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ORIGINAL PAPER

The relationships among different abrasion tests on deteriorated and undeteriorated rocks

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Abstract

In ancient times, the most widely used rocks, especially in construction of roads and monuments, were sedimentary and magmatic rocks. Natural stones used in the buildings and historical monuments are subjected to atmospheric effects such as freeze-thaw, salt crystalisation and wetting and drying cycles which accelerates abrasion. Therefore, wear resistance of natural stone materials is important for selection of suitable materials in engineering projects. In order to investigate the effect of deterioration on abrasion properties of natural rock samples, three different abrasion tests (Böhme abrasion (BA), wide wheel abrasion (WWA) and aggregate impact value (AIV)) were applied to undeteriorated and artificially deteriorated (samples were subjected to accelerated weathering tests (AWT)) natural rock samples in this study. For the first time, the relationship between AIV-WWA and BA-AIV tests was experimentally investigated. Consequently, the relationships among BA-WWA, BA-AIV and AIV-WWA values were examined, the empirical formulas showing these relationships were developed and high correlations ($R^2 > 0.80$) were obtained. Finally, an abrasion class was proposed using classification of WWA for determining BA and AIV of natural rock samples in this study.

Keywords Böhme abrasion · Wide wheel abrasion · Aggregate impact value · Natural building stone · Deterioration · Relationship

Introduction

It is important to select the proper natural stone that will be used in civil engineering structures because of the abrasions created by vehicles on the roads, waves on breakwater, wind and water on outdoor flooring and pedestrians on sidewalks and stairs. While most of the building stones are used for flooring and decorative purposes, they are also widely used in the form of aggregate in the abrasion layer of roads. Natural stones are selected not only for their appearance but also for their abrasion resistance properties. As a result of deterioration due to abrasion, engineering problems may occur. In addition, the aesthetic properties such as the colour and brightness of the natural stones may change. On the other hand, due to the environmental conditions (such as freeze-thaw cycles and salt crystallisation), natural stones may deteriorate throughout the life of the civil engineering structures. Therefore, early determination of abrasion resistance of natural stones is of great importance.

Abrasion estimates are often made in the laboratory under accelerated conditions using idealised sample geometries (Sutton et al. 2014). With regard to stone materials, the most commonly used abrasion resistance test methods are specified in the European Standards (TS EN 14157 2004; TS EN 14157 2017) and in the American Standards (ASTM 2005). Although the standards used in determining abrasion resistance are mostly related to concrete building materials (concrete paving, kerbs, etc.), they are widely used for evaluation of abrasion resistance of building stones in recent years. Currently, EN 14157 Standard (TS EN 14157 2004) which was revised in 2017 is the national standard for many European countries. This new standard includes two test methods (wide wheel abrasion (WWA) and Böhme abrasion (BA) tests) to determine the abrasion resistance of building stones used in civil engineering structures. Although different apparatuses are used, stone sample was abraded with a rotating steel disc and normalised abrasive material in both tests. The most widely used method for determining the abrasion

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resistance is the Böhme abrasion (BA) which was developed in the 1950s. In recent years, wide wheel abrasion (WWA) test which takes less time than Böhme test and causes less environmental pollution is being widely used. In addition, Los Angeles (ASTM, C131/C131M-14 2006) and aggregate impact value (AIV) (BS 812-112 1990) tests are the most commonly used methods for the determination of abrasion resistance of aggregates.

In recent years, research was concentrated on marble, limestone and travertine rocks (Yavuz et al. 2005; Yavuz et al. 2008; Çobanoğlu and Çelik 2017; Özvan et al. 2018). Studies have also been conducted on rare examples of hard specimens such as granite (Sousa 2014; Sousa 2013; Yılmaz et al. 2017). Apart from these studies, the relationship between BA and WWA was also obtained (Çobanoğlu and Çelik 2017; Mac Gregor and Chiu 2000; Karaca et al. 2012). However, due to the lack of sufficient published material as emphasised in the relevant European Standard Annex (TS EN 14157 2004), potential correlations between these tests are needed on natural rock samples.

On the other hand, since the natural stones used in civil engineering structures are under environmental effects, it is also important to evaluate the abrasion resistance of deteriorated natural stones. The mineral content and the deterioration potential of minerals play an important role on abrasion wear resistance of natural stones. In addition, other most important factors that accelerate the abrasion process of natural rocks are environmental effects such as climate and loading conditions.

BA test is unpractical due to long testing time. Also, BA test has a negative impact on environmental pollution since too much abrasive powder is used in BA test when compared to WWA and AIV tests. In this experimental study, unlike the previous studies, the abrasion wear resistance tests were conducted on undeteriorated (original) and deteriorated natural rock samples with different structure and hardness values. For this purpose, three different abrasion tests (BA, WWA and AIV) (Fig. 1) were applied to undeteriorated natural rock samples and rock samples subjected to accelerated weathering tests (AWT) (freeze-thaw cycles and salt crystallisation). Two different types of samples (cube and aggregate) were tested and the abrasion resistance of these samples was presented for deteriorated and undeteriorated rock samples. These results were then used to obtain the empirical relationships among the BA, WWA and AIV tests. By using these relationships, practicing engineers may have the opportunity to conduct relatively easier tests such as WWA or AIV tests and obtain indirectly BA resistance values for natural rock samples.

Materials and methods

Thirteen different rocks with different chemical, mineralogical, structural and textural properties obtained from different regions of Turkey and Iran were used in this study. Thin sections of each rock sample were prepared to determine the mineralogical compositions of these samples (Table 1) and the rates of major oxides of these samples were determined by the XRF analysis (Table 1). Dry density, effective porosity and water absorption (by weight) values of cubic samples were determined by using ISRM-suggested method (ISRM 2007). In addition, longitudinal sonic velocity (V_p) and uniaxial compressive strength (UCS) values of the samples were determined according to ISRM methods (ISRM 2007; ISRM 2015).

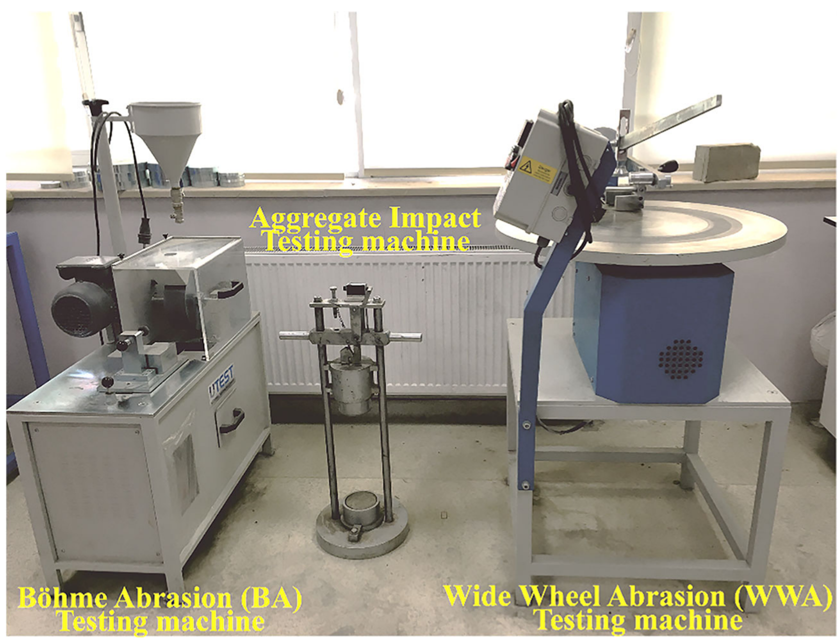
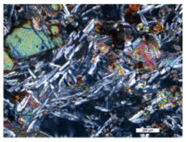
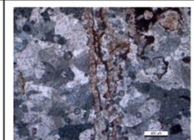
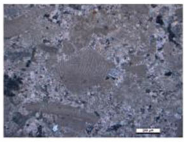
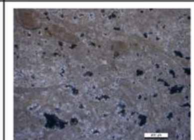
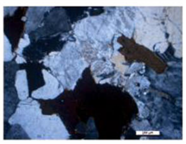
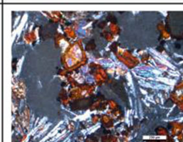
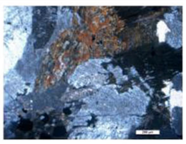
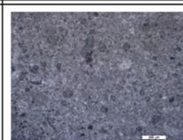
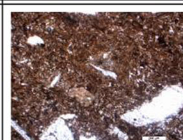
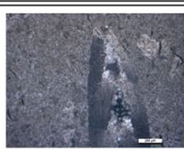
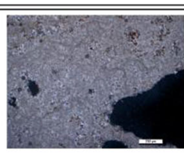


Fig. 1 An image of the devices used in the WWA, AIV and BA tests

Table 1 Mineralogical and major oxide properties of the samples that were used in the study

Rock Name	Micrograph of the rock	Petrographic description	Main major oxides	Rock Name	Micrograph of the rock	Petrographic description	Main major oxides
(1) BASALT		Holo/hypo-crystalline porphyritic texture with ophitic plagioclase and clinopyroxene.Olivine is rare and gnawed.	SiO_2: *42.14%* Al_2O_3: *18.63%* Fe_2O_3: *10.25%* MgO: *5.24%* CaO: *11.82%* Na_2O: *3.82%* K_2O: *1.10%*	*(13) TRAVERTINE*		Slightly equidimensional and subhedral calcite crystals with abundant vesicles and rare silicate mineral set in a microcrystalline carbonate matrix.	SiO_2: *0.03%* Al_2O_3: *-%* Fe_2O_3: *0.79%* MgO: *0.33%* CaO: *55.41%* Na_2O: *-%* K_2O: *-%*
(2) CALCARANITE		Abundant foraminifera fossils and more than 50 percent, of detrital sand-size (0.0625 to 2 mm in diameter), carbonate grains.	SiO_2: *1.77%* Al_2O_3: *0.52%* Fe_2O_3: *0.56%* MgO: *0.86%* CaO: *53.41%* Na_2O: *0.13%* K_2O: *0.06%*	*(14) LIMESTONE*		Microcrystalline calcite ooze is cut by veins of coarse calcite ± dolomite fillings.	SiO_2: *0.23%* Al_2O_3: *0.07%* Fe_2O_3: *0.07%* MgO: *0.52%* CaO: *54.71%* Na_2O: *-%* K_2O: *0.01%*
(4) GRANITE		Holocrystalline-granüler granit with primary assamblage of plagioclase, alkalli feldspat, biotite, amphibole and Fe-Ti oxides. Amphibole and mica are occasionally altered into cholorite and opaque aggregates.	SiO_2: *71.18%* Al_2O_3: *13.34%* Fe_2O_3: *3.37%* MgO: *0.55%* CaO: *1.51%* Na_2O: *2.82%* K_2O: *5.80%*	*(15) BASALT*		Plagioclase, olivine, pyroxene, augite. Weakly weathered olivines in the sound aphanitic basalt. A strongly or completely weathered olivine forming reddish-brown iddingsite and green nontronite in the weathered vesicular basalt.	SiO_2: *46.63%* Al_2O_3: *17.42%* Fe_2O_3: *12.95%* MgO: *4.47%* CaO: *9.35%* Na_2O: *3.51%* K_2O: *1.57%*
(5) GRANITE		Holocrystalline-granüler granit with primary assamblage of plagioclase, alkalli feldspat, biotite, amphibole and Fe-Ti oxides. Amphibole and mica are occasionally altered into cholorite and opaque aggregates.	SiO_2: *60.95%* Al_2O_3: *17.43%* Fe_2O_3: *3.06%* MgO: *1.45%* CaO: *4.67%* Na_2O: *4.02%* K_2O: *6.27%*	*(24) LIMESTONE*		There is calcite and clay	SiO_2: *0.44%* Al_2O_3: *0.14%* Fe_2O_3: *0.04%* MgO: *0.31%* CaO: *54.69%* Na_2O: *0.03%* K_2O: *-%*
(6) LIMESTONE		There are calcite and fossil fragments	SiO_2: *1.22%* Al_2O_3: *0.38%* Fe_2O_3: *0.14%* MgO: *2.96%* CaO: *51.70%* Na_2O: *0.03%* K_2O: *0.05%*	*(25) IGNIMBRITE*		Hypocrystalline-porphyritic texture with phenocrysts of feldspar, pyroxene, biotite and quartz set in microcrystalline volcanic matrix. Pumice and Rock fragments.	SiO_2: *66.43%* Al_2O_3: *14.19%* Fe_2O_3: *4.50%* MgO: *0.19%* CaO: *1.66%* Na_2O: *5.16%* K_2O: *5.31%*
(8) LIMESTONE		There are calcite and fossil	SiO_2: *1.02%* Al_2O_3: *0.25%* Fe_2O_3: *0.09%* MgO: *6.61%* CaO: *47.71%* Na_2O: *-%* K_2O: *0.03%*	*(26) IGNIMBRITE*		Hypocrystalline-porphyritic texture with phenocrysts of feldspar, pyroxene, biotite and quartz set in microcrystalline volcanic matrix. Pumice and Rock fragments.	SiO_2: *66.76%* Al_2O_3: *14.16%* Fe_2O_3: *4.71%* MgO: *0.15%* CaO: *1.61%* Na_2O: *5.31%* K_2O: *5.36%*
(12) TRAVERTINE		There is calcite	SiO_2: *0.05%* Al_2O_3: *0.02%* Fe_2O_3: *0.06%* MgO: *0.17%* CaO: *55.96%* Na_2O: *-%* K_2O: *-%*				

From each rock type, 23 cube specimens (70 × 70 × 70 mm^3 ± 1.5 mm) for BA and WWA test (EN 1926 2006) and 10–14-mm size aggregates for AIV test (BS 812-112 1990) were prepared (Fig. 2). In the selection of samples, cracked and altered specimens were not used. Five-cube specimens were used to evaluate the physical and mechanical properties of each rock sample. For BA and WWA abrasion tests, 9 samples (3 original, 3 samples subjected to freeze-thaw cycles and 3 samples subjected to salt ($MgSO_4$) crystallisation cycles) were used. For determining abrasion properties (BA and WWA tests) of deteriorated rock samples, each cube specimen was subjected to 30 freeze-thaw cycles (TS EN 12371 2002)and 30 $MgSO_4$ cycles (RILEM 1980). The mechanical properties as well as the abrasion resistance of deteriorated and undeteriorated rock samples were then evaluated. For AIV test of deteriorated 10–14-mm size aggregates obtained from natural rock samples, 10 freeze-thaw cycles and 5 $MgSO_4$ cycles were performed. The freeze-thaw cycles were carried out by cooling to − 17.5 °C in water and then thawing in a water bath at about 20 °C. In $MgSO_4$ test, two test samples consisting of aggregates having a grain size between 10 and 14 mm were dipped 5 times in saturated magnesium sulphate solution in each cycle and dried at 110 ± 5 °C in drying oven (Fig. 3) (TS EN 1367-2 2010).

BA and WWA tests were performed according to TS EN 14157 (2017) and AIV test according to BS 812-112 (1990). The abrasion resistance of each sample was evaluated on each undeteriorated and deteriorated rock samples under accelerated weathering tests. Corundum abrasive (white fused

Fig. 2 An image of the samples used in the experiments

alumina) in accordance with standard FEPA 42 F 1984 was used in WWA tests. This abrasive was not used for more than three times. In addition, the Boulonez marble in the WWA test was used for calibration as indicated in the standard.

In BA test, the standard abrasive was used according to TS EN 14157. The loss in specimen volume after 16 cycles was determined as indicated in the relevant standard. The mean value of individual tests was taken as the BA resistance value for each rock sample (TS EN 14157 2017). In BA test, the sample was tested for 16 cycles with 20-g abrasive (corundum) under a constant load of 294 ± 3 N. In each cycle, the sample was rotated on the disc at 22 rpm with abrasive. After each cycle, the contact area was cleaned and the sample was rotated by 90° and the material loss was calculated as $cm^3/50\ cm^2$.

In AIV test, the impact strength of the aggregate was determined by the free fall of 13.6-kg platform on the sample from a distance of 38.1 cm (Eq. (1)).

$$\text{AIV}\ (\%) = \frac{\text{B}}{\text{A}} \times 100 \quad (1)$$

If A-(B + C) is larger than 1 then the experiment was repeated.

where:

A is the mass of the oven-dried test specimen in grams.

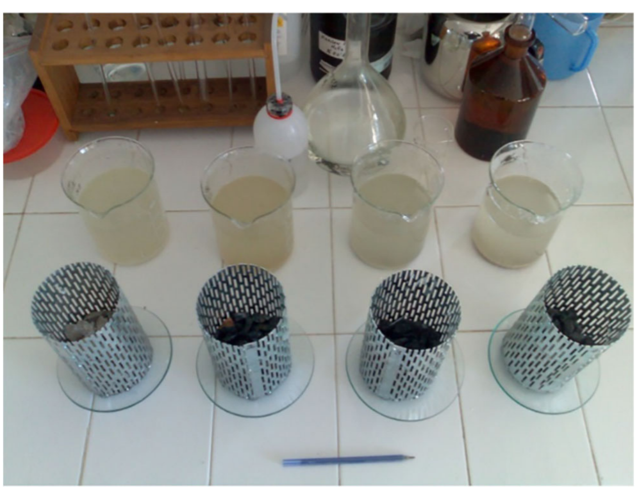


Fig. 3 An image of the salt crystallisation ($MgSO_4$) test on aggregates

B is the mass of the oven-dried material passing the 2.36-mm test sieve in grams.

C is the remaining amount of wear material (in gram).

The results were then statistically analysed by using analysis of variance (ANOVA), *R*-square and *P* value. In these analyses, the conventional 5% significance level has been adopted. Accordingly, a P value of ≤ 0.05 was accepted as statistically significant at a confidence level of 95%. The correlations between the dependent and independent variables were described as weak for $R^2 < 0.50$, medium for $0.50 \le R^2 < 0.70$, strong for $0.70 \le R^2 < 0.90$ and very strong for $R^2 \ge 0.90$.

Experimental results

Physical and mechanical properties of used rocks

Physical properties of the rocks were determined according to the EN 1936 (2006) standard. The apparent density of the rock samples was found to be between 1.33 and 3.07 g/cm^3. Basalt samples showed the highest apparent density, while the ignimbrites showed the lowest. The effective porosity of the samples ranged between 0.34 and 62.69%. The lowest porosity was determined in the calcarenite sample while the highest porosity was determined in ignimbrites. The uniaxial compressive strength values of the rock samples ranged between 11.65 and 150.68 MPa (the highest strength values were determined in granite and basalt samples, and the lowest strength values were determined in ignimbrites and clayey limestones) (Table 2).

The physical properties of undeteriorated (original) and deteriorated samples (subjected to accelerated weathering tests) were determined by using ultrasonic test which is one of the commonly used non-destructive test methods. Longitudinal wave velocity (V_p) values of the cube samples were measured before and after 30 freezing-thawing and salt crystallisation cycles, and the difference is calculated and given in Table 3. After freeze-thaw cycles, a slight decrease in V_p values was observed.

Table 2 Physical and mechanical properties of undeteriorated (original) samples

Samples	*N* (sample count)	Density (g cm^{-3})	Weight water absorption (%)	Effective porosity, *N* (%)	UCS σ_c (MPa) (before AWT)	Vp (m/s)
(1) Basalt	5	2.68	2.06	3.72	99.73	4932.80
(2) Calcarenite	5	2.73	0.19	0.34	106.59	5528.20
(4) Granite	5	2.24	2.75	5.35	97.53	4149.40
(5) Granite	5	2.58	0.61	1.11	150.68	4474.40
(6) Limestone (fossiliferous)	5	2.62	1.45	2.55	124.29	5329.60
(8) Limestone (fossiliferous)	5	2.69	2.69	4.81	88.66	6168.80
(12) Travertine (grey)	5	2.63	1.12	2.05	65.13	5540.20
(13) Travertine (red)	5	2.49	1.46	2.75	62.54	5238.40
(14) Travertine (beige)	5	2.66	1.27	2.30	99.01	5473.20
(15) Basalt (weathered)	5	3.07	1.33	2.28	131.85	5303.00
(24) Limestone (clayey)	5	2.02	9.71	20.28	11.70	3533.20
(25) Ignimbrite (red)	5	1.33	27.41	62.69	12.69	2196.80
(26) Ignimbrite (brown)	5	1.56	21.74	32.90	11.65	1884.80

Deterioration of cubic samples after salt crystallisation experiment using $MgSO_4$ salt was found to be more severe than freeze-thaw cycles (Akın and Özsan 2011; Özvan et al. 2011; Erdoğan and Özvan 2015, Özvan et al. 2015, Akın et al. 2017). Due to the amount of salt deposited in the sample pores after salt crystallisation, there was a significant increase in Vp value especially in ignimbrites having high porosity. After salt crystallisation test, some cracks were observed in the rock samples. The least affected rocks were basalt and the most affected rocks were ignimbrites and some travertines. In particular, due to severe cracks observed in ignimbrites, they cannot be used for further tests (Fig. 4). The longitudinal sonic wave velocity (V_p) after deterioration increased. This shows that the physical and mechanical properties of the rocks change as the samples deteriorate (Fig. 4).

Table 3 Velocity change percentages of V_p after freeze-thaw and salt crystallisation on cubic sample

Samples	Vp (%)	
	Freeze-thaw after 30 cycles	Magnesium sulphate after 30 cycles
(1) Basalt	98.38	101.92
(2) Calcarenite	98.92	98.11
(4) Granite	103.43	102.12
(5) Granite	93.4	96.8
(6) Limestone (fossiliferous)	87.73	94.14
(8) Limestone (fossiliferous)	94.34	102.93
(12) Travertine (grey)	88.29	77.68
(13) Travertine (red)	87.21	93.95
(14) Travertine (beige)	99.53	102.18
(15) Basalt (weathered)	96.97	98.75
(24) Limestone (clayey)	97.12	102.41
(25) Ignimbrite (red)	85.62	151.72
(26) Ignimbrite (brown)	85.47	139.13

Wide wheel and Böhme abrasion test results

The results of abrasion tests of undeteriorated rock samples ranged between 5.58 and 87.02 $cm^3/50\ cm^2$ for BA test and between 20.90 and 49.52 mm for WWA test. After the freeze-thaw test, the results of BA test ranged between 11.46 and 83.60 $cm^3/50\ cm^2$, while the results of WWA test ranged between 19.32 and 40.94 mm. In addition, after salt crystallisation test, the BA test results were between 11.12 and 78.11 $cm^3/50\ cm^2$, while WWA test results were between 20.66 and 42.70 mm (Table 4).

When data obtained from WWA and BA tests were examined, the effect of the abrasion after accelerated weathering tests (AWT) was more clearly observed in the BA test. After WWA test, the abrasion resistance of some of the deteriorated rock samples was found to be lower than undeteriorated rock samples (Fig. 5). In the WWA test, the contact area between the rotary disk and the test sample is important for the width of the abrasion surface. The width of the obtained groove grows as a function of time; the resistance to deterioration caused by the sample increases due to the ever-increasing contact area. This is because the groove in the WWA test wears off the rock on a particular line, not on its entire surface resulting in higher or lower abrasion resistance values (Fig. 6). This condition may occur especially in deteriorated rocks, fossil rock and rocks that include pores or fissures. Therefore, WWA method has some serious drawbacks in practical applications.

Fig. 4 Deterioration image of the sample number 25 after 30 salt crystallisation cycles (**a**) and V_p % change graph after the deterioration of all samples (**b**)

Table 4 Average results of BA and WWA tests conducted on different types of rock samples

AWT	Sample name	Böhme abrasion (cm^3/50 cm^2)	Wide wheel abrasion (mm)
Undeteriorated	(1) Basalt	12.50	21.46
	(2) Calcarenite	11.96	22.94
	(4) Granite	5.58	21.85
	(5) Granite	8.94	20.90
	(6) Limestone (fossiliferous)	18.57	23.36
	(8) Limestone (fossiliferous)	25.87	28.46
	(12) Travertine (grey)	32.46	31.64
	(13) Travertine (red)	33.18	27.27
	(14) Travertine (beige)	14.60	22.04
	(15) Basalt (weathered)	10.97	20.89
	(24) Limestone (clayey)	65.67	48.00
	(25) Ignimbrite (red)	87.02	40.86
	(26) Ignimbrite (brown)	86.99	49.52
After freeze-thawing	(1) Basalt	14.19	22.57
	(2) Calcarenite	15.31	23.09
	(4) Granite	14.15	21.18
	(5) Granite	12.69	19.32
	(6) Limestone (fossiliferous)	20.94	23.28
	(8) Limestone (fossiliferous)	27.27	25.69
	(12) Travertine (grey)	33.29	28.04
	(13) Travertine (red)	35.00	28.17
	(14) Travertine (beige)	17.24	22.25
	(15) Basalt (weathered)	11.46	22.09
	(24) Limestone (clayey)	83.60	40.94
	(25) Ignimbrite (red)	Sample degraded	Sample degraded
	(26) Ignimbrite (brown)	Sample degraded	Sample degraded
After salt crystalisation	(1) Basalt	13.89	21.41
	(2) Calcarenite	15.48	20.91
	(4) Granite	14.21	22.01
	(5) Granite	11.12	20.73
	(6) Limestone (fossiliferous)	20.53	25.30
	(8) Limestone (fossiliferous)	28.90	25.28
	(12) Travertine (grey)	34.83	27.35
	(13) Travertine (red)	32.69	28.32
	(14) Travertine (beige)	15.01	22.46
	(15) Basalt (weathered)	11.59	20.66
	(24) Limestone (clayey)	78.11	42.70
	(25) Ignimbrite (red)	Sample degraded	Sample degraded
	(26) Ignimbrite (brown)	Sample degraded	Sample degraded

Aggregate impact value

AIV was first determined for undeteriorated aggregate samples, and after that, each type of aggregate was subjected to freezing-thawing (FT) and salt crystallisation (SC) tests in order to compare the change in properties of aggregates after accelerated weathering tests. As the aggregate sample size gets smaller, the aggregate degredation after accelerated weathering tests increases. The minimum and maximum percentage loss at the end of the AIV tests was determined to be between 19.70 and 59.10 (Table 5). In almost all cases, the deterioration after salt crystallisation test was found to be more detrimental (Fig. 6). Therefore, it was observed that as the deterioration effect increases, the abrasion resistance of aggregate samples decreased. When the difference between abrasion resistance of deteriorated and undeteriorated samples is compared, the difference was found to be higher for clayey limestones, ignimbrites and travertines because of their physical and chemical properties such as high porosity and mineral resistance. In addition, the least affected rock was found to be basalt. Since natural stones used as cut-stone veneer should have an AIV less than 30 as specified in CS3 (2013) standard, clayey limestone, travertines and ignimbrites are found to be not suitable for use as cut-stone veneer in building constructions (Fig. 6).

Discussion of the results

It is well known that BA test is expensive, long lasting and has a negative impact on environmental pollution due to use of more abrasion material when compared to other abrasion tests.

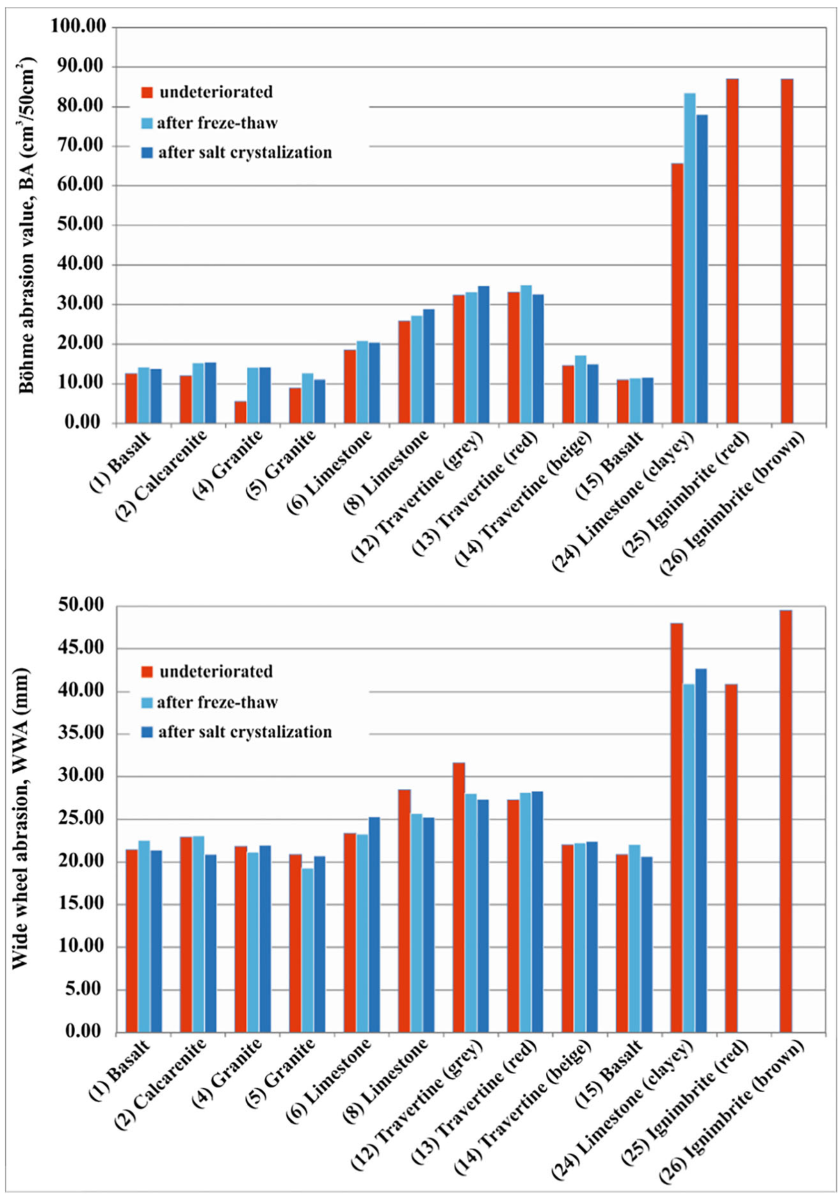
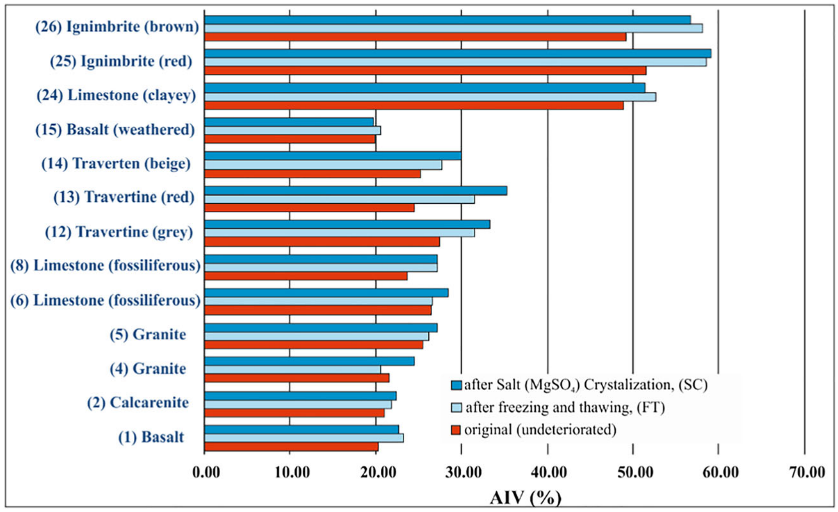


Fig. 5 BA and WWA values for undeteriorated and deteriorated rock samples

Fig. 6 Bar diagram of AIV aggregates before and after AWT tests



Therefore, it is important to develop an empirical equation that will provide the BA resistance of natural rock samples using the results of an easier test such as the WWA. TS EN 14157 proposed an equation (Eq. (2)) which shows the relationship between two commonly used abrasion resistance tests (BA and WWA).

$$\text{WWA (in mm)} = 15.3 + 1.7\text{BA}\left(\text{in mm}^3\right) \quad R2 = 0.84 \tag{2}$$

The authors of this manuscript have noticed an error in this equation. In parallel with this finding, this equation was removed from the standard revised in 2017. Since no new equation was included in this standard, this study proposes new empirical equations between BA-WWA, BA-AIV and AIV-WWA using the results of this detailed study.

Table 5 AIV on aggregates before and after accelerated weathering tests (AWT)

Aggregate impact value (%)			
Samples	Before AWT	After FT	After SC
(1) Basalt	20.30	23.20	22.70
(2) Calcarenite	20.90	21.80	22.40
(4) Granite	21.50	20.50	24.50
(5) Granite	25.40	26.10	27.10
(6) Limestone (fossiliferous)	26.40	26.50	28.40
(8) Limestone (fossiliferous)	23.60	27.10	27.10
(12) Travertine (grey)	27.40	31.50	33.30
(13) Travertine (red)	24.40	31.50	35.30
(14) Travertine (beige)	25.10	27.70	29.90
(15) Basalt (weathered)	19.90	20.60	19.70
(24) Limestone (clayey)	48.80	52.60	51.40
(25) Ignimbrite (red)	51.50	58.50	59.10
(26) Ignimbrite (brown)	49.10	58.10	56.70

The relationship between WWA and BA was also examined by Karaca et al. (2012) and Çobanoğlu and Çelik (2017). While Karaca et al. (2012) (Eq. (3)) examined 25 different rocks, including sedimentary, volcanic and metamorphic rocks, Çobanoğlu and Çelik (2017) (Eq. (4)) generally carried out tests on limestone and travertine. They used a total of 32 samples consisting of 4 magmatic, 1 metamorphic, 2 artificial building materials and 25 sedimentary rocks. Both researchers obtained the following well-correlated linear relationships between WWA and BA (Eqs. (3) and (4)).

$$\text{WWA (in mm)} = 14.828 + 0.2904\text{BA}\left(\text{in cm}^3\right) \quad R2 = 0.84, \tag{3}$$

$$\text{WWA (in mm)} = 16.684 + 0.1926\text{BA}\left(\text{in cm}^3\right) \quad R2 = 0.94, \tag{4}$$

In this study, when the data were tested at 95% confidence level ($P = 0.05$), the confidence interval was found to be the lowest for WWA test results. The standard deviation of the BA test results was found to be higher than WWA and AIV

Table 6 Statistical values of abrasion test results obtained in this study

		Bohme abrasion ($cm^3/50\ cm^2$)	Wide wheel abrasion (mm)	Aggregate impact value (%)
Max		87.02	49.52	59.10
Min		5.58	19.32	19.70
Mean		27.88	26.65	31.99
Standard deviation		23.42	8.01	12.86
P		0.05	0.05	0.05
N (sample size)		35	35	39
Reliability		7.76	2.65	4.04
Confidence intervals	max	35.64	29.31	36.03
	min	20.12	24.00	27.95

test results (Table 6). In BA test, since the entire surface of the sample is affected by the experiment, standard deviation values were found to be high due to the use of rocks with different hardness and textural properties.

It should be noted that, different from previous studies, the relationships among BA-WWA, AIV-WWA and BA-AIV were examined using exponential, linear, logarithmic, polynomial and power relationships. The empirical formulas derived using these analyses are shown in Figs. 7, 8 and 9.

The correlations between BA-WWA test results are found to be very strong ($R^2 > 0.90$) exponential relationships whereas the correlations between BA-AIV and AIV-WWA are found to be strong ($R^2 > 0.80$) exponential relationships (Eqs. (5)–(7)). These results indicate that the AIV can be used to predict BA and WWA abrasion resistance values. In this equation, WWA, BA and AIV are mm, $cm^3/50\ cm^2$ and %, respectively.

$$\mathrm{WWA} = 19.258e^{0.0104\mathrm{BA}} \quad R2 = 0.92 \tag{5}$$

$$\mathrm{A\,IV} = 20.144e^{0.0115\mathrm{BA}} \quad R2 = 0.86 \tag{6}$$

$$\mathrm{WWA} = 12.939e^{0.0237\mathrm{AIV}} \quad R2 = 0.83 \tag{7}$$

On the other hand, unlike previous studies, the exponential relationship between BA-WWA was analysed in this study. Although linear relations give higher R^2 value in rocks with different properties, it is seen that exponential relations contain more meaningful results when the measured and predicted values are compared. Additionally, the fact that the experiments were carried out on rocks of very different characteristics makes the empirical relationship obtained using the results of this study more reliable.

In most of the standards, abrasion values for building blocks are limited by Böhme values and there is no classification according to WWA. In the literature, classifications are intended to be developed for the abrasion resistance of rock materials based on WWA values. The classification proposed by Marradi et al. (2008) consists of three classes; low abradable rocks (WA < 16 mm), moderate abradable rocks (16 ≤ WA ≤ 21 mm) and abradable rocks (WA > 21 mm). However, the used data as well as the methodology to develop this classification are not clear. When the WWA results obtained from this study are examined according to this classification, all samples except granite and basalts can be classified as abrasive material (Table 7). Another classification using WWA and uniaxial compressive strength (UCS) values that was proposed by Çobanoğlu and Çelik (2017) is also consisted of three classes. In this classification, the average UCS (MPa) value for low abradable rocks, moderate abradable rocks and abradable rocks was proposed as 137 MPa, 100 MPa and 60 MPa, respectively. The UCS and

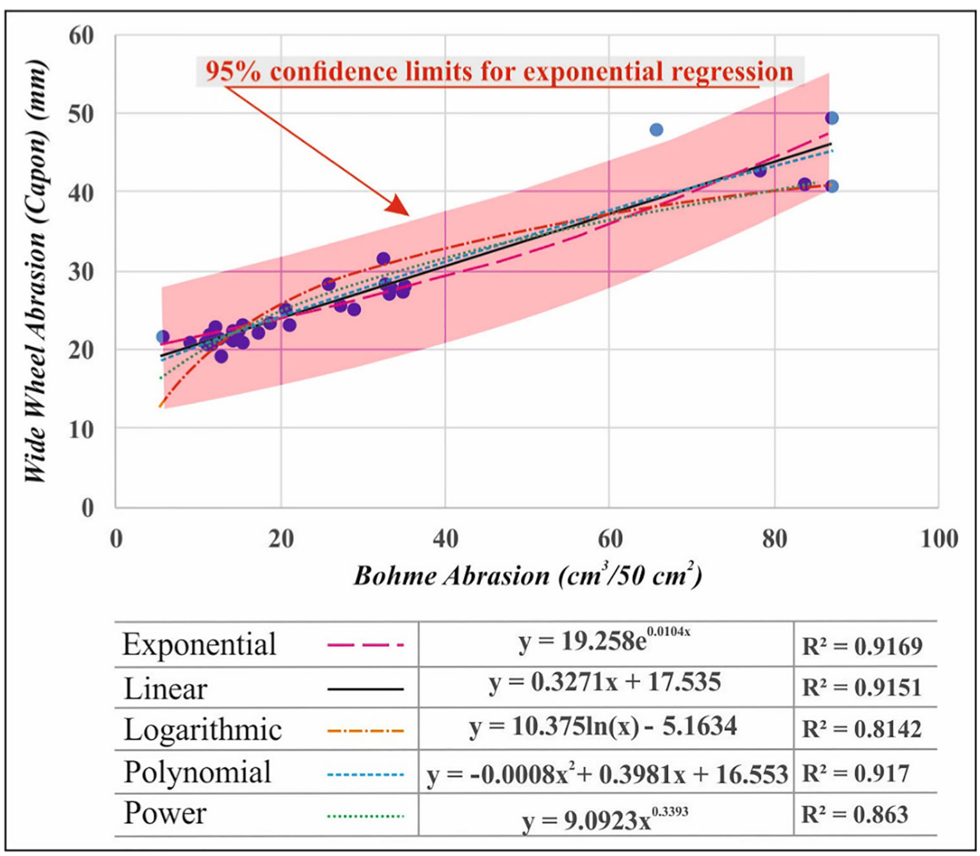


Fig. 7 Relationship between BA and WWA

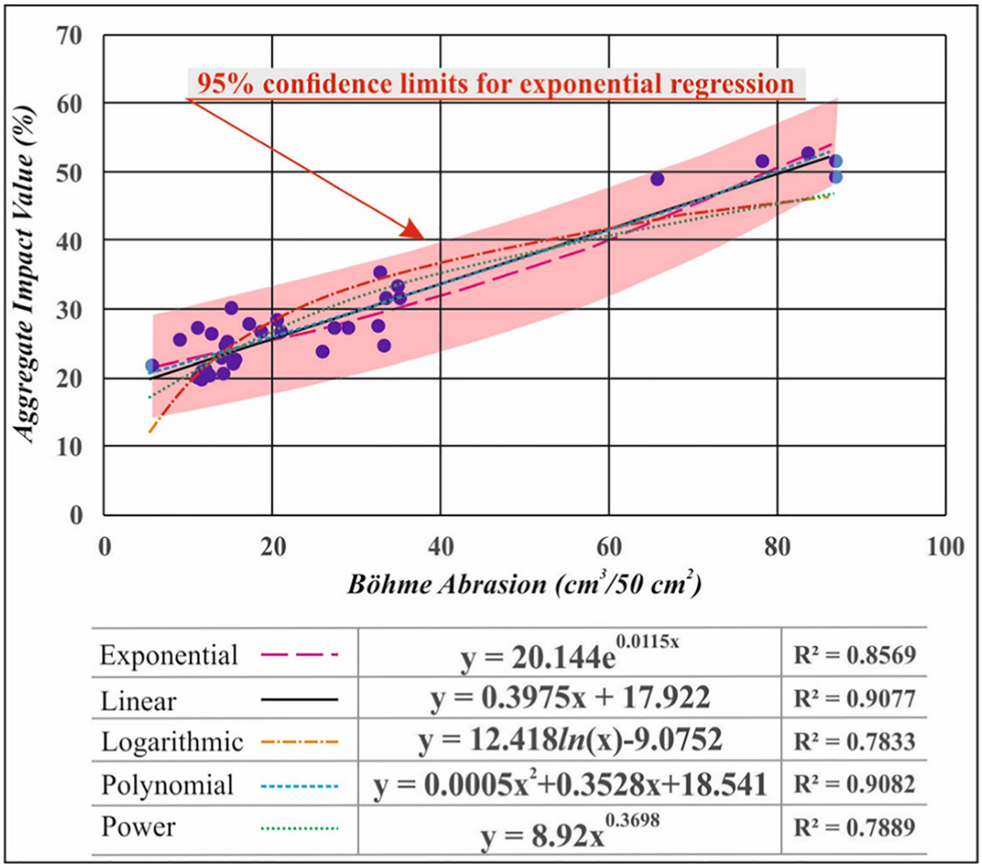


Fig. 8 Relationship between BA and AIV

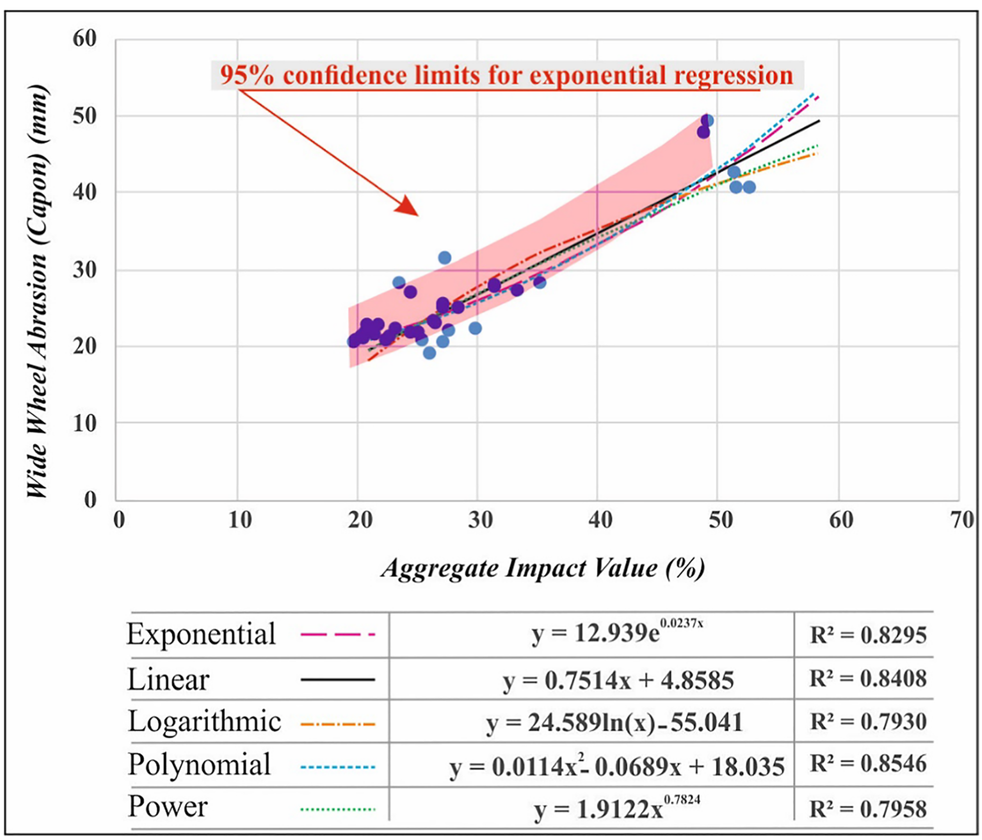


Fig. 9 Relationship between AIV and WWA

Table 7 Abrasion classes based on WWA values for tested rocks

WWA (mm) (from Maradi et al. (2008))	Abrasion class for WWA (mm) (from Maradi et al. (2008))	Average BA ($cm^3/50cm^2$)	Average AIV (%)
WWA < 16	Low abradable rocks	< 7	AIV < 17
16 < WWA < 21	Moderate abradable rocks	7 < BA>20	17 < AIV < 23
WWA > 21	High abradable rocks	BA > 20	AIV > 23

abrasion resistance test values obtained in this study are not in parallel with the ones obtained by Çobanoğlu and Çelik (2017). The disc used in WWA test results in vertical abrasion of a certain line particularly in rocks with heterogeneous structures such as travertine and fossiliferous limestones. Unless more experimental data set considering this condition is conducted to establish a relationship between UCS and WWA, the uniaxial compressive strength characteristics of the rocks should not be represented by the WWA test results.

The data of this study were reviewed and the classification interval for BA, and AIV in Table 7 was proposed for the first time, based on the intervals specified in CS standard (2013). However, it is recommended to support this interval with new studies since the classification range that was proposed by Maradi et al. (2008) is narrow.

Conclusion

The main purpose of this study is to determine the empirical relationships between the abrasion resistance tests of BA, WWA and AIV by conducting experimental tests on deteriorated and undeteriorated samples. The major conclusions that can be drawn from this study can be summarised as follows:

(1) When the abrasion resistance test results are examined, it is observed that the degree of abrasion is influenced by the internal structure of rock samples (cracks, gaps, etc.), as well as the hardness of the minerals contained in the rock (i.e. limestones with large fossils and porous travertines showed high abrasion values).

(2) The difference between abrasion resistance of deteriorated and undeteriorated samples was found to be higher for clayey limestones, ignimbrites and travertines because of their physical and chemical properties such as high porosity and mineral resistance. Therefore, it is suggested to do abrasion tests on deteriorated rock samples for sustainability.

(3) Due to the amount of salt deposited in the porous structure of the rocks, the abrasion resistance of the samples was lower when compared to the samples subjected to freezing-thawing cycles. Since ignimbrite samples were completely crumbled after both accelerated weathering tests, such rocks should never be used on walking paths.

(4) It is concluded that WWA method has some serious drawbacks in determining the abrasion wear resistance of heterogeneous rocks especially due to the fact that the groove in the WWA test wears off the rock on a particular line. This was clearly observed especially in rocks containing fossils or porosity in the texture.

(5) This study proposes new empirical equations between BA-WWA, WWA-AIV and AIV-BA using the results of this detailed study. The correlations between BA-WWA and AIV-BA test results are found to be very strong whereas the correlations between WWA-AIV are found to be strong. These results indicate that the AIV can be used to predict BA and WWA abrasion resistance values.

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