Assessment of the method for abrasion resistance determination of sandstones on Böhme abrasion test apparatus

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Abstract

The article analyses the method of testing the abrasion resistance of sandstones on Böhme abrasion test apparatus and describes the problems related to the implementation of this test, as well as the interpretation of the results. The tests were conducted in accordance with the requirements of the EN14157 standard on 14 samples of dry and water-saturated sandstones. The analysis of the results showed that the correlation coefficient for the results obtained in the case of dry samples tests in relation to water saturation was 0.944. It was also observed that the loss of volume during the abrasion process in the individual stages of the test is smaller with the increase of rotation on the disc. In the case of dry samples abrasion, the reason for this is the mixing of abrasive grain and worn stone. In the case of samples tested under conditions of water saturation, the sample is covered with the abrasive grain, which in further phases is liquefied and mixed with the worn stone mass. In this case, however, the abrasion is worse in comparison with the samples tested in the dry condition, because the liquid and mixed abrasive grain with the worn rock mass causes the sample to slide, which in turn results in the abrasion volume loss. The control of the abrasion resistance results obtained from the stone abrasion according to the EN14157 standard should be a comparison with the abrasion resistance results obtained in the process of calculating the abrasion volume loss of sample determined from height.

Keywords Abrasion resistance · Böhme abrasion test · EN 14157 · Natural stone · Sandstone · Flooring materials · Rock properties

Introduction

As a construction material, natural stone has been used for hundreds of years. It also displays various physical and mechanical properties. These parameters serve as a basis for defining the durability and resistance of natural stone products to the impact of both natural and anthropogenic environment and may also serve to define their potential and conditions of usage (Yilmaz et al. 2011; Strzałkowski 2018). Importantly, the durability and resistance of stone is affected by its type,

composition and structure (Yavuz et al. 2008; Rembiś and Smoleńska 2010; Yilmaz et al. 2011; Figarska-Warchoł and Stańczak 2016, 2019).

Regulation No 305/2011 of the European Parliament and of the Council of 9 March 2011 (Regulation (EU) No 305/2011) specifies that the performance of construction materials, including natural stone products used in construction, should ensure safe usage throughout their lifetime. The performance and applications of natural stone in construction are primarily determined in the process of testing their physical and mechanical properties. European standards regulating the requirements for natural stone mention the test methods and the properties of stone to be tested, depending on its application. If natural stone is intended for use as floor tiles (EN 1341 2013), paving blocks (EN 1342 2013) on outdoor road surfaces, or as floor and staircase elements (EN 12057 2015, EN 12058 2015), it is important to test their abrasion resistance. Abrasion of stone materials used in construction results from their everyday usage. Interestingly, the European standards in force do not categorize or classify the test results (Babińska 2009). This fact entails a number of difficulties in selecting a proper type of stone. With no guidelines on the selection of the

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proper type of stone, the investor or designer has to define these parameters in the technical specifications of the designed or constructed structures. As a result, the responsibility for the selection of the proper stone material is transferred on the designer or on the contractor (Strzałkowski 2018). Except for the aesthetic qualities, which are the typical motivation behind the selection of a construction material at design and construction stages, the construction material is also selected for its possibly best technical parameters. And this decision requires huge experience and knowledge from the designer and the investor, who have to face a great variety of the available stone products.

Abrasion resistance is one of the basic physical properties, which allow estimating the usefulness of a particular stone type in both outdoor and indoor surfaces. It also affects the aesthetic qualities of the stone (Yavuz et al. 2008; Karaca et al. 2012a).

Abrasion of stone is defined as a damage of its top layer due to the friction and/or impact from an element interacting with the stone layer. This friction causes stone particles to separate (loss of mass, volume and stone thickness) due to scratches. Information on the abrasibility of natural stone, expressed as the loss of the top layer of the stone during tests, is fundamental for estimating the life, including wear, of a particular stone type in a particular application (Yavuz et al. 2008).

Depending on the rock type, during the test the top sample layer displays various degrees of abrasibility: harder rocks, which have higher compressive strength, show smaller wear of the top layer, and rocks, which have lower compressive strength, show lower abrasion resistance (greater abrasibility) (Karaca et al. 2012a).

Abrasion occurs when two elements interacting with each other have surfaces of different hardness or when harder, loose particles are introduced between the two surfaces. In the abrasion process on the Böhme apparatus, 3 bodies (disc-abrasive grain-sample) come into contact, with the abrasive grains moving freely when the disc rotates (Yavuz et al. 2008), as

shown in Fig. 1. These grains enter the space under the surface of the weighted sample and as a result they rotate (the so-called rolling of abrasive grains) or slide (the shearing of the sample). Abrasive grains exert their force on the sample (F_{ag}), and the contact between the sample and the abrasive grain produces an impact and a shearing action (F_s), which leads to the destruction of the layer of a sample. Thus, the abrasion of stone material is related to the crushing and ploughing of the tested stone surface, which is a deformation phenomenon and entails the loss of stone material. When rotating, abrasive sharp-edged grains may cause high compressive stress and in effect lead to microscopic-scale crushing at the contact point of the sample and the grain. On the other hand, when the grain slides, the stone surface is mostly scratched and scraped (Karaca et al. 2012a). Obviously, the abrasion process also involves the crushing and shearing of the rotating disc (F_r), and therefore, the standards require the disc to have high abrasion strength. Still, some damage to the top surface of the disc can be observed, albeit in a much longer process.

Abrasion resistance of stone can be tested with a number of methods, including the European standard EN 14157 (EN 14157 2017) and the US standard ASTM C 241-90 (ASTM C 241-90 2005). The European standard EN 14157 covers three natural stone abrasion test methods: wide-wheel (Capon), Böhme and Amsler. The Böhme abrasion test is the most basic and popular abrasion test method (Kılıç and Teymen 2008; Yavuz et al. 2008; Karaca et al. 2012a, b). It has been compared on many occasions with other methods, as well as with the physical and mechanical properties of rocks (Marradi et al. 2008; Babińska 2009; Karaca et al. 2012b). The research has demonstrated correlation between the obtained results. The literature also offers the results of abrasion tests, which were performed after stone samples had been used to simulate exposure to changing climatic conditions (Yavuz 2006; Karaca et al. 2010). However, the methodology of the Böhme abrasion test lacks critical analysis, and therefore, a need has been recognized to investigate the conditions

Fig. 1 Abrasion process on the Böhme apparatus. F_{ag} is force exerted by the abrasive grain on the sample, F_s is rotational and friction force on the sample, F_r is rotational and friction force on the disc (own source based on Karaca et al. (2012a))

Table 1 Petrographic description of the stones

Sample	Photo	Colour	Rock composition, %				Grain size and structure (macroscopic description)	Texture
			Quartz	Feldspar	Other (incl. limonite, mica, heavy minerals)	Binder		
Sandstone 1		Light gray	95	1	0	4 (Clay-siliceous)	Fine-grained, uniform granularity	Non-directional
Sandstone 2		Greyish blue	64	16	2	18 (Clay-siliceous)	Medium-grained, different granularity	Non-directional
Sandstone 3		Yellow	76	13	1	10 (Clay-siliceous)	Coarse-grained, different granularity	Vaguely layered
Sandstone 4		Yellow	81	2	1	16 (Clay-siliceous)	Coarse-grained, different granularity	Vaguely layered
Sandstone 5		Yellow	77	3	2	18 (Clay-siliceous)	Fine-grained, uniform granularity	Vaguely layered
Sandstone 6		Red	80	12	1	7 (Ferruginous-siliceous-clay)	Coarse-grained, different granularity	Non-directional

in which the test is performed and the problems related to the implementation of this test and to the interpretation of its results. In addition, the literature does not offer information on tests performed into the abrasion resistance of both dry and water-saturated natural stone and their correlation. Such tests are particularly significant for determining the abrasion

resistance of stones used outdoors, where they are exposed to changing weather conditions (e.g. rain). This article analyses the Böhme abrasion test method for dry and water-saturated sandstones and indicates problems related to the tests and to the interpretation of their results. These studies can provide a basis for further consideration of the abrasion

Table 1 (continued)

Sandstone 7		Greyish yellow	91	1.5	0.5	8 (Siliceous-clay)	Fine-grained, uniform granularity	Vaguely layered
Sandstone 8		Greyish white	85	3	2	10 (Siliceous-clay)	Fine-grained, uniform granularity	Non-directional
Sandstone 9		Light yellow to rusty	69	17	2	12 (Clay-siliceous)	Medium-grained, uniform granularity	Layered
Sandstone 10		Greyish pink	97	0.5	0	2,5 (Siliceous-clay)	Medium-grained, uniform granularity	Non-directional
Sandstone 11		Greyish white	96	1	0	3 (Siliceous-clay)	Fine-grained, uniform granularity	Non-directional
Sandstone 12		Red	78	8	2	12 (Ferruginous-siliceous-clay)	Medium-grained, uniform granularity	Non-directional
Sandstone 13		Greyish red	70	7	1	21 (Ferruginous-siliceous-clay)	Fine-grained, uniform granularity	Non-directional
Sandstone 14		Light yellow	80	1	2	17 (Siliceous-clay)	Fine-grained, uniform granularity	Layered

testing methodology for determining the abrasion resistance of other stone materials.

Materials and methods

The abrasion resistance tests were performed for 14 different sandstones obtained from southern Poland and having different grains and compositions (Table 1). These rocks are of different colour and consist of individual mineral grains of different sizes. Coarse-grained sandstones (grain size 1–2 mm), medium-grained (grain size 0.5–1 mm) and fine sandstones (grain size 0.1–0.5 mm) can be distinguished. Sandstones, which belong to compact rocks, are characterized by different composition. The main rock forming component of sandstones is quartz and other mineral forms of silica. These are the most resistant components, and their contribution can be a quantitative indicator of the intensity of destruction processes.

The abrasion resistance tests were conducted on representative samples of sandstone in accordance with EN 14157 (EN 14157 2017) using a Böhme abrasion test apparatus. The Böhme abrasion test method (Fig. 2) consists in the grinding of a natural stone sample during 352 revolutions of the Böhme disc and in calculating the wear due to abrasion after 16 cycles as a mean volume loss of the sample. The abrasion test was performed for both dry and water-saturated samples.

Each dry sample was dried to a set mass in the temperature of 70 ± 5 °C. The water-saturated samples were immersed in water for 7 days. Prior to the tests, the samples were measured and weighed with accuracy down to 0.1 mm and 0.1 g. Their volume density was also measured.

The tests consisted in placing the sample in a clamp and loading it with an axial force of 294 ± 3 N. After 20 g of standard abrasive grain (artificial corundum) had been placed on the test track, the sample was subjected to 22 revolutions at 30 ± 1 rpm. During the tests, special attention was paid to keep the abrasive grain on the track on which the sample was guided. After each cycle, the discs and the front face of the sample were cleaned and the sample was rotated by 90°. The test was repeated 16 times, and after each 4 cycles the sample was weighed with accuracy down to 0.1 g.

In the case of water-saturated samples, the track was additionally wetted before each cycle and the application of the abrasive grain. Starting at the beginning of the test, water was applied to the track at approximately 13 ml/min. After the test, the sample was dried to a set mass and weighed with accuracy down to 0.1 g.

The abrasibility was calculated as the volume loss of the sample ΔV :

$$\Delta V = \frac{\Delta m}{\rho_b}, \text{ mm}^3 \quad (1)$$

ΔV is volume loss after 16 cycles (measured from mass), mm^3 ,

Δm is mass loss after 16 cycles, g,

ρ_b is volume bulk density of the sample, g/mm^3 .

In order to additionally compare the tested abrasion resistance, described as the lost volume of the sample, a control abrasion resistance value was measured from the lost height of the sample ΔV_h :

$$\Delta V_h = \Delta h \cdot F, \text{ mm}^3 \quad (2)$$

ΔV_h is volume loss after 16 cycles (measured from height), mm^3 ,

Δh is sample height loss after 16 cycles, mm,

F is sample surface subjected to abrasion, mm^2 .

Results and discussion

The properties of sandstones vary depending on their lithological characteristics, such as granulation or porosity. An important role in shaping the properties of sandstones has the binder, its type, quantity and degree of recrystallization (Nieć 2007). From each batch of stones tested, 2 representative cubic samples of 71 ± 1.5 mm size were cut out with a saw. On these sandstone samples, volume loss due to abrasion was tested. The test results served to identify mean abrasion volume losses per 50 cm^2 of the sample base. Additionally, the bulk density and open porosity of the tested sandstone samples

Fig. 2 Böhme abrasion test apparatus. 1—counterweight, 2—test track, 3—loading weight, 4—sample holder, 5—sample, 6—rotating disc (EN 14157 2017)

Table 2 Abrasion resistance test results for dry and water-saturated sandstones

Sample	Bulk density (kg/m ³)	Porosity (%)	Böhme abrasion test for dry samples				Böhme abrasion test for wet samples				Average difference between abrasion volume loss dry and wet of samples determined from mass (%)	
			Average sample mass loss after 16 cycles (g/50cm ²)	Average height loss after 16 cycles (cm)	Average abrasion volume loss of sample determined from mass ΔV (cm ³ /50cm ²)	Average abrasion volume loss of sample determined from height ΔV_h (cm ³ /50cm ²)	Average sample mass loss after 16 cycles (g/50cm ²)	Average height loss after 16 cycles (cm)	Average abrasion volume loss of sample determined from mass ΔV (cm ³ /50cm ²)	Average abrasion volume loss of sample determined from height ΔV_h (cm ³ /50cm ²)		
Sandstone 1	2003.26	13.41	148.87	1.48	74.31	74.22	117.79	1.17	58.82	58.41	26.33	
Sandstone 2	2514.21	4.89	38.21	0.28	15.20	13.91	33.41	0.27	13.29	13.28	14.37	
Sandstone 3	2158.73	10.97	56.72	0.50	26.27	24.84	55.16	0.51	25.55	25.44	2.82	
Sandstone 4	2076.95	10.51	53.75	0.52	26.88	26.06	39.61	0.36	19.07	18.19	40.93	
Sandstone 5	1977.48	14.87	140.26	1.41	70.93	70.38	85.74	0.86	43.33	42.94	63.69	
Sandstone 6	2308.69	8.16	57.32	0.48	24.83	24.13	43.39	0.37	18.80	18.72	32.10	
Sandstone 7	2232.09	5.81	80.39	0.69	36.01	34.44	58.79	0.51	26.33	25.50	36.78	
Sandstone 8	2090.43	11.41	117.72	1.11	56.33	55.34	115.80	1.10	55.42	54.94	1.63	
Sandstone 9	2236.78	8.23	41.55	0.37	18.57	18.30	40.88	0.35	18.28	17.63	1.63	
Sandstone 10	2106.37	10.02	134.47	1.27	63.84	63.56	130.78	1.21	62.09	60.25	2.82	
Sandstone 11	2067.74	15.28	192.61	1.86	93.17	93.00	139.78	1.35	67.65	67.47	37.72	
Sandstone 12	2449.82	6.75	124.68	1.01	50.97	50.50	101.51	0.82	41.44	41.16	23.01	
Sandstone 13	2139.40	10.98	112.35	1.02	52.54	51.00	76.12	0.70	35.60	35.19	47.59	
Sandstone 14	2076.49	15.19	161.31	1.54	77.71	77.00	120.33	1.15	58.01	57.63	33.95	

Fig. 3 Examples of how samples are crushed during the abrasion resistance test

were determined (according to EN 1936 2010). The results are shown in Table 2.

The results allow an observation that the sandstones have different abrasion resistance. As observed in Yavuz et al. (2008), the structure of a natural stone may provide general information about its abrasion resistance. This research indicates that natural stones representing rocks of the same lithology may also have different abrasion resistances. Additionally, the method for calculating abrasion resistance from mass and volume density, as recommended in EN 14157, seems imprecise. For dry samples the tests of abrasion volume loss determined from height demonstrate that it is smaller by up to 8% than the volume loss determined from mass. This difference, however, is smaller in the case of abrasion resistance tests of water-saturated samples. In this case, the difference between the volume losses of sample determined from mass and height decreases with increasing hardness of natural stone. Differences resulting from the abrasion calculations for sandstones according to Eqs. (1) and (2) may be due to the variable structure of the stone and the local occurrence of heavier and harder stone forming grains. In addition, crushing of sandstones was observed during the dry test (Fig. 3), which significantly affects

the sample mass measured in order to identify the volume loss. This effect was caused by the liability of sandstone to be crushed and by the vibration of the samples during the tests. Therefore, it is recommended to control and compare the abrasion volume loss of stone samples determined from mass with the abrasion volume loss of stone samples determined from height, especially when the test stone is brittle. This analysis allows for a more reliable assessment of the abrasiveness of the stone.

The crushing of samples is mainly observed at the initial stage of abrasion. Therefore, it is important placing of the abrasive grain on the Böhme disc accordingly. The grain should be placed directly in front of the sample, as such configuration minimizes the splitting of a natural stone which has relatively limited hardness and strength parameters (such as sandstones). Obviously, such crushing is marginal in the case of stones having high hardness and compression strength (e.g. granites).

The performed macroscopic descriptions and sandstone abrasion resistance tests have demonstrated that the abrasion volume loss of sandstone sample decreases with increasing grain size (Fig. 4). The abrasion volume loss of dry and

Fig. 4 Relation between abrasion volume loss determined from mass and grain size of the sandstones

Fig. 5 Relationship between abrasion volume loss (from sample weight) for dry and wet samples, $\text{cm}^2/50 \text{ cm}^3$

water-saturated samples has been observed to be the lowest for sandstones of coarse and different grain sizes. The porosity with respect to grain size and structure has been also observed to show a similar relationship. Additionally, the relative difference of abrasion resistance for fine-grained dry and wet sandstones is smaller than in the case of and coarse-grained sandstones. In addition, the tests conducted did not show a

clear correlation between the lower abrasiveness of the tested tests and the amount of binder.

The abrasion tests of dry and wet natural stone (Fig. 5) indicate a high correlation of 0.944 between the obtained results. Although the results are so well correlated, the abrasion volume loss of dry samples is even up to 65% greater than in the case of abrasion resistance tests on water-saturated samples (Fig. 6). In addition, the correlation coefficient between the open porosity and the abrasion volume loss of dry samples (determined from Eq. (1)) has been observed to be greater (0.790) than in the case of wet samples (0.698). The correlation coefficient between the bulk density and the abrasion volume loss of dry samples (as determined from Eq. (1)) was 0.625 and for the wet samples 0.580.

During the tests, phenomena that influence the results of abrasion resistance of the sandstones tested were observed. During abrasion resistance tests of dry stone, an increase in the number of disc revolutions is accompanied by the mixing of the ground stone mass with the abrasive grain (Fig. 7). It has been observed that the abrasion process at individual

Fig. 6 Comparison of abrasion volume loss (from sample weight) for dry and wet samples, $\text{cm}^2/50 \text{ cm}^3$

Fig. 7 Abrasive grain behaviour during the abrasion resistance tests of dry natural stone (a after 1 Böhme disc revolution cycle, b after 12 Böhme disc revolution cycles, and c after 22 Böhme disc revolution cycles)

Fig. 8 Variability of abrasion volume loss in the number of cycles

grinding stages is not constant and the abrasion volume loss after successive revolutions of the Böhme disc decreases with increasing number of revolutions (Fig. 8). The loss after the final revolution is smaller by 40% in comparison to the loss after the first revolution. This phenomenon is due to the mixing of the abrasive grain and the worn stone, which after mixing decreases the abrasive capacity of the abrasive grain and its proper distribution on the test track. In addition, it seems that in the initial stage of the abrasive process of sandstones, sharp-edged stone grains are more susceptible to the abrasive process due to the high-stress concentration on their sharp edges.

In abrasion resistance tests of water-saturated sandstones, the increase in the number of disc revolutions is accompanied by the liquefying of the abrasive grain and the worn stone. In the first phase of the abrasion resistance test, the sandstone sample is covered with the abrasive grain (pink colour in Fig. 9a), which in further phases is liquefied and mixed with the worn stone mass (Fig. 9b, c). As a result of this phenomenon, in the first abrasion phase the volume loss of the tested sandstone samples was minimal due to the insufficient interaction between the applied quantity of abrasive grain and the sample. In further disc rotation cycles the grain liquefies, facilitating the abrasion process, but because the liquefied grain mixes with the worn rock mass, its interaction is not as satisfactory as in the abrasion process of dry samples. The liquefied abrasive grain with the worn rock mass additionally

causes a sliding motion (reduced friction between the abrasive and the test sample), affecting the volume of sample lost due to abrasion.

When comparing the results of abrasion resistance tests for dry and water-saturated samples, it must be stressed that the two methods vary significantly with respect to sample preparation and the testing procedure. The quantity of water applied in the abrasion resistance tests of wet samples seems too high, as the abrasive grain and the worn stone mass liquefy excessively, causing the abrasion volume loss to be significantly limited and fail to reflect the actual conditions in which the stone surfaces are used. This is particularly important when testing stone with high hardness and compressive strength. Such natural stones suffer less mass loss, which results in an even greater liquefaction of the abrasive grain.

In addition, the methodology is limited to the interaction between the loose abrasive grain and the stone sample. The authors believe that the abrasion volume loss of a stone sample would be different if the abrasive grain was cemented. This would limit the rolling and sliding of the abrasive grain.

Conclusion

The abrasion resistance test of natural stone is the basic property to determine the usefulness of natural stone on surfaces. The sandstone abrasion test results shown in the publication indicate that the current EN 14157 standard defining the method for testing the abrasion of natural stone on the Böhme abrasion test apparatus needs to be specified. This will allow a more accurate representation of the actual use of the natural stone.

According to the authors, it is required to introduce additional determination of the volume loss of sample determined from height resulting from the abrasion process. This is particularly important in the case of testing materials of relatively low durability and compressive strength, which are crushed during the test. The authors also believe that it is necessary to

Fig. 9 Abrasive grain behaviour during the abrasion resistance tests of wet natural stone (a after 1 Böhme disc revolution cycle, b after 12 Böhme disc revolution cycles, and c after 22 Böhme disc revolution cycles)

modify the method of testing the abrasion of natural stone in the state of water saturation. The amount of water applied is too high and causes excessive liquefaction of the abrasive grain and the worn rock mass. This has the effect of significantly reducing the sample volume loss.

The sandstone abrasion tests conducted in the article indicate problems with the determination of abrasion resistance on Böhme abrasion test apparatus, as well as the need for further research to evaluate the abrasion resistance testing methodology for other stone materials. In particular, abrasion tests should be conducted for other natural stones with high hardness and compressive strength (e.g. granites, basalt). In addition, a broader analysis of the abrasive properties of the stone should be conducted, depending on composition and structure of natural stone.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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