Strength and abrasive properties of andesite: relationships between strength parameters measured on cylindrical test specimens and micro-Deval values—a tool for durability assessment

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Abstract

Aggregates are necessary materials for the construction industry. Owing to their favourable properties, andesites are frequently used rock materials; hence, the investigation of their mechanical and aggregate properties has great significance. This paper introduces the analyses of 13 Hungarian andesite lithotypes. The samples were collected from six andesite quarries in Hungary. Cylindrical specimens and aggregate samples with 10.0/14.0-mm-sized grains were made from rock blocks. The specimens were tested in dry, water-saturated and freeze–thaw subjected conditions. Bulk density, uniaxial compressive strength, modulus of elasticity, indirect tensile strength and water absorption were measured. The abrasion resistance was tested by micro-Deval tests. The flakiness indexes of the samples were also measured. The data set of the laboratory test results provided input for further, one- and two-variable statistical analyses. According to the test results, there is no significant difference between the strength parameters measured in water-saturated and in freeze–thaw subjected conditions. The correlation and regression analyses revealed relationships between some rock mechanical parameters, as well as between micro-Deval coefficient and uniaxial compressive strength.

Keywords Andesite · Uniaxial compressive strength · Micro-Deval value · Correlation

Introduction

Natural stones are essential building materials, as they are used as dimension stones and aggregates (Přikryl 2017). Their applicability is controlled by their mechanical properties. Andesite, which is one of the most common igneous rock types in Hungary, has favourable properties. It is often used as aggregate, in concrete (Zhang et al. 2013; Beushausen and Dittmer 2015), road (Xu et al. 2015; Kong et al. 2017) and railway constructions (Gálos and Kárpáti 2007; Ferestade et al. 2017), or as armour stone in hydraulic engineering (Ertas and Topal 2008; Ozden and Topal 2009).

Numerous test methods have been introduced to evaluate the aggregate properties: the polished stone value (PSV) test (Szatkowski and Hoskings 1972; Descantes and Hamard

2015), the aggregate impact (AIV) test (Afolagboye et al. 2017), the aggregate crushing value (ACV) test (Shipway 1964; Palassi and Danesh 2016), the Nordic test (Eerola et al. 1982; Erichsen et al. 2011), the Hummel test (Hummel 1954; Reznák et al. 1982), the Stübel test (Reznák and Ács 1965), the slake durability test (Hudec 1978; Ghobadi and Babazadeh 2015; Mišćević and Vlastelica 2011) and many more. Nowadays, the Los Angeles (Woolf and Runner 1935; Räisänen and Torppa 2005; Ajalloeian and Kamani 2017) and the micro-Deval tests (L'Haridon 1965; Tourenq 1971; Czinder and Török 2017; Liu et al. 2017) are the most common aggregate tests in Europe. Both of them apply rotating drums, and the test results are the ratio of the fragmented/abraded and the original mass of the sample. The micro-Deval test, which is also the focus of the present paper, was developed in the 1960s in France (Tourenq 1971; Hanna et al. 2003), and a multitude of test results have been gained to date. New test methods are also developed to investigate specific properties of the aggregates, for example, Fischer (2017) introduced a new laboratory test method, namely, the laboratory pulsating test, to evaluate the railway ballast breakage more realistically than Los Angeles and micro-Deval tests do.

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Fig. 1 The origin of the studied andesites

The correlations between the different rock mechanical parameters have been studied thoroughly. Correlation between the uniaxial compressive strength (UCS) and modulus of elasticity (Marek and Szabó-Balog 1987; Dinçer et al. 2004; Görög 2007; Engidasew and Barbieri 2014; Török and Czinder 2017), between bulk density and UCS (Marek and Szabó-Balog 1987; Siratovich et al. 2012; Török and Czinder 2017) and between the point load index and UCS (Rigopoulos et al. 2013; Kahraman 2014; Karaman et al. 2015) has been found. The relations among aggregate properties can be also investigated by correlation analyses. Links were suggested between the LA test results and the micro-Deval coefficients (M_{DE}) (Xirouchakis 2013; Tabatai et al. 2013; Török 2015); between the PSV , M_{DE} and LA values (Đokić et al. 2015); between the LA , AIV and ACV values (Al-Harhi 2001; Fowler et al. 2006; Palassi and Danesh 2016); and between the M_{DE} and Deval values (Emszt

2005). Applying different standards to the same aggregate test leads to test results that are difficult to compare. Gökalp et al. (2016) made MDE tests according to the EN and ASTM standards and compared the abrasion losses.

The rock mechanical and aggregate properties also showed dependence. Interrelation was found between LA and bulk density (Ugur et al. 2010). According to numerous studies, UCS correlates with LA (Al-Harhi 2001; Kahraman and Fener 2007; Ugur et al. 2010; Rigopoulos et al. 2013) and M_{DE} (Capik and Yilmaz 2017).

The shape properties of the grains, namely the flakiness and the shape indexes, also affect the aggregate properties. The effects were analysed by Los Angeles (Kausay 1971a; Kausay 1971b) and micro-Deval tests as well (Rigopoulos et al. 2013; Bobály and Gálos 2016). According to the results, the flaky grains reduce the resistance to abrasion or fragmentation. Guo et al. (2018) studied the effect of grain size and shape on resistance to fragmentation with image analysis. Imaging techniques were also used to measure and describe the aggregate shape properties (Profitis et al. 2012, 2013) or the grain size (Profitis et al. 2013). According to Wang et al. (2015), correlation was found between gradient angularity and M_{DE} values.

Mineralogical properties affect rock mechanical and aggregate properties. The micro-fabric (Přikryl 2001, 2013), micro-cracks (Freire-Lista et al. 2015; Freire-Lista and Fort 2017), pore size and the interconnections of pores (Benavente et al. 2004; Germinario and Török 2019) significantly affect rock durability and weathering. In the case of andesitic rocks, the relative abundance of phenocrysts affects UCS (Ündül 2016). The inverse proportional effect was found between the mean

Table 1 Short description of studied andesites

Sample ID	Locality	Symbol used for the locality	Short description
Andesite-1	Gyöngyössolymos	G	Grey, porphyric slightly pilotaxitic andesite with large plagioclase phenocrysts
Andesite-2	Gyöngyössolymos	G	Dark grey, porphyric slightly pilotaxitic andesite with plagioclase and pyroxene phenocrysts
Andesite-3	Gyöngyössolymos	G	Brownish dark grey, fine porphyric slightly pilotaxitic andesite with plagioclase and pyroxene phenocrysts
Andesite-4	Gyöngyöstarján	GT	Dark grey, porphyric hyalopilitic andesite with small plagioclase and altered pyroxene phenocrysts
Andesite-5	Gyöngyöstarján	GT	Dark grey, porphyric hyalopilitic andesite with small plagioclase and pyroxene phenocrysts
Andesite-6	Komló	K	Grey porphyric-micro-holocrystalline amphibole andesite with small plagioclase needles
Andesite-7	Komló	K	Reddish grey porphyric-micro-holocrystalline amphibole andesite with small plagioclase needles
Andesite-8	Nógrádkövesd	N	Dark grey holocrystalline basaltic andesite with large plagioclase phenocrysts
Andesite-9	Recsk	R	Brownish grey porphyric holocrystalline slightly silicified andesite, with calcite cement
Andesite-10	Sáropatak	S	Grey porphyric hyalopilitic andesite with plagioclase and pyroxene phenocrysts
Andesite-11	Sáropatak	S	Slightly lilac grey porphyric hyalopilitic andesite with small pores
Andesite-12	Sáropatak	S	Lilac grey porphyric hyalopilitic andesite with pyroxene phenocrysts and recrystallised mottles
Andesite-13	Sáropatak	S	Greenish-grey porphyric hyalopilitic andesite with flow banding, pores and with plagioclase phenocrysts

Fig. 2 Microscopic images of selected andesite types. **a** Andesite 1—Gyöngyössolymos. **b** Andesite 4—Gyöngyöstarján. **c** Andesite 7—Komló. **d** Andesite 8—Nógrádkövesd. **e** Andesite 9—Recsk. **f** Andesite 13—Sárospatak. All images were taken with single polar, except image **e** where crossed polars were used (scale bar 0.5 mm) (compare the textural descriptions given in Table 1)

grain size (crystal size) of the rock material and *UCS*, and the connection was described by linear (Yılmaz et al. 2011; Khanlari et al. 2015) and logarithmic (Přikryl 2001) functions. The size of quartz and plagioclase grains has significant positive effect, and the grain size of the biotite has negative effect on indirect tensile strength (Yılmaz et al. 2015). The mineralogical composition (Pang et al. 2010) and wearing of the rocks (Erichsen et al. 2011) as well as weathering (Mišćević and

Vlastelica 2019) also affect aggregate properties. The increasing amount and decreasing average grain size of hornblendes reduce the resistance to fragmentation (Räisänen 2004). Relationships were also found between the amount of the aluminium, sodium and iron oxides and LA coefficient in the case of sandstones (Tugrul and Yılmaz 2012). Textural properties can affect the physical and mechanical properties as well (Afolagboye et al. 2016), as Wang et al. (2015)

Table 2 Laboratory tests, number of results and relevant standards

Laboratory tests	Number of test results	Relevant standard
Bulk density	1273	EN 1936:2007
Propagation speed of ultrasonic wave	1263	EN 14579-2005
Water absorption	333	EN 13755:2008
Determination of frost resistance	163	EN 12371:2010
Uniaxial compressive strength	297	ASTM D7012-14e1
Modulus of elasticity	286	ASTM D7012-14e1
Tensile strength	257	ASTM D3967-16
Micro-Deval coefficient	108	EN 1097-1:2012
Flakiness index	86	EN 933-3:2012

Fig. 3 Failure of a micro-cracked specimen from Gyöngyössolymos (**a** stress–strain curve; **b** intact specimen; **c** broken specimen)

obtained a relationship between the change of the texture index and the micro-Deval coefficient. The porosity or water absorption may also affect the M_{DE} values (Rogers et al. 1991; Capik and Yilmaz 2017; Holleran et al. 2017).

Recent paper introduces the results of a research what is dealing with strength and aggregate properties of andesites. The statistical investigation uses previous (Török and Czinder 2017) and new laboratory test results.

Materials

In this study, 13 andesite lithotypes from different parts of Hungary were analysed. The andesite samples were mainly obtained from operating quarries of Hungary (Fig. 1). Seven lithotypes were from the Mátra Mountains (three from Gyöngyössolymos, two from Gyöngyöstarján and one from Reck), two lithotypes were from the Mecsek Mountains (Komló) and four lithotypes were from the Zemplén Mountains (Sárospatak). The andesites of the most important quarries of Hungary were involved in the research.

Fig. 4 Boxplot diagram: water absorption values of the andesite from Reck

The tested andesite shows a wide range of lithological characteristics (Table 1). Their micro-fabric ranges from porphyric hyalopilitic, porphyric slightly pilotaxitic to porphyric holocrystalline (Fig. 2).

Methods

Laboratory tests

The laboratory tests involved both strength tests (carried out on regularly shaped specimens) and the analyses of aggregate properties. The cylindrical specimens were drilled from rock blocks and cut with cutting disc. The cut surface of the specimens was polished. The aggregate test samples were prepared by crushing the rock blocks and sieving. The samples were grouped by block. The cylindrical specimens were tested in dry (D), water-saturated (W) and freeze–thaw (F–T) subjected conditions.

The cylindrical specimens were grouped according to the bulk density and the propagation speed of the ultrasonic wave.

Table 3 The number of the excluded elements based on the analyses of the outliers (test conditions: D, dry; W, water-saturated; F–T, freeze–thaw subjected)

Measured properties	Test conditions		
	D	W	F–T
Bulk density	16	12	12
Propagation speed of ultrasonic wave	17	3	1
Uniaxial compressive strength	3	2	2
Modulus of elasticity	2	4	1
Indirect tensile strength	1	5	2
Water absorption	14		
Weight loss caused by F–T cycles	8		

The measured strength parameters included the uniaxial compressive strength (UCS), indirect tensile strength (σ_t) and modulus of elasticity (E). The UCS values were calculated with the following equation:

$$UCS = \frac{UCS_m \cdot d^{0.18}}{1.78 + 0.485 \cdot \frac{d}{h}},$$

where UCS is the modified compressive strength value recalculated from specimens with a diameter of 50 mm and a height of 100 mm, UCS_m is the measured compressive strength value, d is the diameter and h is the height of the specimen (Hoek and Brown 1980; Gálos and Vásárhelyi 2006). The freeze–thaw subjected specimens were analysed after 50 F–T cycles. The water absorption and weight loss caused by the F–T cycles were also measured. The tests were carried out according to the relevant European and American standards (Table 2).

The abrasive properties were analysed by the micro-Deval abrasion test. Five hundred grams of 10.0/14.0-mm-sized

samples (10.0/11.2 mm, 150 g; 11.2/14.0 mm, 350 g) were used. The samples are loaded in steel drums (height, 154 mm; diameter, 200 mm) and rotated by 12,000 times with a 100 rot/min rate. The abrasive impact is provided by 1500 ml water and 5000-g steel balls (diameter, 10 mm). The abraded samples should be washed and sieved on a 1.6-mm sieve. The result of the test is the micro-Deval coefficient (M_{DE}), which is the ratio of the abraded mass and the original mass of the test sample in percentage by mass. The micro-Deval tests were carried out according to the EN 1097-1:2012 standard (Tests for mechanical and physical properties of aggregates. Part 1: Determination of the resistance to wear—micro-Deval).

The flakiness index (FI) of the samples was also measured. The relevant European standard (EN 933-3:2012—Tests for geometrical properties of aggregates. Part 3: Determination of particle shape. Flakiness index) prescribes the investigation of particle size fractions of 10.0/12.5 mm or 12.5/16.0 mm with bar sieves at a slot width of 6.3 mm or 8.0 mm. Since there is no suggestion in the standard to the investigation of the particle size fraction of 10.0/14.0 mm, the flakiness of some samples was determined with grid sieve at a 6.3-mm slot width and others with sieves at a 8.0-mm slot width. Flakiness index is the proportion of the mass that passed the bar sieve and the total mass of the sample denoted in percentage by mass. Both FI and MDE tests were made in pairs. Their average value was used in further analyses.

The laboratory tests, the number of test results and the relevant standards are shown in Table 2. The D, W and F–T subjected conditions are not divided here. Altogether, 777 cylindrical specimens were created and measured.

Statistical analyses

The laboratory test results provided the database for further statistical analyses, for which Microsoft Excel as well as IBM SPSS Statistics 22 were used. The one-variable analyses included the determination of the statistical indices: minimum,

Fig. 5 The uniaxial compressive strength of the studied andesites (D, dry condition; U, a united group of water-saturated and freeze–thaw subjected conditions)

Fig. 6 The modulus of elasticity of the studied andesites (D, dry condition; U, a united group of water-saturated and freeze–thaw subjected conditions)

average, maximum and median values, standard deviation, coefficient of variation (which is the ratio of the standard deviation and the average value, a coefficient without dimension) and number of the results.

Outliers were excluded from the data set in two steps. First, the *UCS* values were analysed based on their stress–strain curves. In some cases, micro-cracks reduced the *UCS* of the specimens, which had a visible effect on the irregular shape of the stress–strain curve (Fig. 3). In those cases, the measured *UCS* values were not representative and, therefore, the values were excluded from the data set. The second step was the selection of the outlier elements by analyses of the outliers according to the dispersion (described by the interquartile range) of the studied parameter. Boxplot diagrams (Fig. 4) were used. The grey box represents the interquartile range, the line across that is the median. Outliers are signed with circles, the difference between them and the edge of the interquartile box is less than the treble of the interquartile range, but more than 1.5 times of it. The outliers, which do not satisfy this criterion, are the extreme outliers and are marked by stars (Sajtos and Mitev 2007). The extreme outliers were excluded from further statistical analyses in all cases.

The significance of the difference between the strength parameters in D, W and F–T conditions was analysed by

Welch's *t* test. Welch's test is a two-sample statistical test, which is suitable to investigate the equality of the mean values of two independent variables at a certain significance level. The test does not require the equality of the standard deviations of the studied random variables (Bolla and Krámlí 2006). The Welch's *t* test was applied if the number of elements reached 3. In other cases, the investigation of the equality of two groups of results was controlled by the average values and the distributions of them.

The interrelations of the different variables were analysed by correlation and regression analyses. The average values of the results determined for each rock blocks and each rock type were managed separately. The strength of a relationship was described by the R^2 value.

Results and discussion

According to the evaluation of the stress–strain curves of the compressive tests, 19 *UCS* and *E* values were excluded from the database. Test results were also excluded from further research based on the analyses of the outliers (Table 3).

Previous studies have shown that strength reduction can be observed after water saturation (limestones: Ertas and Topal

Fig. 7 The indirect tensile strength of the studied andesites (D, dry condition; U, a united group of water-saturated and freeze–thaw subjected conditions)

Table 4 The mean values (Mean), the standard deviation (Std.) and the number (Num.) of the laboratory test results of the studied andesites after the selection of overhanging elements. Conditions: D, dry; W, water-saturated; F–T, freeze–thaw subjected; U, a united group of W and F–T (ρ , bulk density [kg/m^3]; w_a , water absorption [%]; F , weight loss caused by the F–T cycles [%]; V_p , propagation speed of the ultrasonic wave [km/s]; UCS , uniaxial compressive strength [MPa]; E , modulus of elasticity [GPa]; σ_t , indirect tensile strength [MPa]; M_{DE} , micro-Deval coefficient [%])

Sample ID	ρ		w_a		F		V_p		UCS		E		σ_t		M_{DE}
	D	W	F–T	(%)	D	W	F–T	(km/s)	D	U	D	U	D	U	
	(kg/m^3)								(MPa)		(GPa)		(MPa)		(m%)
And-1	Mean	2684	2710	0.71	–0.05	5.2	4.9	5.1	101.12	74.95	26.69	23.94	10.85	5.82	16.03
	Std.	35	36	0.16	0.04	0.5	0.2	0.2	20.34	22.72	6.68	10.48	1.67	1.48	2.57
	Num.	62	34	34	17	62	35	17	15	17	15	17	8	11	12
And-2	Mean	2704	2726	0.51	–0.03	5.4	4.9	5.2	107.21	93.58	26.11	23.97	10.31	6.37	10.53
	Std.	35	29	0.04	0.03	0.3	0.2	0.1	10.35	20.83	11.80	6.97	2.55	2.44	2.72
	Num.	33	20	16	11	32	21	10	5	8	6	8	5	12	10
And-3	Mean	2718	2732	0.58	–0.03	5.5	5.0	5.2	127.48	114.79	20.34	40.78	11.94	8.42	7.37
	Std.	13	11	0.06	0.03	0.3	0.1	0.2	29.50	28.29	4.22	17.92	2.23	0.40	0.07
	Num.	16	11	11	5	16	11	5	3	6	3	6	3	4	4
And-4	Mean	2379	2457	3.69	–0.13	4.1	4.1	3.8	101.06	55.76	21.54	13.33	5.91	3.58	16.18
	Std.	36	24	0.50	0.09	0.4	0.2	0.2	10.00	7.09	2.40	2.50	2.92	0.94	
	Num.	25	15	15	7	25	15	5	6	9	6	9	4	5	2
And-5	Mean	2459	2521	2.54	–0.05	4.7	4.5	4.4	99.82	65.86	25.84	22.96	6.60	4.99	18.51
	Std.	13	8	0.17	0.03	0.1	0.2		11.99	10.85	3.99	14.11	2.45	0.86	
	Num.	10	6	6	3	12	5	2	3	4	3	4	3	3	2
And-6	Mean	2535	2579	1.51	0.00	5.2	4.4	4.4	164.35	114.33	29.07	25.60	11.15	8.73	21.00
	Std.	19	14	0.18	0.00	0.4	0.2	0.3	41.38	39.28	4.21	7.93	4.09	1.79	2.62
	Num.	110	45	48	20	109	46	22	12	20	12	19	14	23	8
And-7	Mean	2573	2606	1.04	0.00	5.7	4.7	4.5	164.25	136.11	32.38	26.90	7.71	9.98	11.95
	Std.	26	16	0.23	0.00	0.3	0.2	0.3	19.09	29.13	4.46	6.69	1.16	3.08	1.01
	Num.	65	25	26	11	65	25	12	9	13	9	14	6	12	10
And-8	Mean	2710	2735	0.91	–0.03	5.0	5.0	5.1	87.58	77.99	23.16	26.23	7.90	6.10	19.95
	Std.	9	9	0.07	0.02	0.3	0.3	0.2	24.32	19.45	7.27	8.01	2.41	1.81	1.38
	Num.	117	76	79	39	114	79	39	19	36	19	37	20	38	26
And-9	Mean	2714	2730	0.46	–0.03	7.2	5.6	5.2	270.79	253.44	48.71	47.86	9.82	7.35	4.10
	Std.	28	24	0.14	0.04	0.6	0.3	0.4	36.17	29.20	5.33	3.75	4.68	2.96	0.59
	Num.	265	59	57	31	268	61	35	28	29	23	22	22	29	26
And-10	Mean	2603	2635	1.33	–0.03	4.6	5.0	4.6	116.22	70.01	27.97	20.72	7.60	6.39	14.89
	Std.	22	20	0.12	0.05	0.2	0.2	0.0	6.74	18.51	4.23	5.09	2.49	1.73	
	Num.	23	13	12	5	22	13	3	6	6	6	6	4	7	2
And-11	Mean	2361	2502	2.53		3.4	4.5		73.00	53.60	18.02	15.08	6.11		19.95

Table 4 (continued)

Sample ID	ρ		w_a		F		V_p		U_{CS}		E		σ_t		M_{DE}	
	D	W	F-T		D	W	F-T		D	U	D	U	D	U	D	U
	(kg/m ³)			(m%)	(km/s)			(MPa)	(GPa)	(MPa)	(m%)					
Std.	102				0.2											
Num.	3	1	0	1	3	1	0	1	1	1	1	1	1	0	2	2
Mean	2440	2502	2510	3.17	3.9	4.2	4.0	87.54	65.47	18.77	15.33	6.99	5.79	19.39		
Std.	38	26	24	0.36	0.4	0.2		14.74	7.19	0.46	2.94		0.29			
Num.	13	7	3	7	13	7	2	3	4	3	4	2	3	2		
Mean	2425	2485	2509	2.56	3.7	4.4	4.1	52.67	49.59	12.00	15.67	5.09	4.22	25.60		
Std.	52	44	36	0.18	0.3	0.2		8.31	6.81	6.22	3.73	1.12	1.48			
Num.	19	8	4	8	19	8	2	4	4	4	4	5	5	2		

2008; Török and Vásárhelyi 2010) and freeze–thaw testing (andesites: Fener and İnce 2015; Yavuz 2011). According to the current results of the Welch's t tests, there is no significant difference between the strength parameters (U_{CS} , E , σ_t) measured in W and F–T conditions on the significance level of 0.05, with the exception of E of andesite-8, as well as U_{CS} , E and σ_t of andesite-9. On the 0.01 significance level, there are no significant differences between these parameters in W and F–T conditions. In consequence, the strength parameters of the W and F–T conditions were managed collectively in a united group (signed with U). The strength reduction (caused by the water saturation) changed in a wider range (andesite-9, 6%; andesite-4, 45%) (Fig. 5) according to the level of weathering. Similar results were measured on other andesite lithotypes (Zalooli et al. 2018); Fener and İnce (2015) detected 24% strength reduction after 30 F–T cycles, and Yavuz (2011) detected 8% after 30 and 13% after 50 cycles.

The highest uniaxial compressive strength and modulus of elasticity values were measured in the case of andesite-9 (Figs. 6 and 7). Contrary to what was suspected, andesite-9 provided lower indirect tensile strength than other lithotypes, and andesite-1, andesite-2, andesite-3 and andesite-6 produced higher values in dry conditions. The high uniaxial compressive strength and modulus of elasticity of andesite-9 can be attributed to the alteration, i.e. silicification, that modified the micro-fabric of the andesite.

The test results of the studied andesites are shown in Table 4. The test results were compared with previously published data sets of other lithotypes (Table 5). The highest U_{CS} were measured on andesite-9 (271 MPa; detailed in this study), on basalt from Ethiopia (256 MPa; sample ID, 21; Engidasew and Barbieri 2014) and on a Turkish andesite (175 MPa; sample ID, 16; Engin 2013) (Fig. 8) in dry condition.

Two-variable analyses

Two data sets were analysed in the course of the two-variable tests. Both included every test result; the difference is the groupage of them:

- DS-1: The properties of the different rock blocks were managed separately. The mean values of the laboratory test results of 61 rock blocks were included in the investigation.
- DS-2: The different lithotypes were managed separately. The mean values of the laboratory test results of 13 lithotypes were included in the investigation.

The evaluation of both data sets was necessary. On the one hand, the results of the investigations DS-2 are more general. On the other hand, the higher level of reliability was found at

Table 5 Rock mechanical and aggregate properties of several lithotypes, measured in dry condition (ρ , bulk density [kg/m³]; UCS, uniaxial compressive strength [MPa]; E , modulus of elasticity [GPa]; σ_t , indirect tensile strength [MPa]; M_{DE} , micro-Deval coefficient [m%])

Sample ID	Rock type	References	ρ	UCS	E	σ_t	M_{DE}
1	Andesite-1 (Hungary)	in this paper	2684	101.1	26.7	10.8	13.5
2	Andesite-2 (Hungary)	in this paper	2704	107.2	26.1	10.3	13.3
3	Andesite-3 (Hungary)	in this paper	2718	127.5	20.3	11.9	8.0
4	Andesite-4 (Hungary)	in this paper	2379	101.1	21.5	5.9	16.2
5	Andesite-5 (Hungary)	in this paper	2459	99.8	25.8	6.6	18.5
6	Andesite-6 (Hungary)	in this paper	2535	164.3	29.1	11.1	21.0
7	Andesite-7 (Hungary)	in this paper	2573	164.2	32.4	7.7	12.0
8	Andesite-8 (Hungary)	in this paper	2710	87.6	23.2	7.9	20.0
9	Andesite-9 (Hungary)	in this paper	2714	270.8	48.7	9.8	4.1
10	Andesite-10 (Hungary)	in this paper	2603	116.2	28.0	7.6	14.9
11	Andesite-11 (Hungary)	in this paper	2361	73.0	18.0	6.1	19.9
12	Andesite-12 (Hungary)	in this paper	2440	87.5	18.8	7.0	19.4
13	Andesite-13 (Hungary)	in this paper	2425	52.7	12.0	5.1	25.6
14	Rotokawa andesite (New Zealand)	Siratovich et al. 2012	2540	127.8	29.5	15.4	
15	Cömlekçikuyu andesite (Turkey)	Ozden and Topal 2009	2308	40.4			45.8
16	Afyon andesite (Turkey)	Engin 2013	2350	175.0	15.8		
17	Hüseyingazi andesite (Turkey)	Sonmez et al. 2004	2480	91.1	8.7		
18	Hüseyingazi andesite (Turkey)	Sonmez et al. 2004	2310	49.9	7.4		
19	Andesite (Turkey)	Çelik and Aygün 2019	2720	60.7			
20	Andesite (Turkey)	Dinçer et al. 2004	2560	82.5	13.6		
21	Basalt (Ethiopia)	Engidasew and Barbieri 2014	3030	256.0			
22	Basalt (Turkey)	Gökarp et al. 2016	2700				10.4
23	Basalt (Turkey)	Gökarp et al. 2016	2600				9.4
24	Basalt (Turkey)	Dinçer et al. 2004	2620	86.5	16.0		
25	Trachybasalt (no marked origin)	Tuncay et al. 2016	2735	147.2			4.9
26	Porphyritic granite (Norway)	Erichsen et al. 2011	2750				11.0
27	Gabbro (Serbia)	Đokić et al. 2015	2950				14.0
28	Orthogneiss (Sweden)	Johansson et al. 2009	2740				19.0
29	Diorite (Greece)	Rigopoulos et al., 2013	2760	118.1			7.3
30	Diorite (Greece)	Rigopoulos et al. 2013	2620	162.8			5.7
31	Granodiorite (Norway)	Erichsen et al. 2011	2670				9.0
32	Dolerite (Serbia)	Đokić et al. 2015	2750				16.0
33	Dolerite (Serbia)	Đokić et al. 2015	2910				8.0
34	Trachyte (Greece)	Rigopoulos et al. 2013	2520	132.7			7.7
35	Trachyte (Greece)	Rigopoulos et al. 2013	2540	128.6			9.1
36	Tertiary sandstone (Iran)	Ghobadi and Babazadeh 2015	2580	170.2		16.0	
37	Tertiary sandstone (Iran)	Ghobadi and Babazadeh 2015	2440	98.8		6.4	
38	Dolomite (no marked origin)	Tuncay et al. 2016	2709	135.8			7.2
39	Degirmencayi limestone (Turkey)	Ertas and Topal 2008	2371	35.7			19.6
40	Limestone (no marked origin)	Tuncay et al. 2016	2590	118.2			10.1
41	Tirtal upper level limestone (Turkey)	Ertas and Topal 2008	2590	32.8			22.2
42	Tirtal lower level limestone (Turkey)	Ertas and Topal 2008	2264	14.7			57.1
43	Hamedan limestone (Iran)	Khanlari and Naseri 2018	2720	82.9		16.8	
44	Limestone (Bahrain)	Caricato et al. 2010	2580	59.3			
45	Limestone (Turkey)	Gökarp et al. 2016	2700				21.3
46	Limestone (Turkey)	Gökarp et al. 2016	2700				11.7
47	Travertine (no marked origin)	Demirdag 2013	2371	62.0			
48	Gerdoee travertine (Iran)	Jamshidi et al. 2016	2550	60.7		5.9	

Table 5 (continued)

Sample ID	Rock type	References	ρ	UCS	E	σ_t	M_{DE}
49	Marble (no marked origin)	Deliormanlı 2012	2706	102.9			
50	Marble (no marked origin)	Deliormanlı 2012	2709	149.9			
51	Marble (no marked origin)	Deliormanlı 2012	2650	45.7			

lithotypes where higher number of rock blocks were tested (DS-1).

In Figs. 10, 11, 12, 13, 14, 15, 16 and 17, the different colours mean the different origins of the studied andesites:

- G—andesites from Gyöngyössolymos—andesite-1, andesite-2, andesite-3
- GT—andesites from Gyöngyöstarján—andesite-4, andesite-5
- K—andesites from Komló—andesite-6, andesite-7
- N—andesite from Nógrádkövesd—andesite-8
- R—andesite from Recsk—andesite-9
- S—andesites from Sárospatak—andesite-10, andesite-11, andesite-12, andesite-13

In the case of the investigation of DS-1, the regression curves and the Pearson coefficients associated with the different origins are also presented. There is one exception, namely, the andesites from Gyöngyöstarján (andesite-4 and andesite-5) where only two data points were obtained from that group.

From the results of the correlation analyses, the R values are summarized in correlation matrices (Tables 6 and 7).

The correlation coefficient matrix of the strength parameters available in the literature (collected in Table 5) is represented in Table 8. The number of the related parameters (except the relationship between the bulk density and the uniaxial compressive strength) is not sufficient to perform the correlation analyses appropriately.

Similarly to previous studies, a strong linear correlation was found between bulk density measured in D and W conditions (Figs. 9 and 10), and the R^2 value reached 0.98 (Török and Vásárhelyi 2010, $R^2 = 0.97$; Török and Czinder 2017, $R^2 = 0.95$ –0.98). A relationship between the water absorption (w_a) and the bulk density measured in dry condition (ρ_d) was found. It has been also proved for other lithotypes (Marek and Szabó-Balog 1987; Engidasew and Abay 2016; Török and Vásárhelyi 2010). The Pearson coefficients of the relationships between water absorption and the bulk densities are 0.831 (DS-1) and 0.879 (DS-2) (Fig. 11). The correlation between the w_a and ρ_d values was found for the andesites of Komló (K), Recsk (R) and Sárospatak (S).

Multiple researchers have found relationships between UCS and E in the case of andesites (Dinçer et al. 2004; Török and Czinder 2017) and other lithotypes (Dinçer et al. 2004; Engidasew and Barbieri 2014). The currently studied andesites showed similar trends in dry condition (DS-1: $R^2 = 0.799$; DS-2: $R^2 = 0.877$) and in the case of the united group of W and F–T conditions (DS-1: $R^2 = 0.698$; DS-2: $R^2 = 0.763$). Lower R^2 values can be observed if the Origin is considered as the initial point of the curve (Fig. 12). (D condition: DS-1: $R^2 = 0.699$; DS-2: $R^2 = 0.745$. U condition: DS-1: $R^2 = 0.401$; DS-2: $R^2 = 0.540$)

A positive linear relationship was found between the UCS values under the D and U conditions, which are in accordance with the results reported by Török and Vásárhelyi (2010). The Pearson coefficients are 0.868 (DS-1, Fig. 13) and 0.906 (DS-

Fig. 8 The uniaxial compressive strength of the different lithotypes (red columns: results of andesites; blue columns: results of other lithotypes; sample ID: according to Table 5)

Table 6 The correlation matrix of the correlation analyses of DS-1 (*R*, Pearson coefficient; *N*, number of elements). Conditions (signed in subscript): D, dry; U, a united group of W and F–T (ρ , bulk density [kg/m³]; w_a , water absorption [m%]; *F*, weight loss caused by the F–T cycles [m%]; V_p , propagation speed of the ultrasonic wave [km/s]; UCS, uniaxial compressive strength [MPa]; *E*, modulus of elasticity [GPa]; σ_t , indirect tensile strength [MPa])

	ρ_U	w_a	<i>F</i>	$V_{p,D}$	$V_{p,U}$	UCS _D	UCS _U	<i>E_D</i>	<i>E_U</i>	$\sigma_{t,D}$	$\sigma_{t,U}$
ρ_D	<i>R</i>										
ρ_U	0.991 60	-0.912 59	0.078 56	0.636 61	0.757 60	0.400 59	0.414 49	0.434 57	0.582 46	0.406 60	-0.032 55
w_a		-0.893 59	0.094 56	0.621 60	0.761 60	0.388 58	0.398 49	0.433 56	0.573 46	0.384 59	-0.032 55
<i>F</i>			-0.093 55	-0.740 59	-0.781 59	-0.519 57	-0.526 48	-0.552 55	-0.601 45	-0.420 58	-0.190 54
$V_{p,D}$				0.122 56	0.023 56	0.247 54	0.165 48	0.162 52	0.092 45	0.044 55	0.425 52
$V_{p,U}$					0.854 60	0.857 59	0.899 49	0.820 57	0.826 46	0.366 60	0.229 55
UCS _D						0.695 58	0.739 49	0.732 56	0.770 46	0.375 59	-0.007 55
UCS _U							0.932 48	0.894 57	0.718 45	0.403 58	0.273 53
<i>E_D</i>								0.821 47	0.836 46	0.189 48	0.164 46
<i>E_U</i>									0.643 45	0.246 56	0.206 52
$\sigma_{t,D}$										0.227 45	0.136 43
											-0.046 54

Bold characters refer to high correlations between parameters, while italics means low or non existing correlations between the parameters

Table 7 The correlation matrix of the correlation analyses of DS-2 (*R*, Pearson coefficient; *N*, number of elements). Conditions (signed in subscript): D, dry; U, a united group of W and F–T (ρ , bulk density [kg/m³]; w_a , water absorption [m%]; *F*, weight loss caused by the F–T cycles [m%]; V_p , propagation speed of the ultrasonic wave [km/s]; UCS, uniaxial compressive strength [MPa]; *E*, modulus of elasticity [GPa]; σ_t , indirect tensile strength [MPa])

	ρ_U	w_a	<i>F</i>	$V_{p,D}$	$V_{p,U}$	UCS _D	UCS _U	<i>E_D</i>	<i>E_U</i>	$\sigma_{t,D}$	$\sigma_{t,U}$
ρ_D	<i>R</i>										
ρ_U	0.987 13	-0.937 13	0.358 12	0.790 13	0.849 13	0.466 13	0.548 13	0.520 13	0.754 13	0.779 13	0.504 12
w_a		-0.947 13	0.334 12	0.757 13	0.871 13	0.440 13	0.531 13	0.503 13	0.744 13	0.774 13	0.478 12
<i>F</i>			-0.469 12	-0.784 13	-0.861 13	-0.506 13	-0.586 13	-0.550 13	-0.751 13	-0.776 13	-0.643 12
$V_{p,D}$				0.312 12	0.268 12	0.275 12	0.323 12	0.228 12	0.314 12	0.379 12	0.734 12
$V_{p,U}$					0.792 13	0.878 13	0.903 13	0.877 13	0.902 13	0.688 13	0.638 12
UCS _D						0.617 13	0.711 13	0.685 13	0.824 13	0.542 13	0.395 12
							0.963 13	0.937 13	0.800 13	0.495 13	0.594 12

Table 7 (continued)

	ρ_U	w_a	F	$V_{p,D}$	$V_{p,U}$	UCS_D	UCS_U	E_D	E_U	$\sigma_{t,D}$	$\sigma_{t,U}$
UCS_U	<i>R</i>							0.887	0.873	0.496	0.580
	<i>N</i>							13	13	13	12
E_D									0.712	0.434	0.479
									13	13	12
E_U										0.687	0.596
										13	12
$\sigma_{t,D}$											0.619
											12

Bold characters refer to high correlations between parameters, while italics means low or non existing correlations between the parameters

Table 8 The correlation matrix of the correlation analyses of the strength parameters available in the literature (R , Pearson coefficient; N , number of elements) (ρ , bulk density [kg/m^3]; UCS , uniaxial compressive strength [MPa]; E , modulus of elasticity [GPa]; σ_t , indirect tensile strength [MPa])

		UCS	E	σ_t
ρ	R	0.322	0.186	0.4701
	N	28	6	5
UCS	R		0.281	0.334
	N		6	5
E	R			-
	N			1

2, Fig. 14). While strong correlation was found by the investigation of every test result, the separate analyses of the andesites with different origins caused Pearson coefficients lower than 0.5 in every case and lower than 0.01 in the cases of andesite-8 (N—Nógrádkövesd) and andesite-9 (R—Recsk).

Indirect tensile strength did not show correlation with any other rock mechanical parameter. The highest value of Pearson coefficient (R) was 0.42 in the case of the investigation of the relationship between water absorption and indirect tensile strength, according to the data of DS-1.

According to previous studies, a correlation could be found between the rock mechanical parameters and the aggregate properties. In most cases, these correlations were described by logarithmic functions in both cases of UCS vs. LA links (Al-Harathi 2001, $R^2 = 0.78$; Kahraman and Fener 2007, $R^2 = 0.50$ – 0.96 ; Ugur et al. 2010, $R^2 = 0.80$; Rigopoulos et al. 2013, $R^2 = 0.86$) and UCS vs. M_{DE} (Capik and Yilmaz 2017, $R^2 = 0.66$). Previous studies (Al-Harathi 2001, $R^2 = 0.76$; Török and Czinder 2017, $R^2 = 0.84$) suggested that the interrelation between the UCS and M_{DE} could be described by exponential forms too. In the frame of this study, the link between these parameters was sought in linear, logarithmic and exponential forms too (Table 9). The highest correlation was determined for the exponential equations. The values of the different lithotypes are summarized in Table 6 and are also plotted in Fig. 15.

The flakiness of the samples from Gyöngyössolymos (G) and Nógrádkövesd (N) was measured with a bar sieve with the slot of 6.3 mm and others with the 8-mm slotted bar sieve. The effect of the flakiness on the abrasion properties was investigated through the introduction of two variables. These

Table 9 The Person coefficients of the relationships between the uniaxial compressive strength (UCS) and the micro-Deval value (M_{DE}) according to the two analysed data sets (DS-1 and DS-2)

	Linear form		Logarithmic form		Exponential form	
	DS-1	DS-2	DS-1	DS-2	DS-1	DS-2
UCS_d vs. M_{DE}	0.682	0.520	0.700	0.572	0.763	0.633
UCS_U vs. M_{DE}	0.690	0.561	0.667	0.601	0.811	0.728

Fig. 9 Relationship between the bulk densities measured in dry (D) and water-saturated (W) conditions according to DS-1

Fig. 10 Relationship between the bulk densities measured in dry (D) and water-saturated (W) conditions according to DS-2

variables were calculated according to the flakiness and micro-Deval test results (the latter ones were made in pairs):

$$\Delta_{FI} = \frac{FI_2 - FI_1}{FI_1} \cdot 100 \text{ and}$$

$$\Delta_{MDE} = \frac{M_{DE,2} - M_{DE,1}}{M_{DE,1}} \cdot 100,$$

where Δ_{FI} and Δ_{MDE} are the ratios of the flakiness indexes and micro-Deval test results which were made in pair, FI_1 and $M_{DE,1}$ are the test results of the sample with the smaller FI value in the pair and FI_2 and $M_{DE,2}$ are the test results of the sample with the higher FI value in the pair.

Previous studies (Rigopoulos et al. 2013; Bobály and Gálos 2016; Guo et al. 2018) suggested that the shape of the particles affect aggregate properties. Bobály and Gálos (2016)

Fig. 11 Relationship between the water absorption and the bulk densities measured in dry (D) condition according to DS-1

Fig. 12 Relationship between the uniaxial compressive strength and the modulus of elasticity determined in dry (D) condition according to DS-2

Fig. 13 Relationship between the uniaxial compressive strength values measured in dry (D) and in the united conditions (U) according to DS-1

investigated railway ballast of andesite from Komló (Hungary). They found linear correlation between aggregate properties (Los Angeles and micro-Deval values) and shape indicators (flakiness and shape indexes), with R^2 values within 0.526 and 0.800. They also revealed that the sum of FI and SI also correlates with the LA and M_{DE} values. It suggests that flaky or elongated particles are more prone to cracking (Guo et al. 2018). For the ultramafic rocks a linear ($R^2 = 0.456$), for trachyte and mafic rocks, a power function ($R^2 = 0.730$) was

used for the description of the interrelation between FI and M_{DE} (Rigopoulos et al. 2013). The FI and SI values are not independent; a strong positive linear correlation was revealed between them (Xirouchakis 2013).

The minor lithological differences of the studied andesites are also reflected in the results. The porphyric holocrystalline andesites, andesite-6 and andesite-7 (Komló) and andesite-9 (Recsk) (Table 1), have the highest dry uniaxial strength (Fig. 5). However, these high strength values are not prerequisites

Fig. 14 Relationship between the uniaxial compressive strength values measured in dry (D) and in the united conditions (U) according to DS-2

Fig. 15 Relationship between the uniaxial compressive strength values measured in dry (D) condition and the micro-Deval coefficient according to DS-1. Circles: andesites studied in this paper; crosses: test results of other lithotypes (the meaning of the sample IDs are available in Table 5)

Fig. 16 Relationship between the ratios of the flakiness indexes (measured with slot size of 6.3 mm) and the micro-Deval coefficients

of high M_{DE} values, since it seems that later diagenetic processes such as silification can have a more substantial influence on aggregate quality (low M_{DE}) than the primary micro-fabric which is the holocrystalline matrix. It is evidenced by comparing the results of Recsk andesite (andesite-9), which has the highest strength and best aggregate properties vs. the results of andesite-8 which also has holocrystalline micro-fabric, but low strength values and aggregate properties (Table 4). The basalt-like micro-fabric such as pilotaxitic texture can also increase the strength and durability of andesite. A good

example of this is the andesite-3 which has slightly pilotaxitic micro-fabric, but only this fine crystalline variety of Gyöngyössolymos site has high quality, while the other two lithotypes of the same site (andesite-1 and andesite-2) have lower strength and aggregate quality due to the larger crystal size (Table 4).

The test results of the studied aggregates suggest that there is no link between abrasion properties and flakiness in the case of andesites with 10.0/14.0-mm-sized grains. The results of the sieve tests with neither 6.3 mm (Fig. 16)

Fig. 17 Relationship between the ratios of the flakiness indexes (measured with slot size of 8.0 mm) and the micro-Deval coefficients

nor 8.0 mm sieves (Fig. 17) suggest any existing connection between these parameters. Negative Δ_{MDE} values are attributed to those specimens, when higher M_{DE} values were measured on the samples with lower FI . Negative values were observed in a relatively high amount, namely 44% of the measurements. These perceptions do not contradict the results of previous studies since Bobály and Gálos (2016) and Guo et al. (2018) dealt with aggregates with ballast-sized grains, while in this paper, aggregates with smaller particles were studied.

Conclusions

- According to the test results, there is no significant difference between strength parameters (uniaxial compressive strength, modulus of elasticity, indirect tensile strength) measured in water-saturated and freeze–thaw subjected samples. These results were confirmed by Welch's t tests.
- Significant differences were observed between the different andesite lithotypes. The highest strength and the most favourable aggregate properties were measured at the andesite from Recsk: $UCS = 271$ MPa; $M_{DE} = 4$ m%. This is closely linked to the micro-fabric, later post-volcanic processes, namely to the calcite cementation and silicification.
- From the studied thirteen lithological varieties, andesite-3 from Gyöngyössolymos and andesite-9 from Recsk have the highest quality in terms of micro-Deval abrasion, due to their micro-fabric and/or diagenetic alteration.
- Relationships were found between the rock mechanical parameters of the studied andesite. Linear correlations were obtained between:
 - 1 Bulk densities measured in dry and water-saturated conditions
 - 2 Water absorption and bulk density measured in dry condition
 - 3 Uniaxial compressive strengths measured in dry and in the united conditions
 - 4 Uniaxial compressive strength and modulus of elasticity both in dry condition and in the case of the united group of the water-saturated and freeze–thaw subjected conditions

The interrelations were detected if the whole data set of the test results was taken into account. In some cases, when the andesites of different micro-fabrics were analysed, no such connections were found.
- The relationship between uniaxial compressive strength and micro-Deval coefficients was analysed using linear, logarithmic and exponential forms. In contrast to the results of the previous studies, where linear functions were found, the best Pearson coefficients were provided by

exponential functions to describe the connection between rock mechanical and aggregate properties.

- The flakiness and micro-Deval test results did not seem to have a link for the studied aggregates of 10.0/14.0 mm in size, although the relationship between them in the case of larger particle sizes was proved by previous studies.
- Most of the studied andesites (except andesite-13 from Sárospatak) have favourable strength and abrasion properties. According to these tests, the Hungarian andesites are suitable materials of railway ballast, gabions, retaining walls, armour stone structures and aggregates in concrete or asphalt.

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