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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Received: 20 December 2019 / Accepted: 26 September 2020 / Published online: 15 October 2020 © The Author(s) 2020

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 (Gállos 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 (Sztatkowski and Hoskins 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 Čes 1965), the slake durability test (Hudec 1978; Ghobadi and Babazadeh 2015; Miščević 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.
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 (MDE) (Xirouchakis 2013; Tabatai et al. 2013; Török 2015); between the PSV, MDE and LA values (Đokić et al. 2015); between the LA, AIV and ACV values (Al-Harthi 2001; Fowler et al. 2006; Palassi and Danesh 2016); and between the MDE 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 (Uğur et al. 2010). According to numerous studies, UCS correlates with LA (Al-Harthi 2001; Kahraman and Fener 2007; Uğur et al. 2010; Rigopoulos et al. 2013) and MDE (Capik and Yılmaz 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 Gálov 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 MDE values.

Mineralogical properties affect rock mechanical and aggregate properties. The micro-fabric (Příkrýl 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

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**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 | Gyöngyöstorján | GT | Dark grey, porphyric hyalopilitic andesite with small plagioclase and altered pyroxene phenocrysts |
| Andesite-5 | Gyöngyöstorján | 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 | Sárospatak | S | Grey porphyric hyalopilitic andesite with plagioclase and pyroxene phenocrysts |
| Andesite-11 | Sárospatak | S | Slightly lilac grey porphyric hyalopilitic andesite with small pores |
| Andesite-12 | Sárospatak | S | Lilac grey porphyric hyalopilitic andesite with pyroxene phenocrysts and recrystallised mottles |
| Andesite-13 | Sárospatak | S | Greenish-grey porphyric hyalopilitic andesite with flow banding, pores and with plagioclase phenocrysts |
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 (Příkryl 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 (Miščević 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 (Afolagboyé 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         |
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 Recsk), 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.

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

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

where UCS is the modified compressive strength value recalculated from specimens with a diameter of 50 mm and a height of 100 mm, UCSm 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 (MDE), 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,
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 Krámli 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...
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/m³]; w, water absorption [m%]; F, weight loss caused by the F–T cycles [m%]; Vₚ, propagation speed of the ultrasonic wave [km/s]; UCS, uniaxial compressive strength [MPa]; E, modulus of elasticity [GPa]; σₜ, indirect tensile strength [MPa]; MDE, micro-Deval coefficient [m%])

| Sample ID | ρ (kg/m³) | w (m%) | F (m%) | Vₚ (km/s) | UCS (MPa) | E (GPa) | σₜ (MPa) | MDE (m%) |
|-----------|-----------|--------|--------|---------|-----------|--------|--------|--------|
|           | D | W | F–T | D | W | F–T | D | U | D | U | D | U |
| And-1     | Mean | 2684 | 2710 | 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 | 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 | 16 | 34 | 17 | 62 | 35 | 17 | 15 | 17 | 8 | 11 | 12 |
| And-2     | Mean | 2704 | 2726 | 2736 | 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 | 16 | 0.04 | 0.03 | 0.3 | 0.2 | 0.1 | 10.35 | 20.83 | 11.80 | 6.97 | 35.67 | 2.44 | 2.72 |
| Num.      | 33 | 20 | 10 | 10 | 11 | 32 | 11 | 10 | 5 | 8 | 5 | 12 | 10 |
| And-3     | Mean | 2718 | 2732 | 2738 | 0.58 | −0.03 | 5.5 | 5.0 | 5.2 | 127.48 | 114.79 | 26.11 | 23.97 | 11.94 | 8.42 | 7.37 |
| Std.      | 13 | 11 | 7 | 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 | 4 | 11 | 5 | 25 | 15 | 10 | 3 | 6 | 3 | 4 | 4 |
| And-4     | Mean | 2379 | 2457 | 2453 | 3.69 | −0.13 | 4.1 | 4.1 | 3.8 | 101.06 | 77.78 | 29.50 | 28.29 | 4.22 | 17.92 | 2.23 | 0.40 | 0.07 |
| Std.      | 15 | 6 | 7 | 25 | 15 | 5 | 6 | 9 | 6 | 9 | 4 | 5 | 2 |
| Num.      | 25 | 11 | 5 | 15 | 3 | 12 | 3 | 6 | 4 | 3 | 4 | 3 | 2 |
| And-5     | Mean | 2459 | 2521 | 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 | 6 | 0.17 | 0.03 | 0.1 | 0.2 | 0.1 | 11.99 | 10.85 | 3.99 | 14.11 | 2.45 | 0.86 |
| Num.      | 10 | 6 | 3 | 6 | 5 | 2 | 3 | 4 | 4 | 3 | 4 | 3 | 2 |
| And-6     | Mean | 2535 | 2579 | 2580 | 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 | 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 | 20 | 48 | 20 | 109 | 46 | 22 | 12 | 20 | 14 | 23 | 8 |
| And-7     | Mean | 2573 | 2606 | 2605 | 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 | 15 | 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 | 11 | 26 | 11 | 65 | 25 | 12 | 9 | 13 | 9 | 14 | 6 | 12 | 10 |
| And-8     | Mean | 2710 | 2735 | 2732 | 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 | 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 | 38 | 79 | 39 | 114 | 79 | 39 | 19 | 36 | 19 | 37 | 20 | 38 | 26 |
| And-9     | Mean | 2714 | 2730 | 2731 | 0.46 | −0.03 | 7.2 | 5.6 | 5.2 | 270.79 | 253.44 | 48.71 | 47.86 | 8.92 | 7.35 | 4.10 |
| Std.      | 28 | 24 | 21 | 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 | 32 | 57 | 31 | 268 | 61 | 35 | 28 | 29 | 23 | 22 | 22 | 29 | 26 |
| And-10    | Mean | 2603 | 2635 | 2633 | 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 | 17 | 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 | 6 | 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 |

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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 ($UCS$, $E$, $\sigma_t$) 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 $UCS$, $E$ and $\sigma_t$ 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 $UCS$ 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 ($\rho$, bulk density [kg/m$^3$]; UCS, uniaxial compressive strength [MPa]; $E$, modulus of elasticity [GPa]; $\sigma_t$, indirect tensile strength [MPa]; $M_{DE}$, micro-Deval coefficient [%]).

| Sample ID | Rock type | References | $\rho$ | UCS | $E$ | $\sigma_t$ | $M_{DE}$ |
|-----------|-----------|------------|-------|-----|-----|----------|--------|
| 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        | Çötlerekçikuyu andesite (Turkey) | Ozden and Topal 2009 | 2308  | 40.4  |      |          | 45.8   |
| 16        | Afyon andesite (Turkey) | Engin 2013 | 2350  | 175.0 | 15.8 |          |        |
| 17        | Huseyinagzi andesite (Turkey) | Sonmez et al. 2004 | 2480  | 91.1  | 8.7  |          |        |
| 18        | Huseyinagzi andesite (Turkey) | Sonmez et al. 2004 | 2310  | 49.9  | 7.4  |          |        |
| 19        | Andesite (Turkey) | Celik 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) | Gökalp et al. 2016 | 2700  |       |      | 10.4     |        |
| 23        | Basalt (Turkey) | Gökalp et al. 2016 | 2600  |       |      | 9.4      |        |
| 24        | Basalt (Turkey) | Gökalp et al. 2016 | 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        | Deginemencayi 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) | Gökalp et al. 2016 | 2700  |       | 21.3 |          |        |
| 46        | Limestone (Turkey) | Gökalp et al. 2016 | 2700  |       | 11.7 |          |        |
| 47        | Travertine (no marked origin) | Demirdag 2013 | 2371  | 62.0  |      |          |        |
| 48        | Gerdöoe travertine (Iran) | Jamshidi et al. 2016 | 2550  | 60.7  | 5.9  |          |        |
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 Nögrádkövesd—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 ($\rho_d$) 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 $\rho_d$ 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-...
|   | ρ₀ | wₐ | F  | Vₚ,D | Vₚ,U | UCSₐ | UCSₐ | Eₐ | Eₐ | σₐ,D | σₐ,D |
|---|----|----|----|------|------|------|------|----|----|------|------|
| R | 0.991 | −0.912 | 0.078 | 0.636 | 0.757 | 0.400 | 0.414 | 0.434 | 0.582 | 0.406 | −0.032 |
| N | 60 | 59 | 56 | 61 | 60 | 59 | 49 | 57 | 46 | 59 | 53 |
| R | −0.893 | 0.094 | 0.621 | 0.761 | 0.388 | 0.398 | 0.433 | 0.573 | 0.384 | −0.032 | −0.190 |
| N | 59 | 56 | 60 | 60 | 58 | 49 | 48 | 55 | 46 | 59 | 53 |
| R | −0.093 | 0.122 | 0.023 | 0.247 | 0.165 | 0.162 | 0.092 | 0.044 | 0.044 | 0.229 | 0.52 |
| N | 55 | 56 | 59 | 59 | 57 | 54 | 48 | 55 | 45 | 54 | 54 |
| R | 0.695 | 0.854 | 0.857 | 0.899 | 0.820 | 0.826 | 0.366 | 0.352 | 0.346 | 0.229 | 0.55 |
| N | 60 | 60 | 61 | 61 | 59 | 56 | 48 | 56 | 46 | 59 | 55 |
| R | 0.695 | 0.739 | 0.732 | 0.770 | 0.770 | 0.45 | 0.403 | 0.403 | 0.273 | 0.45 | 0.51 |
| N | 60 | 59 | 57 | 49 | 49 | 47 | 52 | 55 | 56 | 57 | 54 |
| R | 0.932 | 0.894 | 0.718 | 0.821 | 0.836 | 0.189 | 0.164 | 0.164 | 0.229 | 0.54 | 0.54 |
| N | 48 | 47 | 45 | 47 | 45 | 47 | 47 | 47 | 47 | 47 | 47 |
| R | 0.821 | 0.806 | 0.744 | 0.774 | 0.774 | 0.744 | 0.774 | 0.774 | 0.478 | 0.478 | 0.478 |
| N | 58 | 57 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| R | 0.582 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 | 0.504 |
| N | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 | 46 |

**Bold characters refer to high correlations between parameters, while italics means low or non-existing correlations between the parameters.**
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-Harthi 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-Harthi 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 8
The correlation matrix of the correlation analyses of the strength parameters available in the literature ($R$, Pearson coefficient; $N$, number of elements) ($\rho$, bulk density [$kg/m^3$]; $UCS$, uniaxial compressive strength [MPa]; $E$, modulus of elasticity [GPa]; $\sigma_t$, indirect tensile strength [MPa])

|     | $\rho$ | $R$  | $E$  | $\sigma_t$ |
|-----|-------|------|------|-----------|
| $\rho$ |       |      |      |           |
| $R$  | 0.322 | 0.186| 0.4701|
| $E$  | 28    | 6    | 5    |
| $\sigma_t$ | | | | |

**Table 9** The Pearson 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 |
|------------------|-------------|------------------|------------------|
| $UCS_D$ vs. $M_{DE}$ | 0.682       | 0.520            | 0.700            |
| $UCS_U$ vs. $M_{DE}$ | 0.690       | 0.561            | 0.667            |

**Table 7** (continued)
Variables were calculated according to the flakiness and micro-Deval test results (the latter ones were made in pairs):

\[ \Delta_{FI} = \frac{FI_2 - FI_1}{FI_1} \times 100 \]  
\[ \Delta_{MDE} = \frac{MDE_2 - MDE_1}{MDE_1} \times 100 , \]

where \( \Delta_{FI} \) and \( \Delta_{MDE} \) are the ratios of the flakiness indexes and micro-Deval test results which were made in pair, \( FI_1 \) and \( MDE_{1.1} \) are the test results of the sample with the smaller \( FI \) value in the pair and \( FI_2 \) and \( MDE_{2.2} \) 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)
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...
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)
nor 8.0 mm sieves (Fig. 17) suggest any existing connection between these parameters. Negative $\Delta MDE$ values are attributed to those specimens, when higher $MDE$ 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; $MDE = 4$ 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.

### Acknowledgements

Open access funding provided by Budapest University of Technology and Economics. The authors are thankful to Bobály János from KÖKA Kö- és Kavicsbányászati Ltd. and to László Ezsács from COLAS Ószakkó Ltd. for providing rock blocks for the laboratory tests. The authors are also indebted to the co-workers of the Laboratory of Engineering Geology and Material Testing Laboratory (Budapest University of Technology and Economics), especially to Gyula Emszt, Bálint Pálinkás, Krisztián Takács and Anna Szijártó for their participation and help in carrying out the laboratory tests.

### Funding

The financial support was provided by the National Research, Development and Innovation (NKFI) Fund (ref. no. K 116532). The research reported in this paper was also supported by the BME-Water Sciences and Disaster Prevention FIKP grant of EMMI (BME FIKP-VÍZ).

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