MISKOLCI EGYETEM
MŰSZAKI FÖLD- ÉS KÖRNYEZETTUDOMÁNYI KAR
MIKOVINY SÁMUEL FÖLDTUDOMÁNYI DOKTORI ISKOLA

THE INFLUENCE OF GEOLOGICAL PROPERTIES OF ROCKS ON BREAKAGE, GRINDABILITY AND ROCK PHYSICAL AND MECHANICAL PROPERTIES

Theses booklet of doctoral (PhD) dissertation

Márkus Izabella Rebeka
earth science engineer
mining and geotechnical engineer

Scientific supervisors:
Dr. Rácz Ádám
Prof. Dr. habil Mucsi Gábor

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES
Head of the doctoral school: Prof. Dr. Péter Szűcs
Professor, Doctor of the Hungarian Academy of Sciences

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I. Aims and scientific background of the research

The continuous growth in global demand for aggregates, coupled with the declining availability of high-quality raw materials, poses a major challenge for the industry. In 2022, aggregate production in Europe reached 1,809 million tonnes, with a per capita consumption of approximately 6 tonnes per year, a figure expected to increase in the near future. One of the most significant cost factors in aggregate production is comminution, which can account for 30–70% of the total energy consumption. Considering both the energy-intensive nature of comminution and the decreasing reserves of high-quality raw materials, the optimization of crushing processes is inevitable. The energy demand of the comminution process is primarily influenced by two factors: the crushing equipment and the properties of the raw material processed. Therefore, understanding the relationships between raw material characteristics, their comminution behaviour, and their impact on final product quality is essential for achieving more efficient production and optimizing energy use.

According to Wills et al. (2006), effective mineral processing technologies require precise knowledge of the petrographic characteristics of the processed raw material, including the mineral components, their spatial distribution, associations, and morphology. The relationship between petrographic features and comminution behaviour, grindability, as well as product quality has been a subject of research for decades. In the Hungarian literature, the works of Beke (1974) and Csőke (1976, 1979) already highlighted in the second half of the 20th century the connection between rock texture and grindability, in contrast to the prevailing view of the time, which primarily explained comminution behaviour in terms of physical–mechanical properties like hardness, elasticity, etc.

In the international literature, most studies focus on ore-bearing mineral resources, where the primary objective is the efficient liberation and recovery of valuable components (Abdelhaffez, 2020; Bonnici, 2012; Comakli & Cayirli, 2019;

Kekec et al., 2006; Lois-Morales et al., 2022; Pérez-Barnuevo et al., 2013; Petruk, 2000; Tugrul & Zarif, 1999). However, the assessment of the role of mineralogical composition and textural factors varies among researchers. Some authors (Yildirim, 2016; Abdelhaffez, 2020) emphasize the significance of mineral composition, particularly the effect of mineral hardness on the grindability, highlighting that secondary sulphates and clay minerals considerably reduce grindability. According to Wang (2015), the distribution of individual minerals and the proportion of minerals with high versus low hardness play a key role in crack formation and propagation: harder minerals tend to deform plastically under stress, whereas softer minerals are more prone to fracture initiation. Consequently, the proportion of softer minerals exerts a substantial influence on the rock breakage. In contrast, other researchers (Kekec et al., 2006; Oyarzún & Arévalo, 2011) suggest that rock texture exerts a more decisive influence: even with identical mineralogical composition, substantial differences in crushability and grindability may arise depending on textural variations. Pérez-Barnuevo et al. (2013) emphasize in particular the irregularities of grain boundaries and the types of mineral intergrowths as critical factors influencing rock strength, and consequently its comminution behaviour.

Numerous studies (Esmailzadeh et al., 2017; Ozturk et al., 2004; Howarth & Rowlands, 1987; Comakli & Cayirli, 2019) have examined the impact of textural characteristics—such as the size, shape, and orientation of mineral constituents—on rock strength and comminution behaviour. These investigations often employ the textural coefficient (TC), a composite index calculated from grain size, shape, and orientation. A higher TC value indicates a more complex rock texture; accordingly, TC shows a positive correlation with uniaxial compressive strength, while displaying a negative correlation with parameters describing crushability. Sun et al. (2017) confirmed this relationship but highlighted that validation across different rock types is hindered by the lack of sufficient high-quality datasets. Popov et al. (2020) found that as grain size decreases, the specific surface area of the grains increases, leading to

stronger cohesive forces; therefore, fine-grained rocks always exhibit significantly higher strength than medium- or coarse-grained rocks. At the same time, Liu et al. (2018) and Comakli & Cayirli (2019) pointed out that in rocks composed of grains with varying sizes influence crack propagation and thereby rock strength. Kekec et al. (2006) showed that within a single rock type, correlations can be established between texture, strength, and crushability, but such correlations cannot be generalized when comparing different rock types. Sun et al. emphasized that although many studies address the relationship between rock texture and strength, the results often show overlap and similarities; however, the lack of sufficient, high-quality datasets across different rock types and origins prevents robust validation of these findings.

The review of the literature suggests that rock texture exerts a stronger influence than mineralogical composition alone. The energy demand of comminution is primarily controlled by the cohesion between grains, the heterogeneity of grain-size distribution, and the proportion and spatial distribution of mineral phases with differing hardness. However, several authors emphasize that due to methodological differences, the results of various studies are often not directly comparable, and systematic investigations based on large datasets of homogeneous samples are still lacking.

In recent decades, research has increasingly focused on the relationship between petrographic features and product quality, particularly resistance to abrasion and fragmentation. These studies primarily focus on rocks used as crushed stone aggregates; however, as most of them are linked to Northern European regions, the investigated materials are largely granites, serpentinites, and limestones due to the prevailing geological conditions. The aim of these investigations is to determine how different mineralogical and textural properties influence the quality of the final product. According to the literature, rock physical properties are determined by the hardness, strength, compressive strength, and elastic modulus of the mineral constituents (Lindqvist et al., 2007). The influence of quartz and feldspar content is contradictory: Afolagboye et al. (2016) reported that high quartz, feldspar, or their combined presence

contributes to increased resistance to abrasion and fragmentation. Similarly, Faruk Apaydın and Yılmaz (2021) demonstrated that increasing feldspar content raises the Los Angeles (LA) value in basalts. In contrast, Okogbue and Aghamelu (2013) and Pomonis et al. (2007) showed through measurements on pyroclastics and dolerites that weathered feldspars tend to reduce rather than enhance resistance to fragmentation and abrasion. Adomako et al. (2021), Askaripour et al. (2022), and Strzałkowski & Kaźmierczak (2021) emphasized the effect of the quartz-to-feldspar ratio. Ademila (2019) and Ajagbe et al. (2015) concluded that this ratio is directly proportional to the Los Angeles value. The amphibole and pyroxene content generally have a negative effect on resistance to wear and fragmentation (Ajagbe et al., 2015; Brattli, 1992; H. Liu et al., 2005). Rock alteration and weathering products, such as smectite and illite, decrease resistance (Petrounias et al., 2018), while the effect of micas varies depending on grain size and orientation (Lindqvist et al., 2007; Nålsund, 2010; Tavares & das Neves, 2008). However, according to Adomako et al. (2021), the presence of serpentine as a weathering product has no measurable effect in ultrabasic rocks.

The influence of texture, as in the case of breakage, is highly significant, and most authors have identified a stronger relationship between texture and rock physical properties (Brattli, 1992). According to Adomako et al. (2021) and Åkesson et al. (2001), average grain size, grain-size differences, and the presence of a fine-grained matrix strongly affect crack propagation and thereby the mechanical properties. Based on the findings of Török and Czinder (2017), andesite with a fine-porphyritic texture exhibited greater resistance to wear than andesite with a coarse-porphyritic texture. The complexity of grain boundaries, along with the shape and surface irregularities of grains, is also a key factor influencing resistance to abrasion and fragmentation (Török & Czinder, 2017; Lindqvist et al., 2007; G. Liu et al., 2018). According to the findings of Åkesson et al. (2003), idiomorphic textures, where minerals display their own crystal form with smooth surfaces, exhibit lower hardness and resistance to fragmentation compared to xenomorphic textures, in which grains have irregular surfaces.

Based on the review of the literature, the following research gaps were identified:

- In the case of non-metallic mineral raw materials—particularly rocks used for aggregate production—the relationship between petrographic properties and breakage behaviour has not yet been systematically investigated.
- Studies specifically focusing on andesite are lacking: the literature typically compares rocks with very different compositions and textures (e.g., granite, limestone, gneiss), which differ fundamentally from the fine-grained, inequigranular texture of andesite.
- No systematic research is available that examines the influence of petrographic properties on breakage behaviour within a single rock type—such as andesite—using samples derived from a single rock body within one quarry.
- Existing studies often focus on individual parameters (e.g., grindability – B_{Wi}, uniaxial compressive strength, abrasion resistance, resistance to fragmentation), while complex approaches that evaluate multiple factors simultaneously are largely missing.
- Limited data are available on the effects of porosity, cracks and weathering, particularly in the case of andesite, where no comprehensive study has yet addressed these factors in detail.
- No research has been found that simultaneously and comprehensively investigates the relationships between petrographic characteristics, breakage behaviour, grindability, uniaxial compressive strength, and rock physical parameters.

Research objectives

The primary aim of this research is to conduct a systematic investigation on a single rock type - namely andesite, which is the most widely used raw material for crushed stone production in Hungary - in order to explore how its petrographic properties influence breakage behaviour and product quality.

II. Materials and methods

Samples:

Sampling was conducted in two quarry sites operated by Colas Északkő Ltd., namely the Tállya and Recsk quarries. Although both sites quarry pyroxene andesite, differences in their geographical setting and the temporal shift in the volcanic events responsible for the formation suggest variations in mineralogical composition and textural characteristics. Within each quarry, heterogeneity in the quality of the extracted raw material was also observed, reflecting these petrographic differences. The sampling strategy was designed to capture this variability by selecting specimens representing distinct degrees of weathering: a fresh andesite with no visible signs of alteration (T_1, R_1), a moderately weathered type (T_2, R_3), and a strongly weathered type (T_3, R_4) (Fig. 1, Fig. 2)

Fig. 1. Sample location and sample types from the Tállyai quarry

Fig. 2. Sample location and sample types from the Recsk quarry

Methods:

The testing methods applied in my research can be classified into two main groups: one aimed at the quantification of petrographic properties, and the other at the measurement and quantification of resistance to applied stresses

The quantification of petrographic properties was carried out through the combined application of several methods:

- Qualitative and quantitative determination of mineral composition by X-ray powder diffraction (XRD).
- Determination of bulk chemical composition by X-ray fluorescence spectroscopy (XRF), the data of which were used for the quantification of weathering.
- Observation and quantification of textural features with polarised light optical microscopy (OM), complemented by scanning electron microscopy (SEM-EDX) and micro-computed tomography (µ-CT) observation and measurements.
- Determination of porosity using the helium pycnometer method, complemented by µ-CT measurements.

The resistance to mechanical stressing was determined using several testing methods based on different principles. In selecting these methods, a key consideration was that

each procedure should represent a distinct type of stressing method, thereby enabling a comprehensive evaluation of the rock behaviour. The applied methods were:

- From the group of single particle breakage tests I applied the drop-weight testing method (Drop Weight Test, DWT), for which the necessary apparatus was designed and constructed in the workshop of the Institute of Raw Materials Preparation and Environmental Technology as part of this doctoral research. The method is applicable across a wide range of particle size fractions; for my own measurements, I selected the following fractions: 8–11.2 mm, 12.5–16 mm, 20–22.5 mm, 25–31.5 mm, and 40–45 mm. The test is characterized primarily by impact loading, which occurs between two surfaces.
- From the group of grindability tests, I applied the Hardgrove Grindability Test, which is widely used due to its relatively low sample requirement and straightforward execution, making it suitable for characterizing grindability across different rock types.
- From the group of rock physical properties tests—primarily aimed at characterizing product quality—I determined resistance to wear using the micro-Deval test and resistance to fragmentation using the Los Angeles test.
- From the group of rock mechanics tests, the determination of uniaxial compressive strength (UCS) was carried out.

III. Scientific results, theses

Based on the quantification of petrographic properties, it can be stated that the pyroxene-andesites quarried in the two locations exhibit broadly similar petrographic characteristics. While no major differences were observed in the principal mineral constituents, their relative proportions varied, and assemblages associated with secondary alteration processes accounted for the main differences. Optical microscopy revealed a porphyritic, holocrystalline texture at both sites, with idiomorphic to hypidiomorphic phenocrysts set in a predominantly microcrystalline, locally cryptocrystalline matrix. The grain sizes of both phenocrysts and matrix fell within a comparable range across the two localities. The progression of weathering was clearly discernible, with two distinct alteration types identified: in the Tállya samples, weathering was associated with increasing porosity and the development of smectite and carbonate minerals, whereas in the Recsk samples alteration was dominated by processes linked to Fe mobilization.

Scanning electron microscopic observations revealed significant microscale textural differences. In the Tállya samples, pores formed by the weathering of mafic minerals (amphibole, pyroxene) were partially filled with secondary mineral assemblages composed of smectite and carbonates, and porosity related to degassing during rock formation was also observed. In contrast, the Recsk samples were characterized by weathering associated with Fe mobilization and the formation of new Fe-rich phases, although in the most intensely weathered sample (R_4), smectite could also be observed.

He-pycnometry porosity measurements—supplemented by micro-CT analyses—revealed that in certain Tállya samples, closed porosity accounts for a substantial proportion of the total porosity.

To evaluate the resistance of the andesite samples to mechanical stressing, I applied a suite of testing methods based on different principles, which together offer a comprehensive characterization of the rocks' mechanical behaviour.

Márkus Izabella Rebeka

Theses

1. For the systematic investigation of the breakage properties of andesitic rocks, a testing apparatus based on the Drop Weight Tester (DWT) principle was developed within the framework of this doctoral research. This device enabled the laboratory-based evaluation of rock breakage susceptibility, expressed by the A×b parameter, under laboratory conditions.

2. I demonstrated that by determining a single breakage index (A×b) for each sample is insufficient to accurately describe the influence of petrographic parameters on the breakage behaviour of andesites. To properly assess these effects, the results need to be analysed by grain-size fraction and sample. The analysis revealed that different petrographic parameters dominate the breakage mechanisms at different size fractions: porosity in the coarser fractions (40–45 mm, 25–31.5 mm), alteration in the intermediate fractions (20–22.5 mm, 12.5–16 mm), and microscale features (identified through optical microscopy, micro-CT, and SEM) in the finest fraction (8–11.2 mm).

To evaluate breakage susceptibility in the drop-weight tests, t_n-model fitting was applied, and a single A×b parameter was derived to characterise the samples' susceptibility to breakage.. In examining the influence of petrographic parameters on breakage, the chosen unit of evaluation—whether the whole sample, fractions irrespective of sample, or fractions analysed within individual samples—plays a decisive role in identifying the effects of specific petrographic characteristics and in interpreting the results. When applied to entire samples, the fitted model characterizes the overall breakage susceptibility with a single A×b value. In this approach, the influence of individual petrographic parameters appeared less pronounced overall, yet the role of alteration and its associated smectite content remained clearly identifiable. By considering both sample types and individual grain-size fractions, a t_n model can be

fitted for each fraction, yielding a separate A×b value for every sample–fraction combination. These fraction-based A×b values provide a more detailed picture of the influence of petrographic properties, although choosing the interpretation unit can be crucial. When evaluating petrographic effects solely by fractions, the results show that the significance of individual parameters varies between size classes. Even so, alteration and smectite content consistently emerged as the most influential factors, while the effect of average hardness was also detectable. The most detailed insight was gained when fractions were further analysed by sample type, where it became evident which petrographic parameters exerted the strongest control: porosity in the coarser fractions (40–45 mm, 25–31.5 mm), alteration in the intermediate fractions (20–22.5 mm, 12.5–16 mm), and microtextural characteristics (as revealed by optical microscopy, micro-CT, and SEM) in the finest fraction (8–11.2 mm).

3. My investigations demonstrated that textural parameters commonly used in the literature and derived from optical microscopy - particularly the Texture Coefficient (TC) - are not suitable for andesite-type rocks with a substantial proportion of microcrystalline matrix when assessing the relationship between textural features and resistance to mechanical stressing. The dominance of the microcrystalline groundmass limits the quantitative evaluation of textural attributes; therefore, optical textural parameters should only be applied in conjunction with microscale textural characterization when used for prediction of breakage behaviour.

In studies examining the relationship between rock texture and strength, the quantification of texture is often carried out using indices calculated from the parameters of the constituent minerals (Askaripour et al., 2022, Comakli & Cayirli, 2019). One of the most commonly applied indices is the texture coefficient (TC) (Esmailzadeh et al., 2017; Howarth & Rowlands, 1987; Ozturk et al., 2004). The

determination of the TC is based on the smallest and largest diameters of the textural components, the grain area, and the orientation of the shape factor:

$$TC = AW\left\{\frac{N_0}{N_0 + N_1} * \frac{1}{FF_0}\right\} + \left\{\frac{N_1}{N_0 + N_1} * AR_1 * AF_1\right\}$$

where

AW- grain packing weighting

N0- number of grains whose aspect ratio is below a pre-set discrimination level

N1- number of grains whose aspect ration is above a pre-set discrimination level

FF0- arithmetic mean of discriminated form-factors

AR1- arithmetic mean of discriminated aspect ratios

AF1- angle factor, quatifying grain orientation

According to examples reported in the literature (Askaripour et al., 2022; Esmailzadeh et al., 2017; Räisänen, 2004), the texture coefficient (TC) shows a strong correlation with rock strength properties in certain lithologies—particularly granites. However, Ozturk et al. (2004, 2014) highlighted that in the case of rocks with complex textures it is difficult to establish a clear relationship between texture and strength. The present calculations demonstrated that in the case of andesite-type rocks with a significant proportion of microcrystalline groundmass, the TC is not suitable for evaluating the relationship between textural parameters and resistance to mechanical stressing, as the high proportion of microcrystalline matrix complicates the quantitative determination of textural features. Consequently, textural parameters determined by optical microscopy can only be considered when complemented with microscale features revealed by electron microscopy when predicting breakage behaviour.

4. I demonstrated that, for the examined andesite-type rocks, the combined use of micro-CT and He-pycnometry is essential for interpreting the influence of porosity, as together they provide the relevant values for total porosity as well as the proportions of different pore types. Based on the integrated analysis of He-pycnometer and micro-CT measurements, it was shown that the proportion of

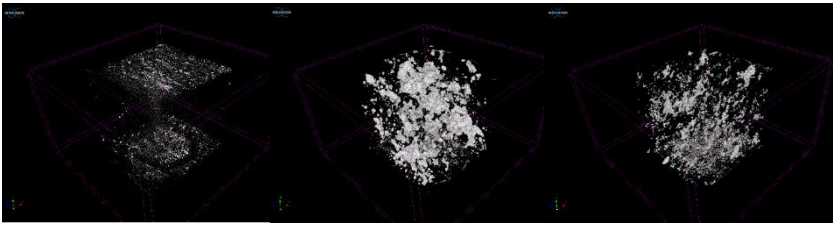
closed porosity is significant; therefore, using only the pycnometric method results in a considerable underestimation of total porosity. In contrast, the micro-CT method not only quantifies the volumetric ratio of pores but also allows the distinction between open and closed porosity.

The porosity of the samples was determined using multiple methods. First, helium pycnometry measurements were carried out, the results of which are summarized in Table 2.

Table 2.: He pycnometry prosity results

Sample	T_1	T_2	T_3	R_1	R_3	R_4
Porosity [%]	0.39	1.4	1.8	0.9	1.08	4.62

The accuracy of the method in determining porosity depends on the pore structure of the rock and the type of porosity present. While it provides precise measurements of density and open porosity, it is not necessarily reliable for quantifying total porosity, particularly in igneous rocks with a significant proportion of closed pores. Therefore, complementary micro-CT measurements were performed (Figure 3), which revealed the presence of closed pores that could not be detected by helium pycnometry.



T_1 T_2 T_3

Fig. 3. The porosity of samples from Tállya imaged with µ-CT method

Table 3 presents the sample volume, which corresponds to the volume scanned during measurement and reconstructed by the software. From this volume, the total porosity and its percentage were determined. The last two rows of the table show the proportions of open and closed porosity expressed as percentages. In the case of sample T_2, the

micro-CT measurements clearly indicate that the proportion of closed pores within the total measured porosity is 2.29%, which is significantly higher compared to the other samples, where closed porosity typically ranges between 0.61% and 0.03%.

Table 3.: Porosity data obtained from the μ-CT measurements

Sample	T_1	T_2	T_3	R_1	R_3	R_4
Volume of the sample [mm^3]	3309.1	3134.6	3094.5	3538.1	3198.35	3556.20
Porosity volume [mm^3]	7.84	124.83	43.56	9.09	6.19	37.7
Porosity [%]	0.23	3.98	1.40	0.26	0.20	1.06
Open porosity [%]	99.81	97.59	99.21	99.84	99.91	99.52
Closed porosity [%]	0.12	2.29	0.61	0.09	0.03	0.30

The presence of the two types of porosity of different origin was further confirmed by scanning electron microscopic observations. Figure 4 illustrates the coexistence of primary and secondary pores characteristic of sample T_2, whereas sample T_3 (Figure 5) was characterized predominantly by the occurrence of large secondary pores.

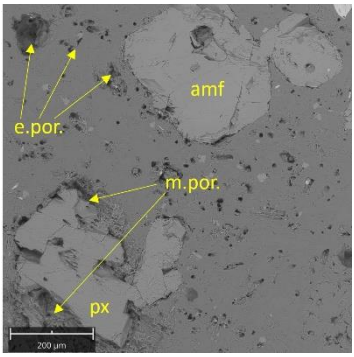


Fig. 4. Primary (e. por) and secondary (m. por) porosity in the T_2 sample (px- pyroxene, amf- amphibole)

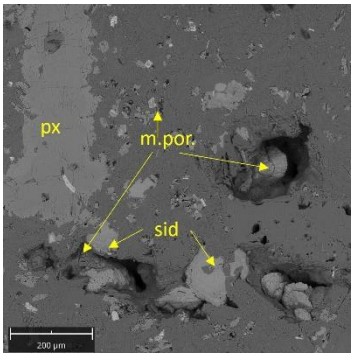


Fig. 5. Large secondary (m. por) pores in the sample T_3 (sid- siderite, px- pyroxene)

5. Based on my investigations, I concluded that in the case of porosity of andesites, it is not the total porosity content but rather its genetic origin - whether primary, formed during rock solidification, or secondary, associated with weathering processes - that governs the breakage behaviour of the rock. Primary pores, formed by degassing, exert little influence on breakage susceptibility, whereas secondary, weathering-related porosity has a pronounced effect on breakage properties. Thus, the formation mechanism of porosity represents a key factor in assessing the resistance of rocks to fragmentation.

Based on the grain-size specific evaluation of different rock types, porosity showed no detectable effect on breakage susceptibility as characterized by the A×b parameter. The results indicated only a weak fit with the applied regression model (R^2 = 0.05–0.25) (Fig. 6, 8). However, porosity data revealed that sample T_2 contained a substantially higher proportion of closed porosity compared to the other samples. When excluding T_2 from the analysis, a moderately strong monotonically increasing linear relationship between porosity and the A×b parameter was identified across all fractions (Fig. 7, 9).

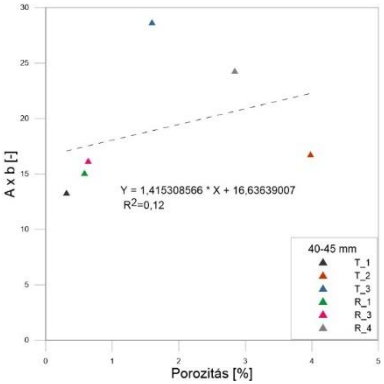


Fig. 6. Relationship between A×b values and porosity in the case of fraction 40-45 mm

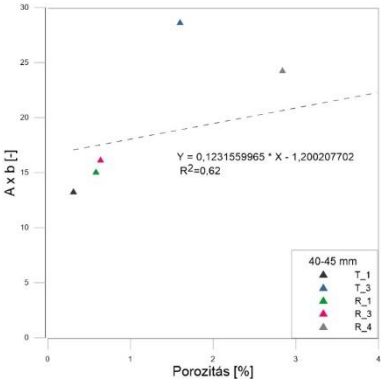


Fig. 7. Relationship between A×b values and porosity without sample T_2 in the case of fraction 40-45 mm

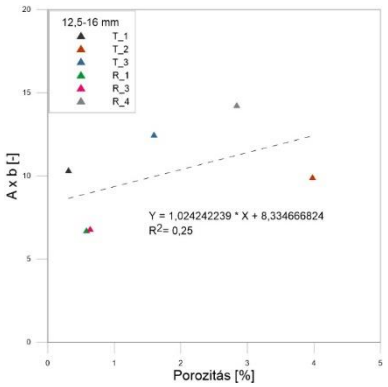
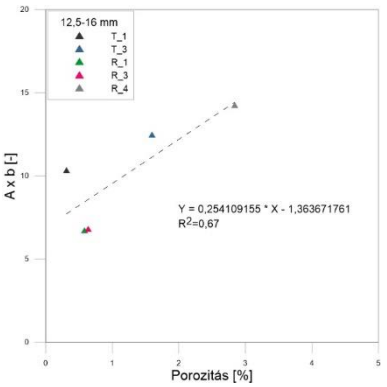


Fig. 8. Relationship between A×b values and porosity in the case of fraction 12.5-16 mm



9. ábra: Relationship between A×b values and porosity without sample T_2 in the case of fraction 12.5-16 mm

6. In my investigations, I have proved the significant influence of weathering on breakage behaviour and rock physical properties. Smectite, a hydrated clay mineral formed during weathering, reflects the degree of alteration in the rock. Since weathering may also manifest through other alteration products beyond smectite content, I introduced the Chemical Index of Alteration (CIA) for the quantification of alteration. In the case of andesitic rocks, this enabled the quantitative assessment of the effect of weathering on breakage and rock physical properties.

The presence of smectite could in some cases already be identified with optical microscopy (Fig. 10) and scanning electron microscopic observations (Fig. 11), primarily as pores formed by weathering with secondary mineral fillings. Its qualitative determination was carried out using X-ray powder diffraction, and the smectite content of the individual samples is presented in Fig. 12.

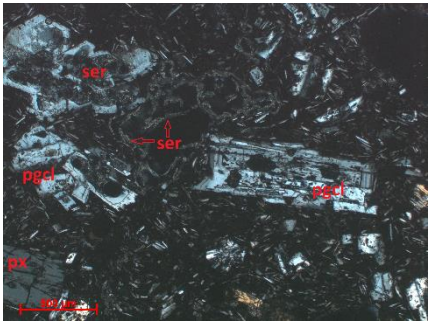


Fig. 10. Smectite content observed in the T_3 sample with optical micorscopy (pgcl- plagioclase, px- pyroxene, sm- smectite)

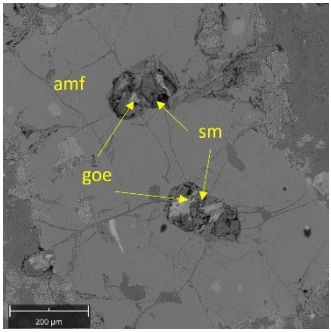


Fig. 11. Smectite content identified with SEM-EDX in the R_4 (sm- smectite, goe- goethite)

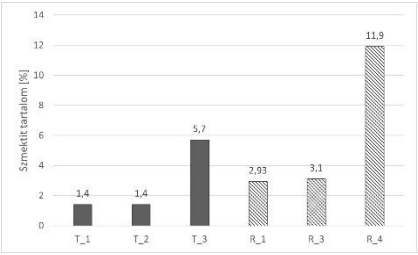


Fig. 12. Smectite content of individual samples

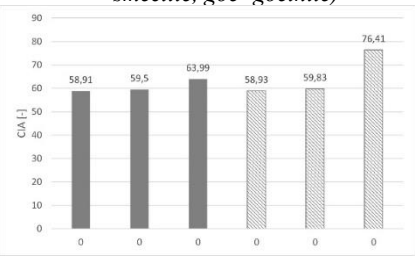


Fig. 13. CIA values of individual samples

Since weathering can manifest not only through smectite content but also via other alteration products—such as goethite in the Recsk samples or kaolinite in sample R_4—the degree of weathering was quantified using the Chemical Index of Alteration (CIA) (Nesbitt & Young, 1982):

$$CIA = \left[\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O}\right] * 100$$

where CaO* is the CaO content included in silicate minerals, excluding other Ca sources, like carbonates, apatite. For the calculation of the weathering index, the chemical composition determined by XRF measurements was used, while the CIA values of the individual samples are presented in Figure 13.

a). A significant relationship was identified between the CIA values, smectite content, and breakage susceptibility, indicating that the degree of weathering progression is reliably reflected in the breakage behavior of the rock.

Regardless of the evaluation unit—whether considering the whole sample, grain-size fractions, or combined sample and fraction analyses—the influence of weathering and smectite content was consistently evident. At the individual sample level, among all parameters, weathering (CIA) (Fig. 14) and smectite content (Fig. 15) proved to be the most decisive factors. Grain-size–based analyses also highlighted the strong impact of these two variables, with the CIA exerting an even more pronounced effect in certain fractions (20–22.5 mm and 25–31.5 mm) (Fig. 16). For smectite content, in the coarser grain-size ranges, the fitted exponential model indicated a stronger relationship (Fig. 17.).

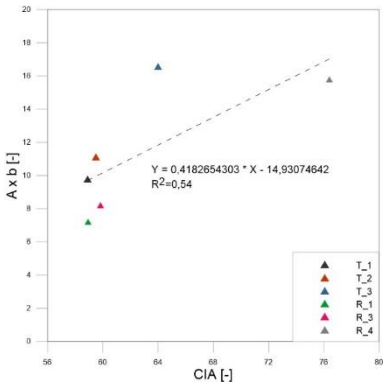


Fig. 14. Relationship between A×b values and CIA for the whole samples

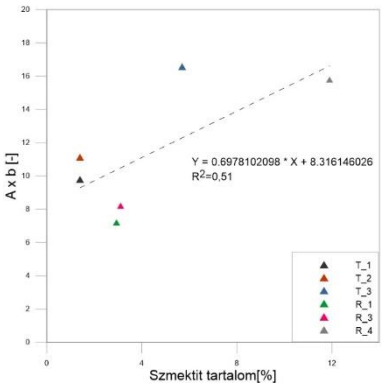


Fig.15. Relationship between A×b values and smectite content for the whole samples

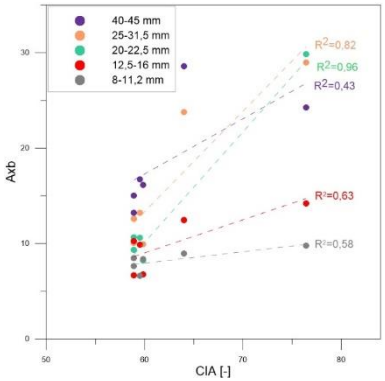


Fig. 16. Relationship between A×b values and CIA for different fraction sizes

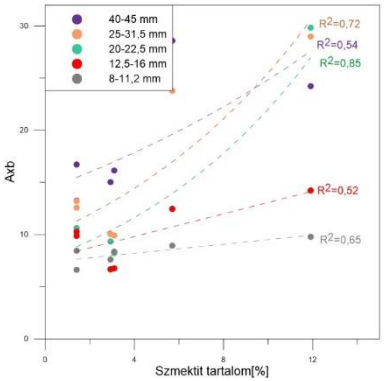


Fig. 17. Relationship between A×b values and smectite content for different fraction sizes

In the combined sample- and grain-size–based approach, the influence of CIA and smectite content also proved to be significant. The fitted linear model showed a monotonically increasing trend across all fractions, with coefficients of determination (R^2) ranging between 0.44 and 0.96, indicating moderate to strong fits. Variations in the weathering index effectively explained the breakage susceptibility of the studied samples, demonstrating that the impact of petrographic parameters can be quantified and evaluated using the A×b index. For example, in the 40–45 mm fraction, the effect of CIA is illustrated in Fig. 18 and that of smectite in Fig. 19, while in the 20–22.5 mm fraction the influence of CIA is shown in Fig. 20 and that of smectite in Fig. 21.

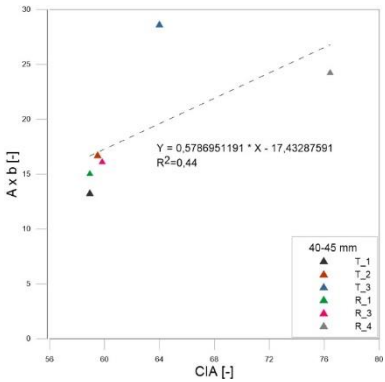


Fig. 18. Relationship between A×b values and CIA for the fraction 40-45 mm

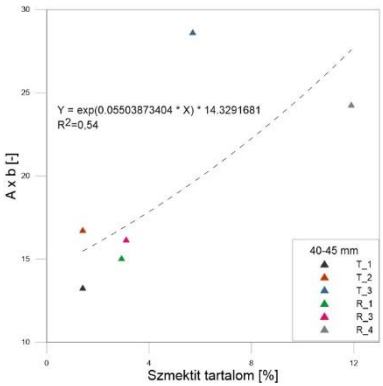


Fig. 19. Relationship between A×b values and smectite content for the fraction 40-45 mm

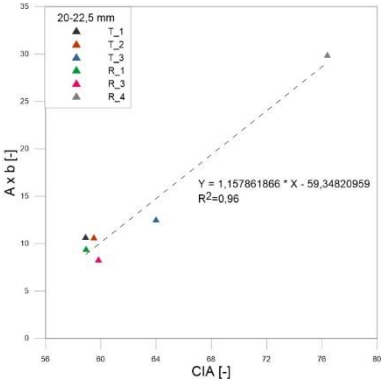


Fig. 20. Relationship between A×b values and CIA for the fraction 20.22.5 mm

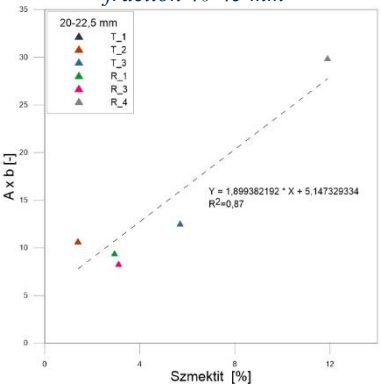


Fig. 21. Relationship between A×b values and smectite content for the fraction 20-22.5 mm

b). In the case of the studied andesite-type rocks, resistance to wear and resistance to fragmentation are mainly influenced by the degree of weathering, expressed by the CIA, and the associated smectite content.

The investigation of andesite-type rocks demonstrated that resistance to wear and fragmentation is primarily controlled by the degree of weathering, effectively expressed by the CIA value, while the closely associated smectite content also exerts a significant influence. In all cases, the fitted regression lines indicated a monotonically increasing trend. The strength of these relationships is reflected in the coefficients of determination: for micro-Deval vs. CIA, $R^2 = 0.97–0.98$ (Fig. 22); for micro-Deval vs. smectite content, $R^2 = 0.92–0.98$ (Fig. 23); for Los Angeles index vs. CIA, $R^2 = 0.93$ (Fig. 24); and for Los Angeles index vs. smectite content, $R^2 = 0.87–0.93$ (Fig. 25). Beyond these two parameters, no other petrographic factors were found to exert a significant effect, indicating that in rocks of comparable mineralogical composition and texture, secondary alteration processes play a decisive role.

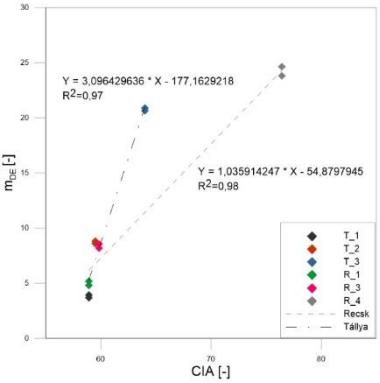


Fig. 22. Relationship between micro-Deval value and CIA

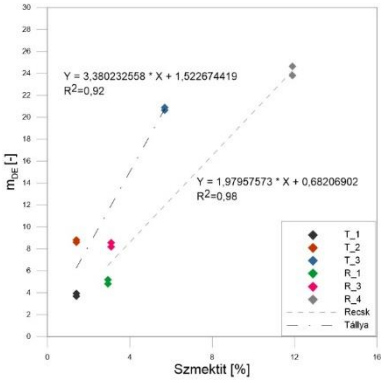


Fig. 23. Relationship between micro-Deval value and smectite content

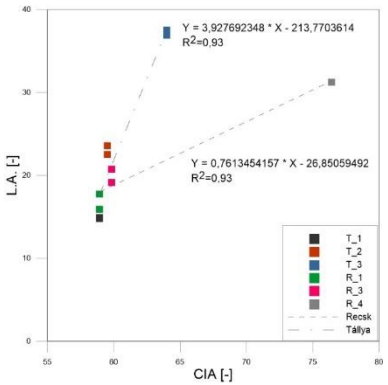


Fig. 24: Relationship between Los Angeles value and CIA

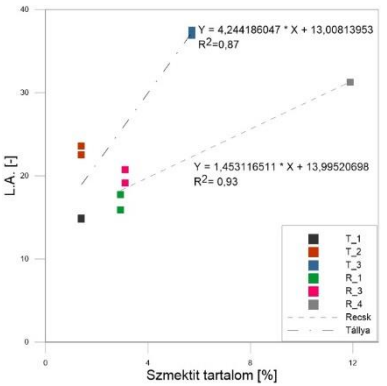


fig. 25. Relationship between Los Angeles value and smectite content

c). Although resistance to wear (wet condition, stressing method abrasion) and resistance to fragmentation (dry conditions, main stressing method impact) represent different stressing mechanisms, the results clearly demonstrated that both weathering and smectite content exert a significant influence in both testing method.

7. I concluded that no clear relationship could be established between the quantity of individual mineral phases - such as quartz or feldspars - and breakage susceptibility or grindability. However, in the case of andesite-type rocks, a clear relationship was identified between the average hardness calculated from mineral composition and both the breakage and grindability properties.

The influence of individual mineral constituents—such as crystalline SiO_2 (quartz + cristobalite), K-feldspar, and plagioclase feldspar—on the breakage susceptibility and grindability of andesites could not be clearly identified. However, based on the mineral composition, the average hardness was determined for each sample, as illustrated in Fig. 26.

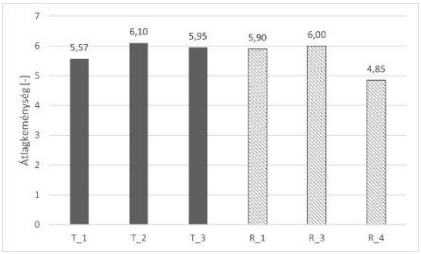


Fig. 26. Calculated average hardness of the samples

a). A moderate monotonic decreasing trend was identified between the average hardness calculated from mineral composition and breakage behaviour—particularly in the intermediate grain-size range. This indicates that the composition-derived average hardness, even in the absence of direct effects from individual mineral phases, can provide valuable information for predicting the breakage susceptibility of andesite-type rocks.

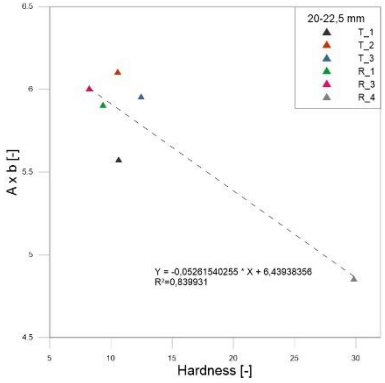


Fig. 27. Relationship between A×b values and hardness for the fraction 20-22.5 mm

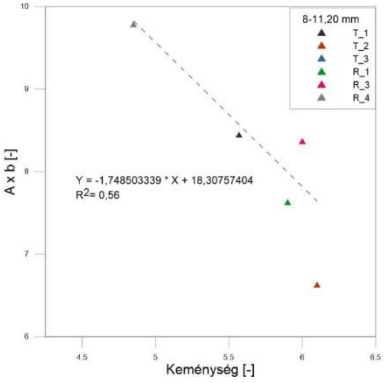


Fig. 28 Relationship between A×b values and hardness for the fraction 8-11.2 mm

In the intermediate grain-size range (20–22.5 mm), the influence of hardness was more pronounced (Fig. 27), whereas in the 40–45 mm fraction no clear relationship was

observed. For the other fractions, the effect remained moderate, as reflected by R^2 values of 0.45–0.60 (Fig. 28). It is important to emphasize that the effect of hardness was identifiable only when analysing by fractions and sample types. This suggests that, with a sufficient number of validating measurements, hardness—despite the absence of direct effects from individual mineral phases—can provide valuable information for predicting the breakage susceptibility of andesite-type rocks.

b). A monotonically decreasing relationship was identified between the average hardness calculated from mineral composition and the Hardgrove Grindability Index (HGI), indicating that average hardness may serve as a suitable indicator of grindability even for andesite-type rocks. However, this requires the accurate quantitative determination of non-crystalline components, such as volcanic glass or weathering products, to ensure that the proportions of crystalline phases forming the basis of the hardness calculation are as precise as possible.

The effect of average hardness on Hardgrove grindability was clearly identifiable: with increasing hardness, the grindability of the samples decreased (Fig. 29). The high R^2 values of the fitted linear function confirm that hardness is a key factor in determining grindability. However, the magnitude of this effect varied between sites, most likely due to differences in the types of secondary rock alteration processes.

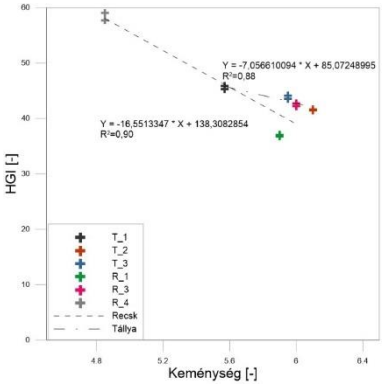


Fig. 29. Relationship between HGI and hardness

c). Hardgrove grindability is not determined solely by the hardness or proportion of individual mineral components but is also strongly influenced by secondary alterations affecting the rock, particularly the textural modifications and mineral phase transformations resulting from weathering.

The parameters influencing grindability showed different tendencies for the samples from the two sites, Tállya and Recsk. In the case of the Recsk quarry samples, correlations were observed with nearly all investigated parameters. However, for sample R_4, XRD analyses revealed a kaolinite content of 21%, a feature unique to this sample, which likely affected its grindability. Alteration processes in the Recsk samples were primarily characterized by the gradual mobilization of Fe from the mafic minerals (amphibole, pyroxene) and the formation of new Fe-rich phases (Fig. 30). As a result, porosity was less characteristic of their texture.

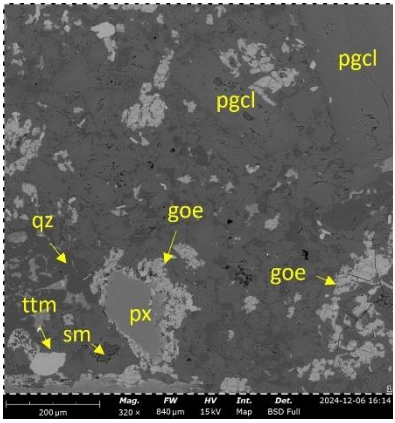


Fig. 30. Fe-rich secondary mineral p phases in the R_3 sample (px- pyroxene, goe- goethite, pgcl- plagioclase, qz. quartz. ttm- titanomagnetite, sm -smectite)

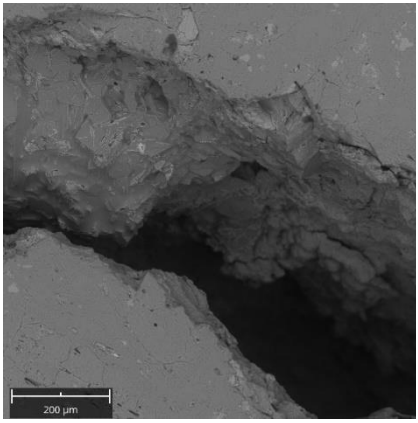


Fig. 31: Large sized pore with carbonate minerals with smectite content in the T_2 sample

In the case of the Tállya samples, the interplay of complex porosity, weathering processes, and associated mineral transformations resulted in a more nuanced picture. For these samples, clear correlations could only be identified with hardness and the average grain size of the matrix. Weathering here produced large pores, which were partially filled by secondary mineral assemblages of carbonates and smectite, formed as a result of subsequent low-temperature hydrothermal fluids (Fig 5 and 31).

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IV. List of publications

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Márkus Izabella Rebeka

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