.49
Digital Schmidt rebound hardness	61.70	64.70	76.80	74.30	59.70	70.60	54.70	78.10	77.90	75.60
Ultrasonic sound value (m/s)	4291	4379	5166	5825	2677	2360	3500	4971	4322	3504
Water content (%)	0.19	0.07	0.42	0.06	4.67	0.50	3.44	1.33	0.81	1.64
Water absorption capacity (by weight) (%)	3.22	4.31	0.95	0.11	12.71	7.61	6.60	2.30	2.06	3.64
The degree of saturation (%)	5.91	1.47	49.26	50.00	36.74	6.55	52.12	58.52	39.36	45.10
Unit volume weight (air-dry) (g/cm^3)	2.32	2.30	2.44	2.64	1.73	1.99	2.13	2.54	2.53	2.26
Mineral grain density (g/cm^3)	2.50	2.55	2.49	2.64	2.09	2.33	2.39	2.66	2.65	2.42
Effective porosity (%)	7.45	9.90	2.30	0.29	20.97	15.05	13.61	5.75	5.17	8.09
Bohme abrasion loss (cm^3/50cm^2)	24.57	25.30	15.20	14.24	26.15	24.05	28.06	9.15	9.72	13.92

abrasive type). The jet will move faster in the pores (where there is no material to be abraded and removed) than in the solid part of the workpiece. As a consequence, the cutting depth is expected to increase with increasing porosity. Agus et al. (1993) noticed that the specific cutting energy decreases as porosity increases [7]. Similarly, Engin (2012) observed that the cutting depth increases with increasing porosity [3]. Water absorption capacity is closely related to porosity as previously revealed by Unal and Altinok (2019) [36]. A high water adsorption capacity rock may have more fractures, porosity, cleavages, weak bonding material, and boundaries than a low water adsorption capacity rock [2, 10]. Accordingly, the relationship between cutting depth, water absorption capacity, and effective porosity is quite similar. Additionally, because ultrasonic waves travel faster through solid than air and liquid, the velocity of ultrasonic waves increases as rock cavities such as fractures, cracks, and pores decrease [15, 37]. Consequently, as the ultrasonic wave velocity increases, so does the cutting depth. However, in the current study, as compared to other physical properties of the rocks, the correlations between cutting depth and ultrasonic wave velocity were obtained at lower values (r: 0.55–0.74 by abrasive type).

Table 11 indicates the relationships between the cutting depth and some mechanical properties of the rocks. Cutting with AWJ is the process of removing material from a workpiece by jet machining it. As a result of this, rocks with high wear loss (less resistant to wear) are expected to perform a more effective cutting process, resulting in higher cutting depths. Engin (2012) found that as the Bohme wear loss increases, so does the cutting depth [3]. In addition, Engin et al. (2013) revealed that the specific energy decreases as the wear loss of the rocks increases [38]. Therefore, the cutting depth can be expected to increase as the specific energy decrease (which means that the jet travels more per unit of time while cutting through the workpiece). Accordingly, higher cutting depths were obtained in the current study for rocks with higher Bohme wear loss (r: 0.87–0.96 by abrasive type). As known, the workpiece begins to cut when the force applied to its surface by the jet (water-abrasive mixture) exceeds the rock's uniaxial compressive strength [3]. Agus et al. (1993) discovered that the specific energy increases as the uniaxial compressive strength increases [7]. Therefore, it can be stated that the cutting depth would decrease as the rock strength increased. Accordingly, in the current study, higher cutting depths were obtained for rocks with lower uniaxial compressive strengths (r: 0.69–0.83 by abrasive type). Similar findings were presented by some researchers [8, 10, 11]. Since point load strength is already used in practice to estimate uniaxial compressive strength, a similar relationship was observed between cutting depth and point load strength (r: 0.71–0.83 by abrasive type). Moreover, the cutting depth tends to decrease as the Brazilian tensile strength increases.

Table 10 Correlations between the cutting depths and some physical properties of the rocks by abrasive type

Rock property	Garnet	White fused alumina	Brown fused alumina	Olivine	Glass bead	Emery powder	Steel shot	Plastic granule
Unit volume weight (air-dry) (g/cm^3)	−0.79	−0.85	−0.86	−0.83	−0.80	−0.88	−0.71	−0.88
Effective porosity (%)	0.85	0.83	0.89	0.85	0.81	0.91	0.76	0.89
Water absorption capacity (by weight) (%)	0.83	0.82	0.86	0.83	0.79	0.90	0.73	0.90
Ultrasonic sound velocity (m/s)	−0.66	−0.68	−0.72	−0.68	−0.62	−0.74	−0.55	−0.68

Table 11 Correlations between the cutting depths and some mechanical properties of the rocks by abrasive type

Rock property	Garnet	White fused alumina	Brown fused alumina	Olivine	Glass bead	Emery powder	Steel shot	Plastic granule
Uniaxial compressive strength (MPa)	−0.69	−0.83	−0.75	−0.78	−0.82	−0.74	−0.74	−0.78
Point load strength (MPa)	−0.71	−0.83	−0.74	−0.78	−0.82	−0.74	−0.74	−0.77
Brazilian tensile strength (MPa)	−0.58	−0.74	−0.65	−0.68	−0.68	−0.66	−0.57	−0.65
Digital Schmidt rebound hardness	−0.83	−0.89	−0.88	−0.88	−0.87	−0.87	−0.85	−0.88
Bohme abrasion loss (cm^3/50 cm^2)	0.87	0.96	0.93	0.95	0.95	0.90	0.89	0.90

Nevertheless, when compared to other mechanical properties of the rocks, the correlations between cutting depth and Brazilian tensile strength are not relatively strong (*r*: 0.57–0.74 by abrasive type). Almost no research has been conducted to investigate the relationship between cutting depth and Brazilian tensile strength. Solely, Engin (2006) found that the cutting depth decreases exponentially as the Brazilian tensile strength increases, but with a moderate coefficient of determination (R^2: 0.5367) [10]. As demonstrated in the current study, Brazilian tensile strength has less of an effect on cutting depth than other mechanical properties of the rocks.

4 Conclusions and recommendations

The study's findings can be summarized as follows:

1. Steel shot (cutting depth: 48.78–125.94 mm by the rock type) and fused alumina (brown and white) (40.40–117.80 mm) were found to be viable alternatives to garnet (31.73–105.23 mm) for achieving higher cutting depths. It was seen that effective cutting could also be achieved with glass beads (27.18–80.00 mm), olivine (21.11–71.05 mm), and emery powder (28.08–69.33 mm), but at much lower cutting depths. It was revealed that plastic granule (5.00–31.53 mm) is not suitable for applications requiring high cutting depths.
2. The study demonstrated that abrasive performance is strongly related to abrasive density and hardness. It was determined that as the density and hardness of the abrasive increase, so does the cutting depth (*r*: 0.63–0.87 and 0.59–0.82 by rock type, respectively).
3. Bohme abrasion loss was found to be the most effective rock property on cutting depth (*r*: 0.87–0.96 by abrasive type), followed by hardness (Schmidt) (*r*: 0.83–0.89), effective porosity (*r*: 0.76–0.91), water absorption capacity (*r*: 0.73–0.90), unit volume weight (*r*: 0.71–0.88), and compressive strengths (uniaxial and point load) (*r*: 0.69–0.83). Brazilian tensile strength and ultrasonic sound velocity were found to have a lower impact on cutting depth (*r*: 0.57–0.74 and 0.55–0.74, respectively).
4. It was revealed that the cutting depth increases with increasing Bohme abrasion loss, effective porosity, and water absorption capacity. It is also observed that it decreases as the strength (uniaxial and point load), hardness (Schmidt), unit volume weight, and ultrasonic wave velocity increase.

The following topics could be considered for further research:

1. The cutting performance of the abrasives can be analyzed for different levels of the cutting parameters and other performance outputs (cutting width, kerf angle, etc.).
2. The effects of abrasive properties on the lifetime of the focusing tube could also be investigated.

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Declarations

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Consent for publication The authors declare that all authors agree to sign the transfer of copyright for the publisher to publish this article upon acceptance.

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