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AN EXPERIMENTAL INVESTIGATION ON ROCK CRUSHABILITY USING JAW AND CONE CRUSHERS

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ABSTRACT

This study covers the investigation of rock crushability using laboratory-scale cone and jaw crushers for five types of hardrocks. For this purpose, physico-mechanical properties of the investigated rocks are determined. Aggregate samples with a particle size range of 10.00 – 14.00 mm are prepared for crushability tests. After performing crushability tests, crushed particles are sieved and considering sieve analysis results, crushability indices are identified for each rock and crusher type. The performance of the crushers concerning their experimental setup is investigated by Taggart method.

It is achieved from crushability tests that, the performance of the cone crusher is approximately two times better than the one of the jaw crusher for their experimental setups. The crushing time (T_c) seems to increase with increasing in rock strength properties. Furthermore, remarkable relationships are obtained between several rock properties and crushability test results. It can be claimed that crushability of rocks are dependent upon crusher type, setup of crushing process, rock strength as well as the mineral hardness. Considering these types of variables, higher achieving benefits of aggregate production could be satisfied at lower costs.

Keywords: Rock crushability, Aggregate, crushed rock, Primary crushers, Size reduction ratio.

INTRODUCTION

The crushing process is the first step of comminution after drilling and blasting operations in rock quarries. Obtaining desired product sizes after crushing processes has an important role on economic efficiency and sustainability of rock quarrying. In this context, gyratory, impactors (i.e. horizontal and vertical) jaw and cone crushers are mainly used for the primary, secondary and tertiary stages of crushing in terms of achieving different size fractions of the product (Terva et al. 2018).

Rock comminution in a jaw crusher evolves like a series of particle crushing events, namely the crushing action takes places between jaw plates and rock aggregates as well as by the inter-particle compression. The fragmentation mechanism in a cone crusher is almost similar to one in jaw crusher apart from several discrepancies. The crushing action in a cone crusher occurs following that the cone head rotates with an eccentric motion. As long as the cone head approaches the crushing chamber, the aggregates are compressed and broken down between cone head and concave chamber.

The crushability of rocks in jaw crusher is associated with rock strength properties such as uniaxial compressive strength (UCS, MPa), Brazilian tensile strength (BTS, MPa) as well as the brittleness index based on UCS and BTS (Kahraman et al. 2018).

Geological properties of rocks have remarkable effects on attrition typology in the crushing process (Heikkilä 1991). Zeng and Forsberg (1992) established remarkable relationships between product size and corresponding energy consumption during comminution processes by a jaw crusher and a rod mill. Bearman et al. (1997) concluded that tensile strength of rocks has a remarkable effect on the performance of cone crusher. Refahi et al. (2010) pointed out that the rock strength properties and aggregates with different shape properties (i.e. cubical and flaky aggregates) being fed could affect the quantity of desired product size in a jaw crusher. Lee and Evertsson (2011) stated that experimental setup of the crushing process is directly associated with particle size distribution (PSD) of the product. Researchers carried out crushing tests using a cone crusher with different experimental setups and they concluded that increasing in the close side setting (CSS) of cone crusher leads to reduce the size reduction. On the other hand, the variation in the eccentric speed of cone head could be linked to achieving different amounts of desired product size (Lee and Evertsson 2011). Köken et al. (2018) investigated the S_{20} brittleness index test in terms of the rock crushability and researchers proposed a classification system for the evaluation of rock crushability (Table 1). Referring to Table 1, the degree of rock crushability could be assessed by the brittleness index of B_3 and mechanical aggregate properties such as the S_{20} and Aggregate Impact Value (AIV).

Table 1. Evaluation of crushing resistance for rock materials (Köken et al. 2018).

S_{20} (%)	AIV (%)	B_3 (MPa ²)	Crushing Resistance
$\geq 66^*$	≥ 40	≤ 65	Extremely low
65.9 – 60	40 – 35	65 – 100	Very low
59.9 – 51.0	35 – 28	100 – 200	Low
50.9 – 41	28 – 22	200 – 430	Moderate
40.9 – 35	22 – 18	430 – 720	High
34.9 – 29.1	18 – 14	720 – 1200	Very high
≤ 29	≤ 14	≥ 1200	Extremely high

* The intervals of S_{20} values were originally adopted from Dahl et al. (2012), AIV: Aggregate impact value (See; BS 812-112 1990), B_3 : Brittleness index (i.e. $B_3 = (UCS \times BTS) / 2$), UCS: Uniaxial compressive strength (MPa), BTS: Brazilian tensile strength.

The quantification of rock crushability was investigated using laboratory-scale jaw crushers by several researchers (Kahraman and Toraman 2008, Toraman et al. 2010, Kahraman et al. 2018, Comakli and Cayirli 2018, Köken and Özarlan 2018). In the studies of Kahraman and Toraman (2008), Toraman et al. (2010) and Comakli and Cayirli (2018), the degree of rock crushability was quantified as a crushability index (CI, %) that was determined by sieve analysis of the crushed rock aggregate particles passing through various sieves (i.e. sieves with different square apertures). Similar to the studies given herein, Köken and Özarlan (2018) identified a new term, compressive crushing value (CCV) whose terminology has several modifications of the CI proposed by Kahraman et al. (2018).

The present study deals with an experimental investigation on rock crushability occurred in jaw and cone crushers. Five types of hardrocks were used in laboratory studies and their rock crushability degrees were investigated. Physical and mechanical properties of investigated rocks were determined. Rock aggregates with particle size range of 10.00 – 14.00 mm were prepared for crushability tests. For each crushability test, individual crushing times (T_c) were recorded. Detailed sieve analyses of crushed particles were carried out and particle size distributions (PSD) before and after crushing processes were established for each rock type. Several relationships were obtained between crushability test results and physico-mechanical properties of rocks. The crushing performance of crushers was also evaluated by Taggart Method.

MATERIAL AND METHODS

Five types of hardrocks with different lithologies were used in this study. Representative rock blocks were obtained from various rock quarries located in the Black Sea region. Physical and mechanical properties were determined in accordance with the suggested methods by the International Society of Rock Mechanics (ISRM 1981). Physical properties of the rocks consist of dry density (ρ_d , g/cm³) and apparent porosity (n_e , %) whereas mechanical properties of rocks determined are uniaxial compressive strength (UCS, MPa) and Brazilian tensile strength (BTS, MPa). Mineral hardness of the rocks was determined using a C-2 type Shore Scleroscope. Moreover, weathering grades of the rocks were determined by thin section observations.

In order to perform crushability tests, rock aggregates with a particle size range of 10.00 – 14.00 mm were prepared. For each crushability test, the amount of 500 ± 5 g aggregates were fed to jaw and cone crushers with a choke feeding method. The technical specifications of the crushers used in this study are listed in Table 2. After crushability tests, crushed particles were sieved and fragmentation patterns were established by detailed sieve analyses. Considering the experimental setups of crushers, the performance of crushers was explored by revealing the size reduction ratio (SRR) of each crushability test.

Table 2. Technical specifications of the crushers used in this study.

Property	Jaw crusher	Cone crusher
Nominal voltage (V)	380	380
Nominal power (kW)	1.5	3.0
Frequency (Hz)	50	50
Feeding gape (mm)	≤ 100	≤ 30
Outlet gap (adjustable, mm)	≤ 30	≤ 20
Feeding capacity (kg/h)	≤ 400	≤ 100
Eccentric speed (rpm)	–	1395
Jaw speed (rpm)	180	–
Power factor	0.85	0.90

LABORATORY STUDIES

The physical and mechanical properties of the investigated rocks were determined in accordance with the suggested methods by ISRM (1981). During the determination of physico-mechanical properties of rocks, each test was repeated at least five times and average values of parameters were declared the related rock property. The tests were performed under oven-dried conditions and the results are given in Table 3. Accordingly, UCS values of rocks vary from 75 to 188 MPa. Considering these values, the investigated rocks were identified hard and very hardrocks according to ISRM (1981). On the other hand, n_e of rocks varies from 0.3% to 1.8%. Consequently, they have a low and very low porosity regarding the porosity classification by Matula (1981).

The weathering degree (W_d) of rocks was investigated by thin section observations. For each rock type, thin sections were prepared and they were analyzed under a polarized microscope. Thin section observations showed that, W_d of rocks was found to be between unweathered (W_0) to moderately weathered (W_2) types. Mineral hardness values of the rocks were determined using a C-2 type Shore Scleroscope.

A total of 40 measurements (i.e. 40 measurements in two equal parts for upper and lower surfaces of the core sample) were recorded for each Shore hardness test. The average value of the measurements was declared Shore hardness (SH), which was in the range of 38 and 87 for the investigated rocks.

Table 3. Physico-mechanical properties of the rocks

Rock type	Location	ρ_d (g/cm ³)	n_e (%)	UCS (MPa)	BTS (MPa)	SH	W_d
Limestone	Güdüllü / Zonguldak	2.62	0.45	94.30	10.90	38.8	W_0
Dacite	Yenice / Karabük	2.57	1.78	115.80	9.50	46.8	W_0 - W_1
Gabbro	Yenice / Karabük	2.88	0.17	188.30	20.25	86.7	W_0
Basalt	Işıkkara / Kütahya	2.74	0.88	143.66	15.47	76.2	W_0
Granite	Küre / Kastamonu	2.68	0.36	75.90	8.21	60.8	W_1 - W_2

ρ_d : Dry density, n_e : Apparent porosity, UCS : Uniaxial compressive strength, BTS: Brazilian tensile strength, SH: Shore hardness, W_d : Weathering degree, W_0 : Unweathered, W_1 : Slightly weathered, W_2 : Moderately weathered. (Note: Weathering classification was adopted from ISRM (1981).

CRUSHABILITY TESTS

Crushability tests are based on the fragmentation and comminution of aggregates after crushing action, namely the evaluation of crushed particles with specific size fractions. In this context, a total amount of 500 ± 5 g aggregates was fed to the crushers to quantify the degree of rock crushability. A choke feeding method was adopted, whereby aggregates were fed to crushers in a single charge by hand. Some of the crushability tests in jaw and cone crushers are illustrated in Fig 1 and Fig 2, respectively.

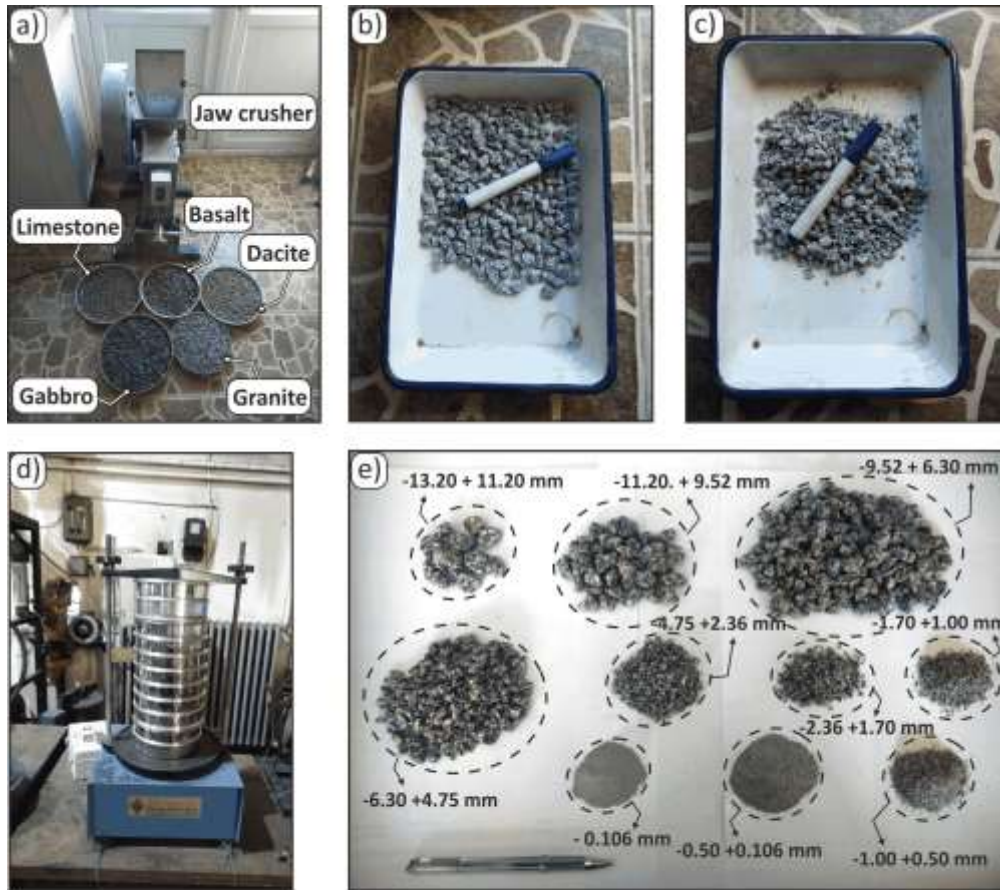
The implementation of crushability tests is simple. Aggregates were prepared with a particle size of 10.00 – 14.00 mm. A total amount of 500 ± 5 g aggregates was weighed and manually fed to the crushers in a single charge. Before crushability tests in the jaw crusher, open side setting (OSS) and closed side setting (CSS) were adjusted as to 12 mm and 8 mm, respectively. For the cone crusher, OSS and CSS were set to 18 mm and 8 mm, respectively. After performing crushability tests, crushed particles were obtained from the collecting vessel and sieved. The PSD of crushed particles were established for each test. Based on these PSDs, crushability indices were determined. Crushability index for cone (CI_c) and jaw crushers (CI_j) are determined by Equation 1 and Equation 2, respectively.

$$CI_c = \left(\frac{W_1}{W_0} \right) \times 100 \quad (1)$$

Where: W_1 is the weight of crushed particles passing through the 4.75 mm sieve (g) and W_0 is the initial weight (g) of feeding aggregates.

$$CI_j = \left(\frac{W_2}{W_0} \right) \times 100 \quad (2)$$

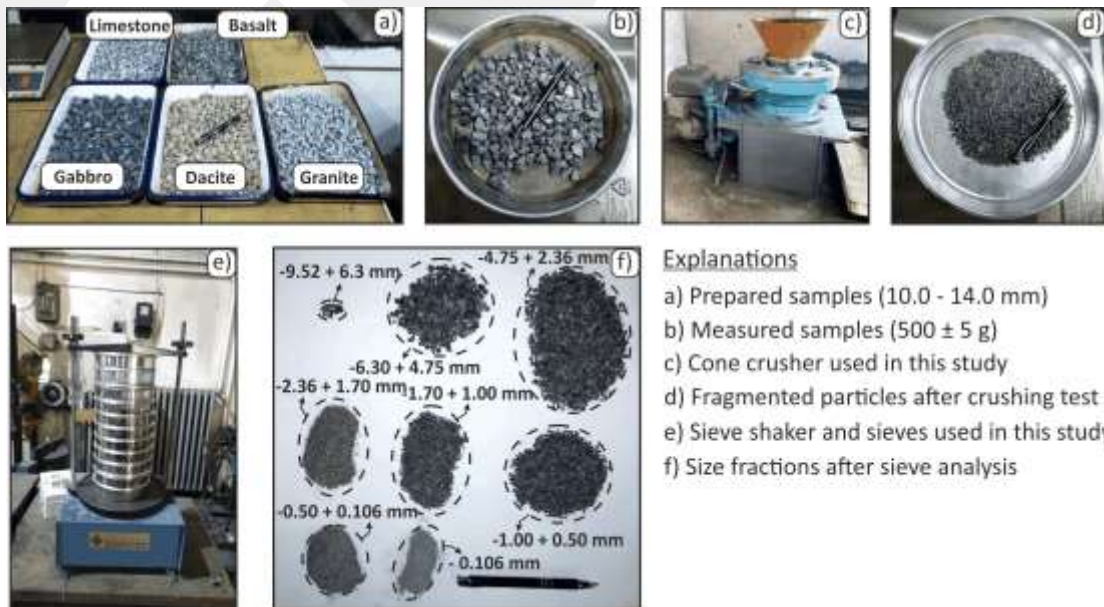
Where: W_2 is the weight of crushed particles passing through the 6.3 mm sieve (g) and W_0 is the initial weight (g) of feeding aggregates.



Explanations

- a) Jaw crusher used in this study and Prepared samples (10.0 - 14.0 mm)
- b) Measured samples (500 ± 5 g)
- c) Fragmented particles after crushing test
- d) Sieve shaker and sieves used in this study
- e) Size fractions after sieve analysis

Figure 1. Crushability testing procedure in jaw crusher.



Explanations

- a) Prepared samples (10.0 - 14.0 mm)
- b) Measured samples (500 ± 5 g)
- c) Cone crusher used in this study
- d) Fragmented particles after crushing test
- e) Sieve shaker and sieves used in this study
- f) Size fractions after sieve analysis

Figure 2. Crushability testing procedure in cone crusher.

Typical PSDs of crushed particles for each crushability test are given in Fig 3. It was shown that the most remarkable separation of crushed particles was observed beginning from the 4.75 mm and 6.3 mm sieves for cone and jaw crushers, respectively (Fig 3). Therefore, these specific size fractions were declared the reference sieve sizes in order to quantify crushability indices if only the present experimental setups were constituted. Furthermore, such PSDs were also adopted to evaluate the performance of crushers.

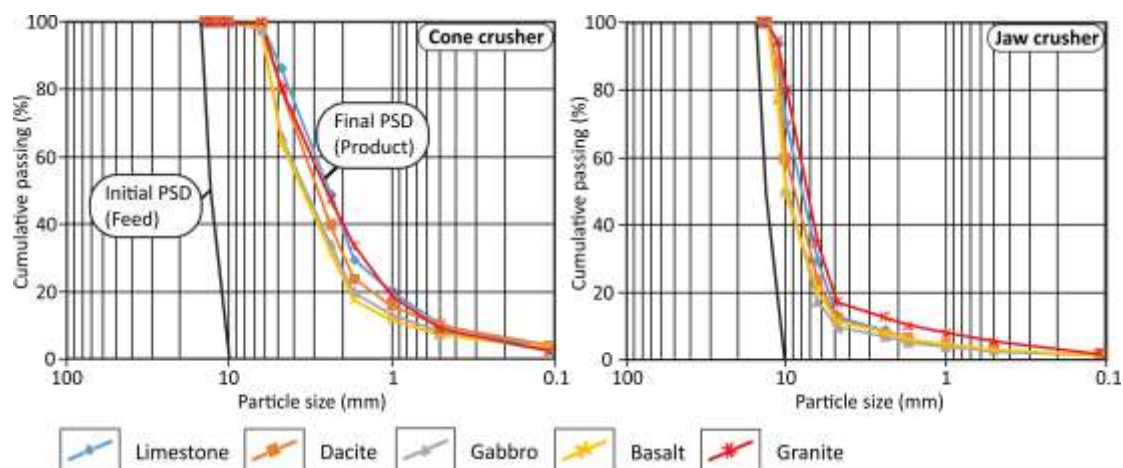


Figure 3. Typical degradation patterns of rock aggregates after crushability tests.

The crushability indices were determined using Equation 1 and Equation 2 for cone and jaw crushers, respectively. Crushability test results are listed in Table 4. Accordingly, CI_j and CI_c vary from 10 – 44 and 62 – 83 for jaw and cone crushers, respectively. Remarkable relationships were obtained between crushability indices and several rock properties. Consequently, BTS of rocks has a dominant role on the rock crushability in cone crusher whereas UCS of rocks becomes more influential for jaw crusher (Fig 4).

Table 4. Crushability test results.

Rock type	Location	Crushability index	
		Jaw Crusher CI_j (%)	Cone Crusher CI_c (%)
Limestone	Güdüllü / Zonguldak	35.96	76.84
Dacite	Yenice / Karabük	23.15	82.26
Gabbro	Yenice / Karabük	10.34	62.56
Basalt	Işıkkara / Kütahya	12.80	67.48
Granite	Küre / Kastamonu	43.84	79.31

The performance of the crushers concerning their experimental setups was investigated by revealing the size reduction ratio (SRR) of each crushability test. In practical minerals engineering approaches, the most common method to quantify the SRR of crushers is Taggart Method. Taggart Method deals with the feeding and product size fractions before and after crushability tests. The SRR is the ratio of the theoretical square mesh aperture that will cumulatively pass 80% of the feed (F_{80}) and 80% of the product (P_{80}) and it is determined by Equation 3.

$$SRR = \frac{F_{80}}{P_{80}} \quad (3)$$

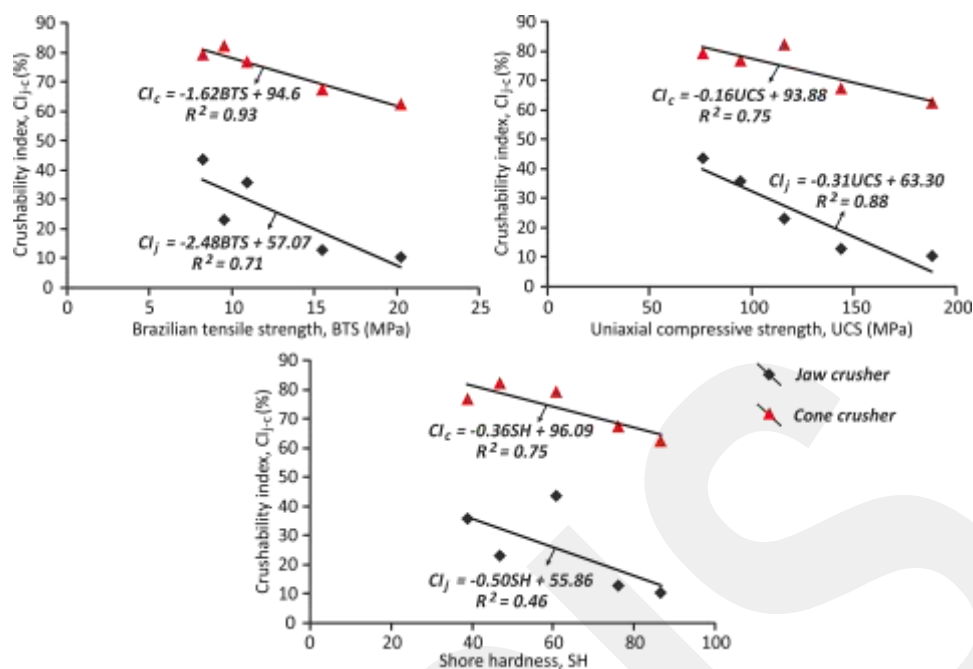


Figure 4. Remarkable relationships obtained in this study.

The performance of crushers with their experimental setup is listed in Table 5. According to Table 5, the performance of cone crusher is approximately two times better than the one of jaw crusher. The SRR values seem to decrease with increasing crushing time whereas they are changeable for jaw crusher. Combining the values given in Table 3 and 5, increasing in rock strength (i.e. UCS and BTS) seems to increase the crushing time during crushability tests.

Table 5. Performance of crushers concerning their experimental setups.

Rock type	Location	Cone crusher				Jaw crusher			
		F ₈₀ (mm)	P ₈₀ (mm)	SRR	Crushing time (s)	F ₈₀ (mm)	P ₈₀ (mm)	SRR	Crushing time (s)
Limestone	Güdüllü / Zonguldak	13.40	4.22	3.17	14.50	13.10	10.46	1.25	7.90
Dacite	Yenice / Karabük	12.85	4.63	2.77	17.80	12.60	10.71	1.17	6.50
Gabbro	Yenice / Karabük	13.20	5.28	2.50	24.80	12.90	11.34	1.14	9.30
Basalt	Işıkkara / Kütahya	12.95	5.35	2.42	26.10	12.85	11.50	1.12	11.40
Granite	Küre / Kastamonu	13.25	4.65	2.85	14.60	12.50	9.87	1.27	7.60

The variation in SRR values due to rock properties is given in Fig 5. Accordingly, the SRR mainly deals with UCS for rock crushability in jaw crusher. This finding seems to comply with the close relationship between CI_j and UCS (Fig 4). On the other hand, SH values have much greater effects on the performance of the cone crusher in terms of the evaluation of rock comminution. Although CI_c is highly dependent upon BTS (Fig 4), the SRR seems to deal with SH of rocks (Fig 5). It should be noteworthy to state that the crushability index described for cone crusher (CI_c) could only reflect the crushing resistance of rocks whereas the evaluation of rock comminution event in cone crusher seem to be related to SH rather than BTS of rocks.

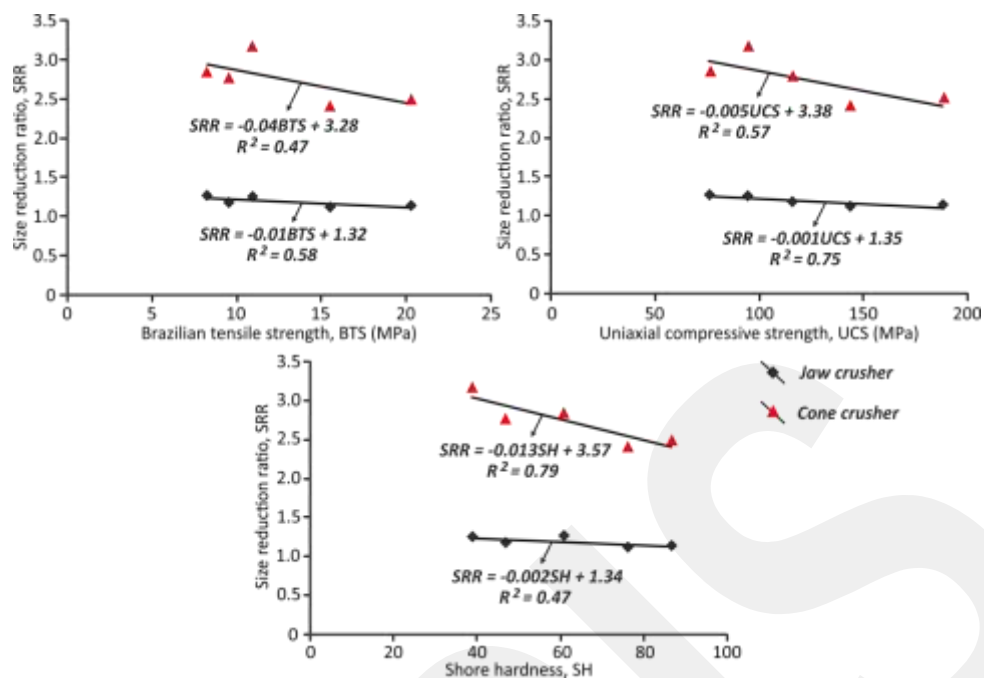


Figure 5. The variation in SRR due to several rock properties.

RESULTS AND DISCUSSION

BTS of rocks has a dominant role on rock crushing events in cone crusher. However, the evaluation of rock comminution process in cone crusher could have a conjunction with SH of rocks. On the other hand, rock crushability in jaw crusher could be evaluated by the variation in UCS values, which was previously stated by several researchers (Kahraman et al. 2018, Comakli and Cayirli 2018, Köken and Özarslan 2018).

In terms of product sizes, particles retained on the 6.3 mm sieve were mainly observed as elongated products for each rock type in cone crusher whereas ones passing through the 4.75 mm were almost cubical. For jaw crusher, products retained on the 6.3 mm were not identical in shapes (i.e. few pieces of products were elongated) but they were almost cubical. Products passing through the 6.3 mm sieve were identical and cubical in shape whereas the amount of flaky products retained on the 12.5 mm sieve occasionally increased for each rock type. In this context, no remarkable relationships were achieved between the quantity of flaky products and crushability indices.

The performances of the crushers with their experimental setups (Table 5) were interpreted considering the variation in SRR values. For the present study, the crushing performance of cone crusher seems to be much better than the one of jaw crusher (Fig 6).

Practically, higher values of SRR are desirable for crushing operations (Gupta and Yan 2016). However, they could not be always an economic option for such cases. Therefore, the optimization of crushing operations should be conducted considering both the variation SRR values and rock properties (i.e. UCS, BTS and SH). In addition, crusher type, the size of rocks/aggregates being crushed and the experimental setup of the crushing operation should also be explored in order to achieving optimum solutions for crushing energy consumption.

Crushing performance and energy consumption are two important variables for rock quarrying. In this context, crushability test results may give an indirect measure about energy consumption. Lower crushability indices could indicate higher energy consumption or vice versa.

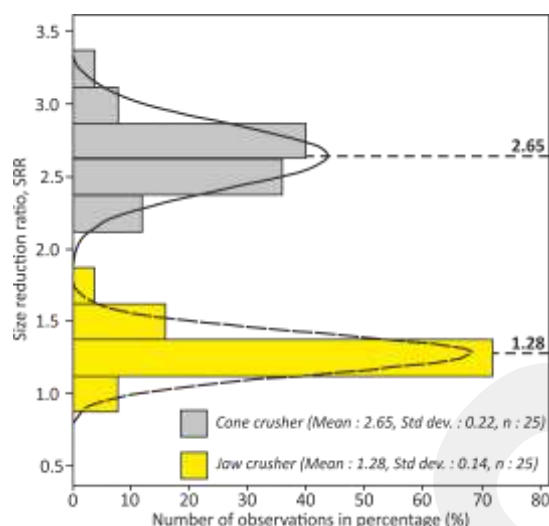


Figure 6. Variation in SRR obtained in this study.

It was observed during crushability tests that increasing in rock strength leads to increase the crushing time. This observation could be satisfactory on linking strength properties of rocks and corresponding energy consumption during their crushabilities. Following that, remarkable relationships were obtained between crushing time (T_c , sec) and several rock properties for cone crusher. However, they were not achieved for jaw crusher. Focusing on the empirical formulae given in Table 6, crushing time could be associated with UCS, BTS and SH of rocks for cone crusher. However, for jaw crusher, the relationships to clarify crushing time as a function of rock properties became less meaningful. The underlying reason of less correlation coefficients (i.e. $R^2 = 0.31 - 0.50$) for jaw crusher could be derived from the quantity of feeding aggregates or the quantity of rock samples (i.e. five types of rocks).

During crushability tests, limited quantity of aggregates (500 ± 5 g) were fed to the crushers and the crushing action were completed between 5 – 14 seconds in jaw crusher. On the other hand, it was between 12 – 30 seconds in cone crusher. Due to the difference in elapsed time throughout the crushing action, UCS, BTS and SH could be an independent variable for the evaluation of T_c in cone crusher. Satisfying continuous feeding methods by means of a belt conveyor could be beneficial for achieving remarkable relationships between T_c and several rock properties for jaw crushers.

Table 6. Relationships between crushing time between rock properties.

Cone crusher		Jaw crusher	
$T_c = 0.12UCS + 5.76$	$R^2 = 0.79$	$T_c = 0.02UCS + 5.58$	$R^2 = 0.31$
$T_c = 0.96BTS + 7.15$	$R^2 = 0.74$	$T_c = 0.26BTS + 5.19$	$R^2 = 0.47$
$T_c = 0.24SH + 5.00$	$R^2 = 0.71$	$T_c = 0.067SH + 4.38$	$R^2 = 0.50$

* The base unit for T_c and rock strength properties such as UCS and BTS is second and MPa, respectively. SH is unitless. It should be noted that recorded crushing times are only valid for the present crushers with their constituted setups.

It is clear that the performance of crushers will change with many factors such as rock strength, size of aggregates, experimental or industrial crushing setup, the quantity of feeding etc. This study could also be beneficial to reveal several effecting factors on rock crushability occurred in jaw and cone crushers to some extent. However, number of samples should be increased in order to achieve a compressive understanding about rock crushability occurred in different crusher types.

CONCLUSIONS

Crushability test results showed that the rock crushability is dependent upon rock strength, mineral hardness, crusher type as well as the experimental setup of the crushing process. Crushability indices could be described for specific crushing operations and they could be utilized as an independent variable to predict several rock properties as long as similar methodologies could be followed. Nevertheless, the number of rock samples should be increased and experimental variations should be explored in order to provide generalized relationships. Mechanical feeding methods should be attempted to investigate possible relations whether the degree of rock crushability is dependent upon the quantity of feed or not. It is also recommended that direct measurements of crushing energy consumption should be measured during crushability tests for further studies. Findings obtained from this study could be assessed in terms of higher achieving benefits of aggregate production at lower costs. However, experimental methodologies followed in this study should be attempted to a crushing – screening plant to observe difficulties and/or similarities of quantifying rock crushability.

REFERENCES

- Bearman R.A., Briggs C.A. and Kojovic T. (1997). The application of rock mechanics parameters to the prediction of comminution behavior, *Minerals. Eng.* 10(3): 255 – 264.
- BS 821-112 (1990) British Standard: Testing aggregates – Method for determination of aggregate impact value (AIV).
- Comakli R. and Cayirli S. (2018) A correlative study on textural properties and crushability of rocks, *Bull. Eng. Geol. Environ.* 1– 17.
- Dahl F., Bruland A., Jakobsen P.D., Nilsen B. and Grøv E. (2012). Classification of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method. *Tunnell. Undergr. Space Tech.* 28: 150-158.
- Gupta A. and Yan D. (2016) *Mineral Processing Design and Operations*, 2nd Edition, Elsevier.
- Heikkilä, P. (1991). Improving the quality of crushed rock aggregate. *Acta Polytech. Scand.* 96: 169.
- ISRM (1981) Suggested methods for rock characterization testing and monitoring. In: Brown, E.T. (Ed.) Pergamon Press, Oxford, pp. 211.
- Kahraman S. and Toraman, O.Y. (2008) Predicting Los Angeles abrasion loss of rock aggregates from crushability index. *Bull. Mater. Sci.*, 31(2): 173 – 177.
- Kahraman S., Toraman O.Y. and Cayirli S. (2018) Predicting the strength and brittleness of rocks from a crushability index. *Bull. Eng. Geol. Environ.* 77(4): 1639 – 1645.
- Köken E., Aydin H. and Özarslan A. (2018). Investigation of S_{20} brittleness index in terms of the crushability of rocks. *Scientific Mining Journal, Special Issue*, 73 – 83 (in Turkish).
- Köken E. and Özarslan A. (2018) New testing methodology for the quantification of rock crushability: Compressive crushing value (CCV), *Int. J. Minerals Metall. Mater.* 25(11): 1227 – 1236.
- Lee E and Evertsson C.M. (2011) A comparative study between cone crushers and theoretically optimal crushing sequences, *Miner. Eng.*, 24: 188 – 194.
- Matula M. (1981). Rock and soil description and classification for engineering geological mapping report by the IAEG Commission on Engineering Geological Mapping, *Symp. on Eng. Geol. Prob. of Const. on Soluble Rocks*, 24(1): 235 – 274.
- Refahi A., Mohandesi J.A. and Rezai B. (2010) Discrete element modeling for predicting breakage behavior and fracture energy of a single particle in a jaw crusher, *Int. J. Minerals. Proc.* 94: 83 – 91.
- Toraman O.Y., Kahraman, S. and Cayirli, S. (2010) Predicting the crushability of rocks from the impact strength index. *Minerals. Eng.* 23: 752 – 754.
- Terva J., Kuokkala V.T., Valtonen K. and Siitonen P. (2018). Effects of compression and sliding on the wear and energy consumption in mineral crushing, *Wear Vol: 398–399*, 116–126
- Zeng Y. and Forsberg E. (1992) Energy consumption in fine crushing and dry rod grinding, *Min. Metall. Explor.* 9(2): 69 – 72.