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Investigation of the Possible Correlations between Specific Characteristics of Crushed Stone Aggregates

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ABSTRACT

This study rigorously investigates the interdependencies among a suite of crushed stone aggregate characteristics to enhance material selection for infrastructure projects. Utilizing data from Colas Északkő Ltd. (andesite quarries), the authors explore the relationships between mechanical and geometrical properties, particularly focusing on the interplay between the flakiness index, shape index, Los Angeles abrasion, Micro-Deval wear, and methylene blue assessments. The presented analysis reveals an unexpectedly robust correlation between FI and SI, proposing a novel paradigm for evaluating grain shape. Notably, the relationship between Los Angeles abrasion and micro-Deval wear values, typically considered disparate, is re-examined, unveiling potential predictive capabilities for environmental wear, especially as indicated by magnesium sulfate soundness testing. Additionally, the current study delineates a significant correlation between methylene blue values and micro-Deval wear performance, highlighting the intrinsic mineralogical influences on aggregate durability. The implications of findings are twofold: they suggest a streamlined approach for aggregate quality assurance and offer strategic insights into the refinement of material selection processes, thereby promising to enhance the durability and service life of transportation infrastructure.

1. Introduction

This section details the measuring opportunities of the characteristics of rock aggregates.

The use of aggregate products is regulated in Hungary, as in the rest of Europe, by product standards for different applications. Among these, the highest demand for raw materials is in the following areas of application:

i. EN 13043:2002, Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas [1];
ii. EN 12620:2002+A1:2008 NA:2016, Aggregates for concrete [2];

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iii. EN 13242:2002+A1:2007, Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction [3];
iv. EN 13450:2002, Aggregates for railway ballast [4];
v. prEN 13383-1:2021, Armourstone. Part 1: Specification [5];
vi. EN 13383-2:2019, Armourstone. Part 2: Test methods [6].

In addition to these, other areas of application have been regulated, such as aggregates for mortars, additives for lightweight concrete mixes, etc., but these are different in nature from the listed stone products, with significantly different testing possibilities, and are therefore not covered in this paper. It is also important to note that this paper does not deal with the different application conditions, the content of National Application Documents (NADs) and their differences between Member States of the European Union (EU) based on product standards, but only with the possible further reduction of the number of test methods in product standards and the correlations that can be identified between the individual test methods.

The primary reason for this is that, although in scientific terms the number of these test methods and possible characteristics is rather limited, in practical terms it is not possible to take all parameters into account in mining processes, in the design of the product, in the crushing-classification processes; in practical terms, this means that manufacturers generally seek and apply to their design processes those parameters that are the priority parameter for a given area of use, or those whose control and implementation in the mining design processes can predict compliance with several expected parameters.

The standards listed above contain the classification options (test procedures) for which the field has standard test methods, and which allow classification and evaluation according to different properties. However, each of the different fields of application has its own specific test procedures, such as the characterization of bituminous adhesion of stone materials used in asphalt mixtures, or the testing of components affecting the bonding-hardening time of concrete admixtures. However, due to the limited number of methods for standard testing of aggregates and the similar approach to the requirements, the same test methods are used as qualifying parameters in all disciplines and are categorized in the standards for the different fields of application as follows:

i. geometrical requirements;
ii. physical requirements;
iii. chemical requirements;
iv. durability requirements.

Each of the elements of the grouping listed includes more than one testing method. A detailed description of these is beyond the scope of this paper and can be found in detail in the product standards. The CE sheets of a crushed stone product show the possible test methods and the classes and requirements adopted by the manufacturer. The following lists contain the relevant parameters for an NZ 4/8 (NZ means fined crushed stone, 4/8 means that the d=4 mm, hence the D=8 mm, where d means the minimal size of the aggregate in mm unit, hence D means the maximal) crushed andesite for asphalt mixtures.

The geometrical requirements:

i. aggregate size (d/D) [7];
ii. grading [7];
iii. overall limits and tolerances for coarse aggregate grading at mid-sieves [7];
iv. tolerances on declared typical grading for fine and all-in aggregates [7];
v. fines content (<0.063 mm) [7];
vi. shape index (SI) [8];

vii. flakiness Index (*FI*) [9];
viii. percentage of crushed or broken particles [10];
ix. angularity of fine aggregates [11];
x. bulk density [tons/m^3] [12].

The physical requirements:

i. fines quality [13];
ii. resistance to fragmentation (*LAA*) [14];
iii. polished stone value (*PSV*) [15];
iv. aggregate abrasion value (*AAV*) [15];
v. resistance to wear (*MDE*) [16];
vi. resistance to abrasion of studded tyres (*AN*) [17];
vii. particle density [tons/m^3] [18];
viii. water absorption (*w*) [18];
ix. resistance to freezing and thawing (*F*) [19];
x. resistance to thermal shock (*VLA*) [20];
xi. affinity to bituminous binder (6 hours) [21];
xii. affinity to bituminous binder (24 hours) [21];
xiii. boiling test for „Sonnenbrand basalt” (*SLA*) [22];
xiv. petrographic description [23];
xv. heavy, lightweight contaminators [24];
xvi. magnesium sulfate soundness of coarse aggregates (*MS*) [25];
xvii. hazardous ingredients.

Other requirements:

i. additional requirements according to NADs (optional) [26].

In this article, a comparative analysis is primarily carried out of those pairs of values, without claiming completeness, for which, according to the purpose of the study, it is possible to draw conclusions from the results of several test methods or, on the basis of the authors’ experience, to assume a good correlation between their results.

2. Literature review

Understanding the critical relationship between the mechanical and physical properties of crushed stone aggregates and its performance is essential for the design and operation of efficient, long-lasting transport infrastructure, e.g., railway systems [27–31]. The selection process for effective railway ballast involves a thorough assessment of aggregate properties, ranging from mechanical resistance to environmental durability. This process combines empirical correlations, advanced predictive models, and rigorous testing methodologies to identify aggregates that meet the stringent requirements of railway construction and maintenance [32]. This method ensures the selection of materials that provide the necessary stability, durability, and performance for railway tracks [32].

Recent advances in predictive modeling and data analysis, such as artificial neural networks (ANN), adaptive neuro-fuzzy inference systems (ANFIS), and gene expression programming (GEP), have revolutionized the selection process for railway ballast [32]. These technologies enable the correlation of basic physical properties with critical performance indicators like the Los Angeles Abrasion Value (*LAA*) and Micro-Deval (*MDE*) coefficients, streamlining the selection process and enhancing the durability and reliability of railway constructions [27,32].

Innovations in aggregate testing and analysis have refined the assessment of rock types for use as railway ballast [33]. Predictive models, relying on empirical data and computational methods, provide a comprehensive framework for evaluating key aggregate characteristics [33]. These advancements facilitate informed decisions about ballast material selection, contributing to more resilient railway infrastructure [33].

The geometry of ballast particles, particularly their angularity and surface texture, significantly impacts railway track stability [34]. Angular and rough-textured aggregates are preferred for their superior interlocking capabilities, crucial for effective load distribution and track structural integrity [34]. This mechanical interlock is pivotal in preventing track deformation and promoting efficient drainage, extending the operational life of railway tracks [34].

The ability of ballast aggregates to withstand crushing under load is vital for their performance [35]. Tests such as the Aggregate Crushing Value (*ACV*) and Ten Percent Fines Value (*TFV*) gauge an aggregate's durability and strength, aiding in the selection of materials capable of withstanding the demands of railway service [35]. High crushing resistance indicates a ballast layer that will maintain structural integrity while effectively distributing loads and preserving track geometry [35].

Strength parameters, like the Point Load Strength Index (*Is(50)*) and Uniaxial Compressive Strength (*UCS*), measure an aggregate's capacity to bear loading without failure [35]. These metrics are crucial for evaluating the performance of ballast materials and for comparing different rock types based on strength. Empirical correlations between these strength indicators and aggregate degradation properties simplify material selection, ensuring long-term stability of railway tracks [35].

A thorough examination of the relationship between aggregate degradation values and rock strength parameters has revealed strong empirical correlations [35]. These correlations facilitate the prediction of aggregate performance based on strength characteristics, allowing for more efficient material selection in railway infrastructure projects [35]. This efficiency contributes to increased track durability and performance, underscoring the importance of empirical data in the selection process [35].

The environmental durability of railway ballast, influenced by the mineralogical composition and porosity of the aggregates, is crucial for long-term performance under various weathering conditions [36]. Understanding how aggregate properties interact with environmental factors is vital for selecting materials that will function optimally throughout the railway track's expected service life, emphasizing the role of environmental considerations in the selection process [36].

As the demand for efficient and sustainable rail transportation grows, the significance of rigorous ballast selection processes becomes increasingly apparent [32]. These processes are essential for the successful implementation of railway projects, requiring a careful balance of mechanical strength, environmental resilience, and long-term performance [32]. The strategic use of empirical data, computational models, and comprehensive testing protocols is necessary to identify aggregates that meet the stringent standards of railway construction, highlighting the ongoing need for research and technological advancement in this critical field of civil engineering [32].

To summarize, meticulous ballast material selection, informed by standardized testing, empirical correlations, and advanced predictive models, is critical for ensuring railway track structural integrity and operational efficiency [32]. These selection processes enable engineers to make informed decisions about the best ballast materials for specific applications, emphasizing the importance of high-quality aggregates with superior mechanical properties [32]. The continued development of analytical techniques and computational models promises to refine these selection processes further, emphasizing the role of ballast in the sustainability and safety of railway infrastructure [32].

Igneous rocks, such as basalt and granite, are frequently chosen as ballast due to their superior mechanical properties over sedimentary and metamorphic rocks [37]. Their selection is based on the ballast's higher hardness and cohesive strength, contributing to less degradation and a longer service life [37]. This preference highlights the significance of geological considerations in ballast selection [37].

This comprehensive narrative, now supplemented with the original reference numbering, ensures a logical flow and retains the importance of each paragraph and reference, providing a structured overview of the critical aspects of railway ballast selection and performance evaluation.

The study by Czinder and Török [38] delves into the relationship between rock mechanical parameters and the micro-Deval coefficient, highlighting correlations identified through correlation and regression analyses. This research sheds light on the interplay between the *MDE* values and *UCS*, offering insights into the durability assessment of andesite based on these parameters.

Qian *et al.* [39] focus on characterizing ballast degradation through the Los Angeles abrasion test and image analysis, aiming to enhance understanding of field degradation trends to improve ballast serviceability and lifecycle performance. This approach emphasizes the importance of visual and mechanical testing in assessing the long-term viability of railway ballast materials.

Adomako *et al.* [40] discuss how the textural composition of rocks, specifically those with fine-grain sizes, can enhance fragmentation and wear resistance. This finding is crucial in understanding the relationship between rock physic characteristics and the performance of aggregates in tests, highlighting the importance of grain size in determining the performance of aggregates in these applications.

Guo *et al.* [41] emphasize the significance of particle morphology, including size and shape, in influencing the performance and deformation of granular materials like railway ballast. This research underlines the critical role of physical geometry in the structural integrity and functional performance of railway systems.

The comparative study by Jing *et al.* [42] reveals differences in abrasion resistance between materials like steel slag and granite ballast, highlighting the variability in durability and longevity across different ballast materials. This comparison is essential for understanding how different materials respond to similar operational stresses and wear conditions.

Suhr *et al.* [43] explore the parametrization of Discrete Element Method (DEM) models for railway ballast, emphasizing the influence of particle shape representation and contact laws on simulation outcomes. This study provides insights into the complex relationship between rock physic characteristics and various abrasion tests, shedding light on the interplay between material properties and simulation parameters.

Vo *et al.* [44] investigate the shear behavior of latite basalt aggregates in triaxial tests to assess their performance as railway ballast. This research focuses on parameters such as flakiness index, particle size distribution, and uniformity coefficient, which are crucial in determining the performance of ballast material in railway applications.

The issue of ballast fouling, as discussed in [45], highlights the challenges posed by fine particles filling the voids of granular materials, impacting railway performance and safety. This research discusses fouling mechanisms, inspection methods, and solutions, emphasizing the importance of efficient inspection and treatment methods, such as ground-penetrating radar and ballast cleaning.

Moaveni *et al.* [46] discuss the use of advanced aggregate imaging systems to evaluate the resistance of aggregate particles to breakage, abrasion, and polishing. This study focuses on capturing changes in shape and size properties of aggregate particles caused by various mechanisms, highlighting the effectiveness of imaging systems in quantifying changes in morphological properties.

The advancements in digital image analysis for quantifying ballast gravel abrasion, as indicated in [043], demonstrate the correlation between roundness and track quality index (TQI), as well as sphericity and maintenance works. This study suggests that ballast replacement should be considered when the abrasion of ballast aggregates reaches around 10%, emphasizing the importance of monitoring abrasion levels in railway ballast to maintain track quality and efficiency.

According to [47], there was no correlation found between the Los Angeles abrasion test and the micro-Deval test results, suggesting that these tests measure different aspects of railway ballast's rock physic characteristics. This indicates that the Los Angeles abrasion test may not provide comprehensive insights into the material's durability as assessed by the micro-Deval test.

Hydzik-Wiśniewska and Bednarek [48] discuss the statistical analysis of mechanical properties, including abrasion, in Carpathian sandstone aggregates. This aligns with the focus on the relationship between rock physic characteristics of railway ballast and abrasion tests, indicating the relevance of these tests in understanding the mechanical properties of rock aggregates used in railway ballast.

Huschek-Juhász *et al.* [49], Lane *et al.* [50], Nener-Plante [51], Czinder and Török [52], Gálos and Kárpáti [53], Knodel *et al.* [54], Árpás *et al.* [55], Pachoukova [56], Orosz *et al.* [57], and Woodside and Woodward [58] contribute further to the understanding of material selection, degradation mechanisms, testing methodologies, and the impact of physical and mechanical properties on the performance and longevity of railway ballast. Each study adds a layer of depth to the narrative, emphasizing the complex interactions between material properties, environmental conditions, and operational stresses in the context of railway infrastructure maintenance and design.

This comprehensive synthesis, integrating detailed insights from a wide range of studies, underscores the multifaceted nature of railway ballast selection and performance evaluation. The combined knowledge from these references paints a detailed picture of the critical considerations in ensuring the durability, stability, and overall performance of railway infrastructure.

Árpás *et al.* [55] evaluate the micro-Deval test for railway ballast aggregates, focusing on wear resistance and presenting numerical results for various andesites and basalts in Hungary. This highlights the micro-Deval test's role in assessing the durability and performance of different rock types under abrasion conditions, essential for railway ballast selection.

Pachoukova [56] addresses the challenges associated with conducting the Los Angeles abrasion and Micro-Deval wear tests, emphasizing their costliness and time-consuming nature. This underscores the significance of these tests in evaluating the rock physic characteristics of railway ballast, including durability and abrasion resistance, providing crucial insights into material performance under stress and wear conditions.

The study by Orosz *et al.* [57] offers insights into how different forms of railway ballast grains influence their breakage under mechanical stress. Their findings regarding the vulnerability of non-compact grains to mechanical failure under shearing forces, common in the operational environment of railway ballasts, contribute to the broader understanding of particle breakage mechanisms. This empirical evidence aids in the development of more accurate predictive models for forecasting the lifespan of railway ballast under various loading conditions.

Woodside and Woodward [58] discuss the wear characteristics of aggregates exposed at the road surface, which can be extrapolated to railway ballast. Presenting data for both the Los Angeles abrasion and micro-Deval wear methods across various rock types, this study provides a comprehensive analysis of the relationship between rock physic characteristics and abrasion resistance. This is crucial in understanding the durability of railway ballast and its impact on infrastructure performance.

The study [59] on crushed fine aggregates highlighted key correlations and insights into their quality assessment. Notably, it discovered a significant correlation between the magnesium sulphate soundness coefficient and the Micro-Deval coefficient, suggesting these tests, which measure resistance to chemical weathering and mechanical degradation respectively, are closely related and indicative of aggregate quality. Furthermore, an unexpected but reasonable correlation was found between the methylene blue value and the sand equivalent test results, linking the presence of clayey materials and the proportion of fine particles in aggregates, which can influence concrete's water demand and overall performance. However, no significant correlations were found for other tested properties, such as water absorption and relative density, underscoring the complexity of aggregate quality assessment and the necessity for a multifaceted approach in evaluating aggregates for construction use. This research provides critical insights into understanding and predicting the behavior of crushed fine aggregates, emphasizing the importance of comprehensive testing to ensure material suitability for construction projects.

Selecting the appropriate quality crushed stone aggregate involves a deep dive into the relationship between the crushed stone aggregates' physical and mechanical traits and their impact on the transport infrastructure’s performance, a crucial step for building and sustaining efficient, long-lasting transport routes. By harnessing the power of cutting-edge predictive technologies like artificial neural networks and gene expression programming, this process taps into a wealth of empirical data and rigorous testing to pinpoint aggregates that stand up to the rigorous standards of railway and/or road construction and upkeep. These technological leaps have revolutionized how someone matches aggregates' attributes with essential performance indicators, significantly boosting the resilience and dependability of road or railway structures. Additionally, ongoing research into the physical shapes and durability of these aggregates underlines the critical importance of choosing materials adept at maintaining, e.g., the railway track stability and enduring through varied environmental conditions. This comprehensive strategy for aggregate selection, rooted in robust evidence and the latest modeling techniques, highlights an enduring quest for innovation and inquiry to keep transport infrastructure’s systems robust and future-proof, spotlighting the essential insights gained from geological studies and the intricate dynamics between aggregates' rock physics and their functional prowess.

The introduced literature does not show unequivocal correlations between the considered parameters of crushed stone aggregates. The current paper aims to give a deeper insight into the analysis and assessment of some selected parameter-pairs.

3. Methodology, and the rationalization of the number of properties that can be measured in a set of rocks, search for predictors

The number of test methods available for the testing of aggregate products varies according to the field of application but can be stated to be between 15 and 30 pieces. It was pointed out in the introduction that, although this number is not particularly high in scientific terms, it is a major challenge for manufacturers of construction products in practical applications to keep the risk of non-compliance with all parameters at a low level throughout the production process. This is usually achieved by manufacturers/mining companies by, on the one hand, not committing themselves to product quality for all parameters, as the National Application Documents (NADs) do not contain national requirements for all testable parameters. On the other hand, they try to include in their mine/quarry planning processes the most important parameters, the fulfilment of which implies the fulfilment of another requirement. In this sense, there are parameters that can be controlled to predict the compliance of a number of other parameters. In this sense, the number of characteristics that need to be focused on in mine planning and whose increased control can significantly contribute to keeping product quality risks at a low level can be significantly reduced.

Among the geometrical requirements for characterizing the grain shape of crushed stone, for example, the characteristics known as the flakiness index (*FI*) [8] and the shape index (*SI*) [8] are utilized. These two parameters, although both used to characterize the shape of the grains, differ significantly in their method of analysis. While the former is determined by dividing the fraction under test into grain size classes and sieving through a bar sieve of a given grain size class, where the proportion of flaked grains is calculated from the mass of grains passing through the given bar sieve sizes, the latter is determined by using a caliper to examine a selected proportion of the grains and the amount of flaked grains is inferred from the ratio of width to thickness results.

Among the physical requirements, perhaps the most important and most widely applied parameters are the Los Angeles abrasion [14] and Micro-Deval wear[16] tests, the results of which, in the authors' experience, show no correlation with each other. However, it is worth investigating whether the Los Angeles abrasion value, used to characterize the strength of the aggregate product, shows any correlation with, for example, the frost resistance of aggregates. This may be justified by the fact that an increase in strength is generally accompanied by a decrease in water absorption, and that higher strength and lower water absorption certainly have a positive effect on the frost resistance of the aggregate.

Both the resistance to freezing and thawing (F) [19] and magnesium sulfate soundness (MS) [25] tests are intended to characterize the durability of aggregates. Both tests are rather time-consuming procedures, and their results usually allow for post-testing and possibly pre-planning before mining/quarrying by evaluating the previously available results on a site-by-site basis.

Occasionally, parameter pairs can be found whose results can be explained by exploring deeper material relationships. One such correlation could be the possible correlation between the test results of Micro-Deval (MDE) and methylene blue (MB, MB_F) [13], presented later. While the former is basically used to characterize the resistance of a set of aggregates to abrasion, the latter, used to characterize the quality of fine aggregates for use in asphalt mixtures, is essentially a function of the mineralogical composition of the aggregate. Surprisingly, the two fundamentally different parameters show a good correlation.

As can be seen from the description, there are a number of rock aggregate parameters that can be used to predict the expected values of additional parameters. There is also a case where, although the predictability is not obvious, the maximum of the expected value of another parameter can be predicted as a function of the absolute value of the parameter. These analyses and correlations may be of interest to us not only because they can reduce the number of parameters to be tested due to their convertibility, but also because there are many cases where a given test cannot be performed on the available samples – for example, due to their fraction – while it is ideal for another test, so that in these cases, the expected values of a parameter can be predicted. Equally important, for example, may be the sometimes significant test time required between tests; for example, of the possible correlations listed earlier, the durability test takes approximately two weeks, whereas the Los Angeles test can be carried out within a day. Thus, when clarifying durability issues, knowing the results of the Los Angeles abrasion test will allow someone to reach conclusions more quickly than waiting for a longer test.

4. Results and discussion

Generally, it can be said that the searching for these predictors is a rather expensive and time-consuming process, as the data needed for the analysis can be obtained from expensive and time-consuming tests. Thus, tests conducted solely for comparability purposes require significant resources. With the generalization of production control systems, there is scope for the collection of a significant amount of data from companies producing aggregate products. The structured collection and structuring of these data can form the basis for these analyses. In the present paper, the data from the production control system of Colas Északkő Ltd. have been used for the analyses, which allow a number of investigations to be carried out. In the analysis, the focus was not on utilizing all the data already available in the production control system, but on collecting a limited amount of data from the database for the examples listed and conducting the assessment on this data. Of course, these analyses draw attention to and provide an opportunity for data processing using the full range of data available in the system, which is beyond the scope of this paper.

In any case, the results published in Sections 1.1, 1.2 and 1.3 could be classified into separate regions, mines/quarries or other material resource locations/places, but this was not the aim of this paper. It can be the basis of a further, detailed investigation. It must be noted that all the tested rock were andesite.

4.1 Correlation between SI and FI

It was explained earlier that although the two parameters (*SI* and *FI*) are both used to measure the volume of disc grains, the methods of the two tests are fundamentally different. Nevertheless, analysis of a few pairs of data clearly shows the close correlation between the two.

Figure 1 shows that the correlation is extremely high, however, due to the small number of data pairs involved in the analysis, it is advisable to replicate the correlation with a larger data set. The results of the assessment confirm the practice that in a country, limits are usually set for either *SI* or *FI* values and that conformity checks are performed using only one or the other of these parameters.

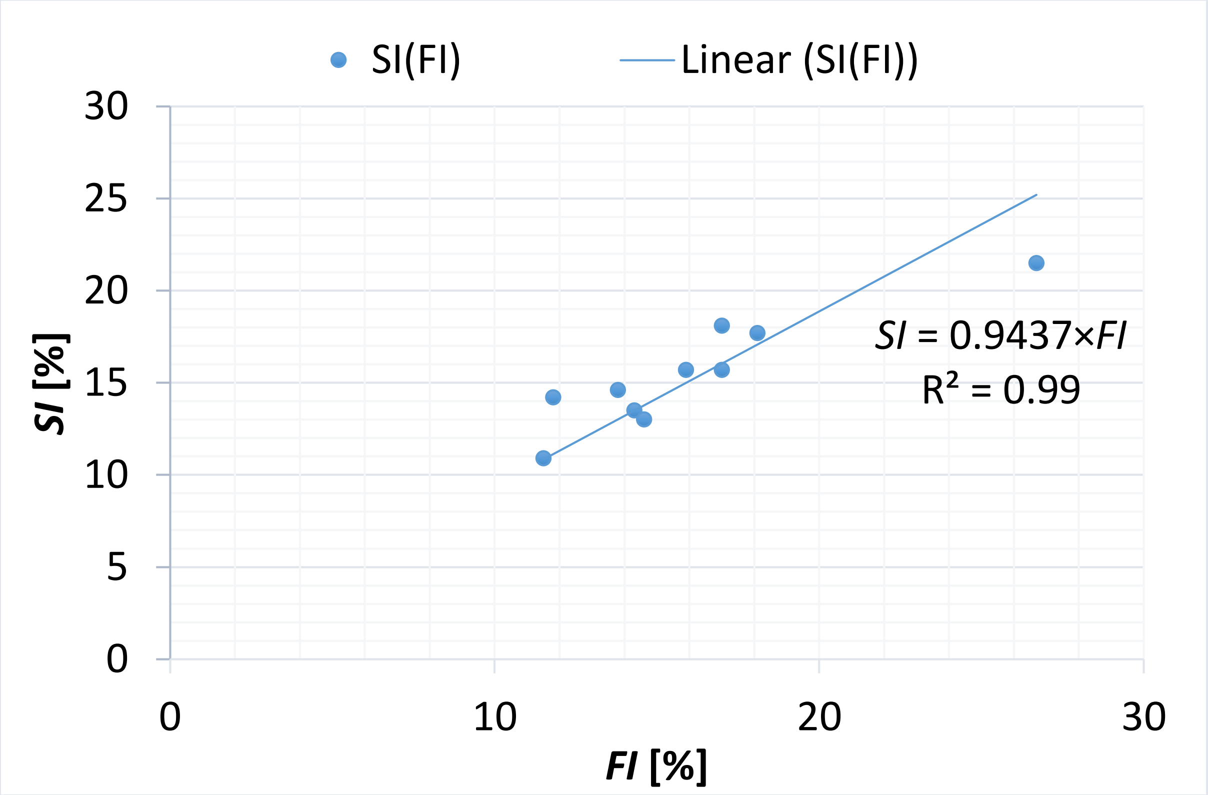

Fig. 1. The calculated correlation between *SI* and *FI* parameters

4.2 Correlation between LAA, MDE and MS

Experience has shown that the correlation between LAA and Micro-Deval is rather limited; there are many sources of rock with desirably low LAA values, while the MDE value of the same sample predicts a distinctly unfavorable wear behavior. Nevertheless, as shown in the figure, the R^2 value suggests a close correlation, but a visual assessment of the data set suggests that there are risks to this. In Figure 2, the correlation of *MDE* and *LAA* parameters is illustrated.

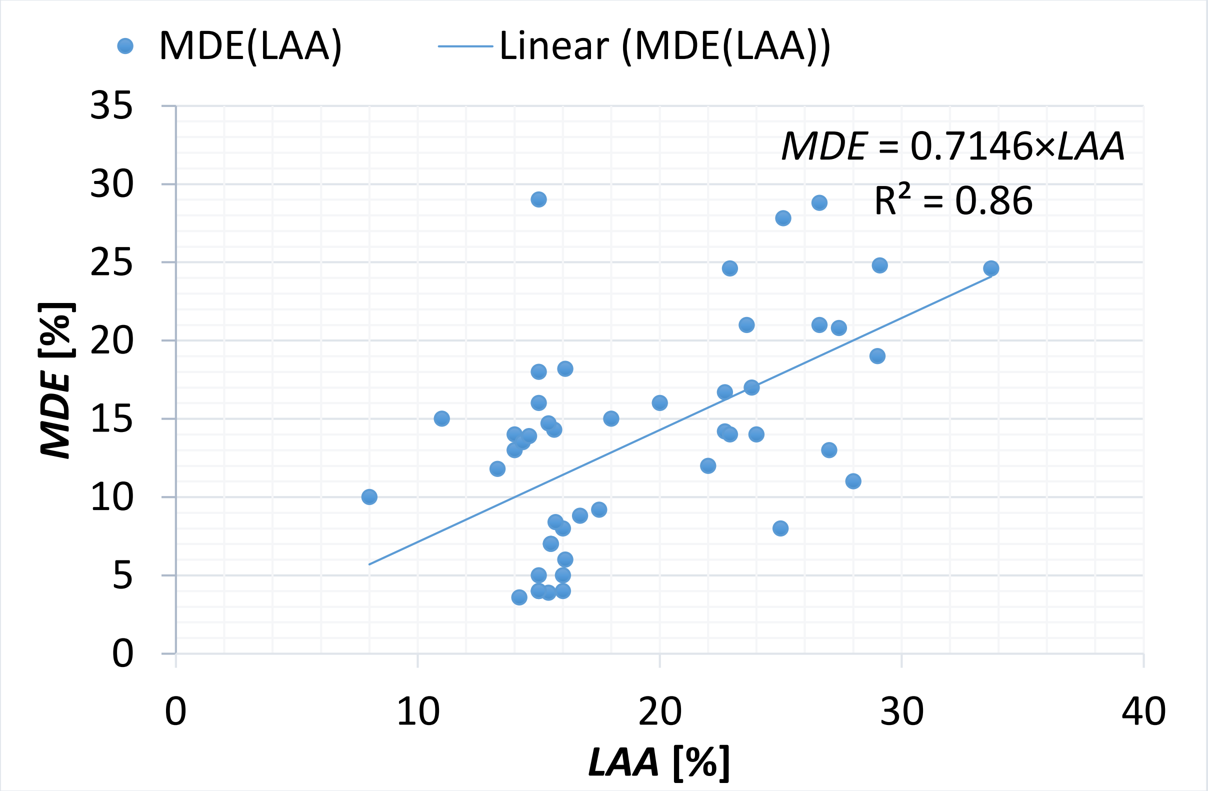

Fig. 2. The calculated correlation between *MDE* and *LAA* parameters

Besides Los Angeles and micro-Deval wear tests, the most commonly applied and studied rock physics parameter is the magnesium sulphate crystallization test (*MS*), which is a possible measure of resistance to weathering. It can be assumed that a more favorable *LAA* value has a lower water absorption and thus a more favorable resistance against frost-thaw cycles. To verify this, it is useful to compare the values of *LAA* and *MS*, as illustrated in Figure 3.

Figure 3 shows a moderate correlation, however, as with the *LAA*-*MDE* correlation, there is a significant variation of results. However, it is useful to consider the correlation from a practical point of view. The general requirements for *LAA* values indicate that a value below 20 generally meets the most rigorous requirements for the application. For the classification of magnesium sulphate (*MS*) fragmentation, the product standards maximize the values for the most favorable class at 18, but for specific applications, more rigorous requirements may be found. Therefore, it is useful to consider whether there is a risk that the MS value, i.e. the durability of the aggregate, could be unfavorable if the LA20 class is achieved even under the strictest requirements.

Figure 3 additionally shows a dashed red line that symbolizes *LAA*=20%. It can be unequivocally stated that MS values are almost certainly below 10, which meets the most stringent application criteria. The further practical significance of this fact is that while the Los Angeles abrasion can be tested within 1 day, the durability test is approximately 10-14 days, i.e., if the *LAA* is verifiably below 20, the verification of *MS* compliance becomes formal.

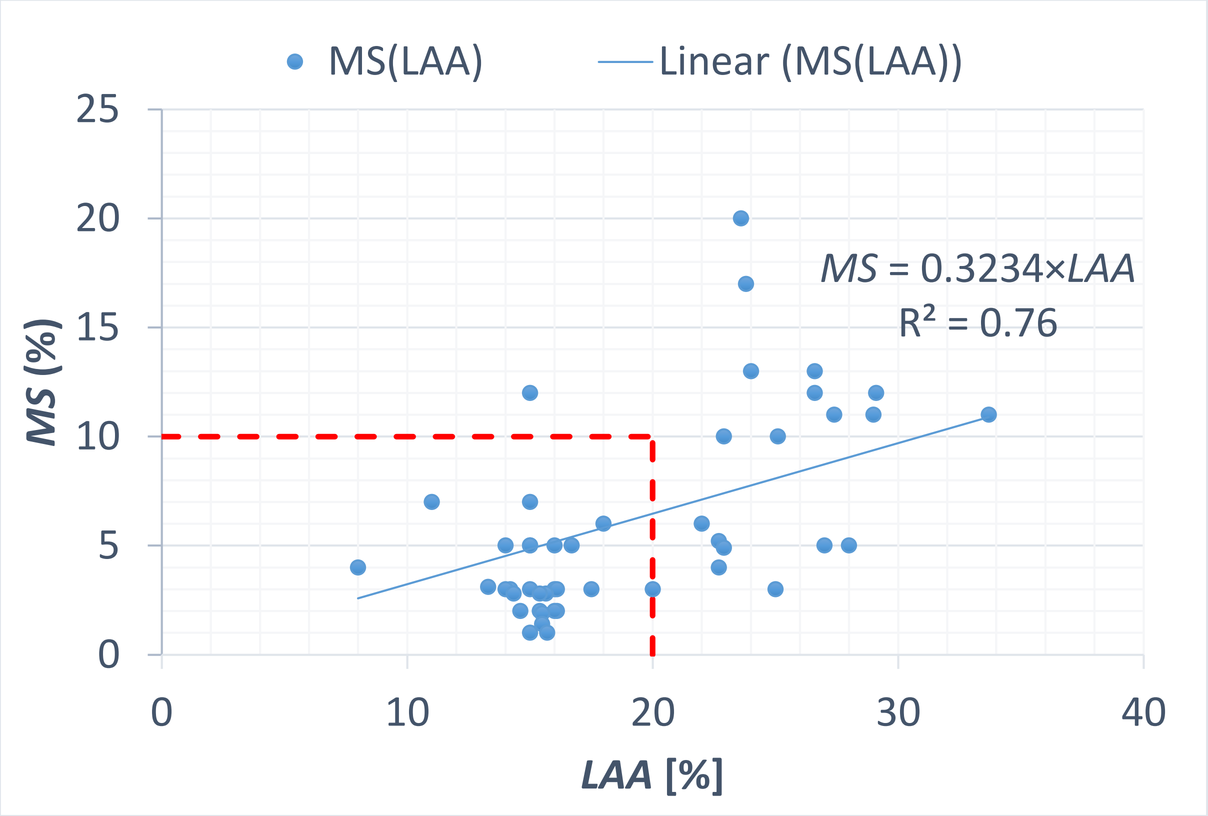

Fig. 3. The calculated correlation between *MS* and *LAA* parameters

4.3 Correlation between MB, MB_F and MDE

Although there is relatively reduced literature analyzing the relationship between methylene blue (*MB* and MB_F) and the micro-Deval wear results, the significant correlation between the results of these two fundamentally different tests is a cause for further research.

The results of both standard tests are strongly influenced by the amount of clay minerals present in the rock, so that, although they are classified as geometrical and physical, it is mineralogical factors that have the greatest influence. In the case of *MB*, min. 200 g 0/2 mm fraction should be considered (Annex B of [13]), whereas for MB_F, 30 g 0/0.125 mm fraction should be tested (Annex A of [13]).

Figures 4 and 5 illustrate the correlations between *MDE* and *MB*, as well as *MDE* and MB_F, respectively.

Figure 4 depicts a relatively good, Figure 5 shows a moderate correlation with linear regression and logarithmic regression functions, respectively.

The hydrothermally disaggregated grains in the andesite rocks for micro-Deval increase the mass loss more significantly for water and abrasion (wear), as in the methylene blue test the same higher amount of clay mineralization – moreover in the finer products, i.e. due to better openings – increases the dye absorption of the suspension, resulting in a higher measured value.

The high correlation between the pairs of values shows that after more detailed analysis and research, it may be possible to approximate one test to the other with a fairly high degree of accuracy, reducing the number of tests to be carried out, or, in the case of few samples available, to estimate the other result.

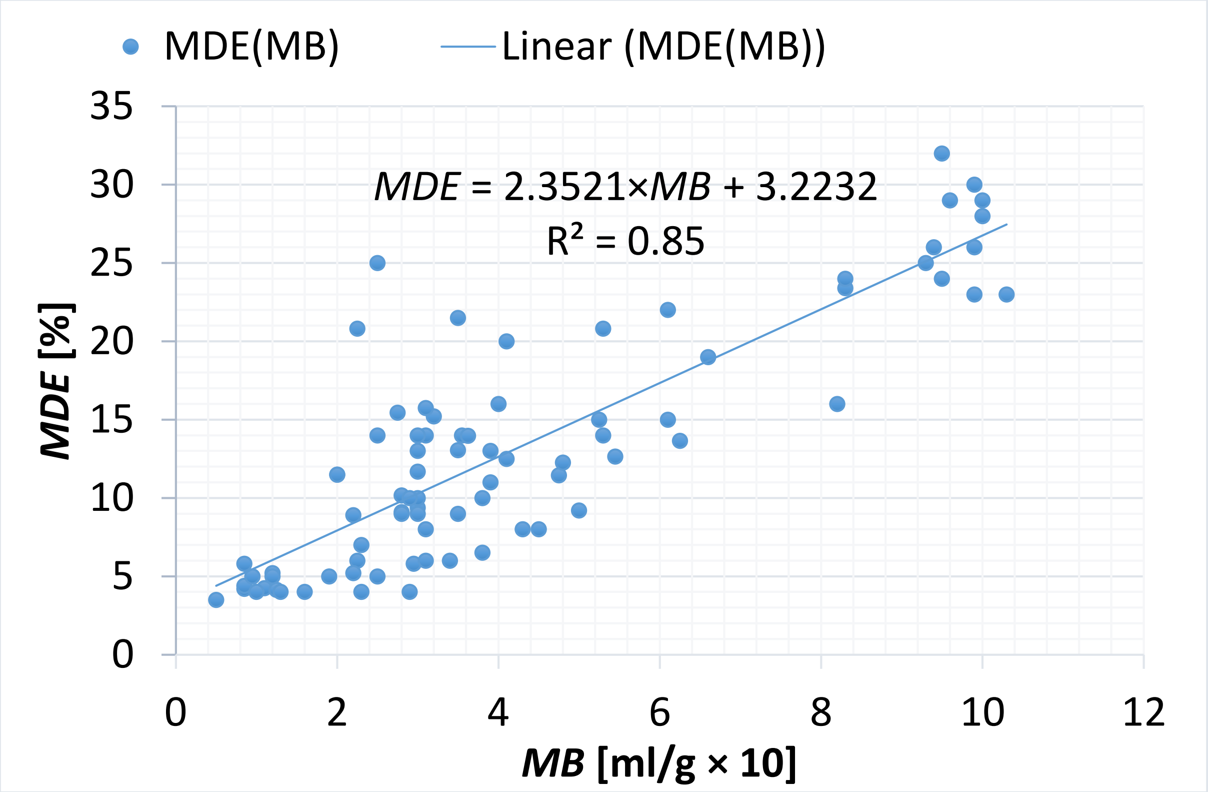

Fig. 4. The calculated correlation between *MDE* and *MB* parameters

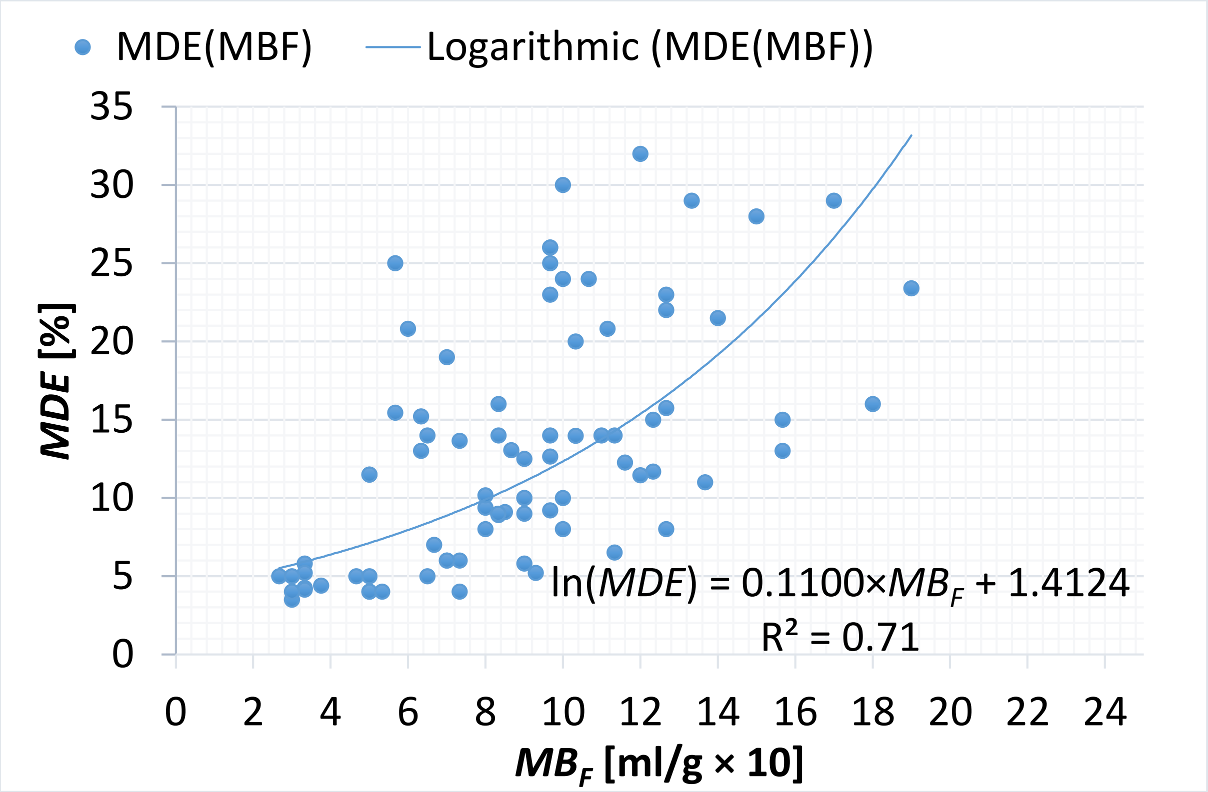

Fig. 5. The calculated correlation between *MDE* and MB_F parameters

5. Conclusions

The research presented in this paper has uncovered important correlations among several properties of crushed stone aggregates, which are vital for choosing materials in infrastructure construction. It points out connections between different characteristics of aggregates that were not previously associated.

The prepared literature review within the study underscores the intricate relationship between the mechanical and physical properties of crushed stone aggregates and their performance, particularly within the context of railway systems. Advanced predictive models, including artificial neural networks and gene expression programming, have significantly improved the selection process of railway ballast, marrying empirical data with performance indicators like abrasion values. Innovations in aggregate testing have refined the selection of suitable rock types for ballast, prioritizing materials with high crushing resistance and environmental durability for their pivotal role in track stability. This compilation of research firmly establishes the importance of comprehensive and technologically supported testing protocols in determining the long-term viability of railway infrastructure materials.

The authors executed more parallel laboratory tests on crushed stone products from the andesite quarries of Colas Északkő Ltd.

The conducted investigation found a notable correlation between the flakiness index (*FI*) and the shape index (*SI*), leading to a new way of looking at grain shape assessment. It appears that measuring either *SI* or *FI* could be adequate for determining grain shape when limits are already established for one of these indices due to their relatedness.

When it comes to the physical qualities of aggregates, examining them with the Los Angeles abrasion (*LAA*) and Micro-Deval wear (*MDE*) tests has shown promise for joint predictive analysis. It has been discovered that good *LAA* values might be indicative of better resistance to environmental damage, an observation that magnesium sulfate soundness (*MS*) test results support.

Additionally, there's a significant relationship between the methylene blue (*MB* and MB_F) values and the performance of aggregates in the *MDE* wear test, suggesting that the mineral composition has a considerable impact on the mechanical integrity and shape retention of the aggregates.

Based on these findings, it's proposed that the number of tests could be reduced by using the outcome of one test to infer the results of another, thereby saving on resources. Especially noteworthy is the possibility that if *LAA* scores fall below certain stringent limits, the longer *MS* tests might not be necessary, which would speed up the process of verifying compliance.

In conclusion, this study lays the groundwork for a more efficient set of testing procedures that can accurately determine the quality and appropriateness of aggregates for use in infrastructure. The research emphasizes the ongoing need to improve predictive modeling and testing techniques in step with current industry standards, which is critical for building strong, long-lasting infrastructure.

Author Contributions

Conceptualization, L.É., R.T. and S.F.; methodology, L.É., R.T. and S.F.; software, L.É., R.T. and S.F.; validation, L.É., R.T. and S.F.; formal analysis, L.É., R.T. and S.F.; investigation, L.É., R.T. and S.F.; resources, L.É., R.T. and S.F.; data curation, L.É., R.T. and S.F.; writing—original draft preparation, L.É., R.T. and S.F.; writing—review and editing, L.É., R.T. and S.F.; visualization, L.É., R.T. and S.F.; supervision, L.É., R.T. and S.F.; project administration, L.É., R.T. and S.F.; funding acquisition, L.É., R.T. and S.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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