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Statistical analysis of mechanical properties on the example of aggregates of Carpathian sandstones

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Abstract: The constantly growing, broadly understood, construction industry requires the use of a large amount of aggregates. The construction of roads, motorways, railway lines and hydrotechnical structures requires the use of aggregates of high quality, which is primarily determined by mechanical properties. The basic parameters describing mechanical properties of aggregates are the Los Angeles (*LA*) fragmentation resistance coefficient and the Micro-Deval (M_{DE}) abrasion resistance coefficient. The *LA* and M_{DE} coefficients depend mainly on the type of rock and its physical and mechanical properties. This has been thoroughly researched and documented as evidenced by the abundant literature in the field. However, the correlation between *LA* and M_{DE} coefficients still gives rise to extensive discussions and some concerns. A number of publications demonstrate dependencies for various types of aggregates. Therefore, research was undertaken to present statistical analysis for one type of aggregate and one geological area.

This article presents the results of the fragmentation resistance test in the Los Angeles drum and the abrasion resistance test in the Micro-Deval drum of aggregates from Carpathian sandstone deposits. Aggregate samples were divided into three groups according to the location of the deposits and the tectonic unit from which they originated. The obtained results were subjected to static analysis to fit the best mathematical function describing the relationship between the two parameters.

Keywords: aggregates; Los Angeles coefficient; Micro-Deval coefficient.

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1 Introduction

Natural rock resources are most frequently used to produce aggregates, which are the basic material used in the broadly understood construction industry. It is mainly used in the production of concrete and mineral and bituminous mixtures for road foundations, railway ballasts and for the erection of hydrotechnical structures. The increasing level of technical advancement of aggregate applications causes the demand for high-quality material [11].

Aggregate performance is primarily influenced by the type and physico-mechanical properties of the rock and the mechanical, physical and geometric properties of the aggregates themselves. The mechanical properties of aggregates are reflected by two parameters: the Los Angeles coefficient (*LA*) and the Micro-Deval coefficient (M_{DE}). The methods of these two mechanical tests express fragmentation resistance (Los Angeles) and abrasion resistance (Micro-Deval). This was demonstrated in the study carried out in [9], in which grain size distribution of aggregates was analysed after testing in the Micro-Deval and the Los Angeles drums. It has been shown that these two methods for testing the mechanical properties of aggregates have quite different characteristics. The grain size after testing in the Micro-Deval drum is much smaller and more rounded than after testing in the Los Angeles drum. This difference is due to the way the tests are conducted. The fragmentation resistance test is potentially shorter because the aggregate is subjected to comminution due to the impact of steel balls in the drum rotating 500 revolutions. However, the abrasion test is longer because the aggregate is subjected to abrasion in the drum, making 12,000 turns with an additional element, which is water.

The relationships between the Los Angeles coefficient and lithology, rock structure and texture are widely described in the literature [1, 2, 29]. The situation is similar in the case of the Micro-Deval coefficient. Moreover, the values of Los Angeles and Micro-Deval coefficients are significantly influenced by the physico-mechanical properties of rocks as evidenced by works [4, 8, 13, 14, 22, 25, 26, 28], in which the correlation between the discussed coefficients and such rock properties as bulk density, porosity, compressive strength, tensile strength, ultrasonic wave velocity, California bearing ratio (CBR) load index and the number of Schmidt hammer strokes was analysed.

The correlation results between Los Angeles and Micro-Deval coefficients are interesting, and the topic was examined, among others, in [6, 7, 15, 21, 26, 27]. Only in study [27], the correlation between these two coefficients was obtained. The analysis was carried out for two groups of rocks: basalt (r^2 = 0.7823) and andesite (r^2 = 0.9148). A good fit of linear regression was achieved by conducting separate analyses for each type of rock. However, in other studies, practically no correlation was observed. This could be caused by the fact that the analyses were conducted for aggregates of various types of rocks.

In the case of abrasion of aggregates, the Micro-Deval coefficient (M_{DE}) is especially taken into account for railway ballasts. Materials used in the railway industry are exposed to changing weather conditions, which is considered to be reflected very well by the Micro-Deval method. In the road construction industry, this study is used to better characterise the material although there is concern that there is no correlation between the fragmentation resistance coefficient and the abrasion resistance coefficient [24]. This article discusses whether in the case of a particular type of aggregate, the correlation between these parameters will be high enough to refute the above concern.

This article presents the results of the fragmentation resistance test in the Los Angeles drum and the abrasion resistance test in the Micro-Deval drum of aggregates from Carpathian sandstone deposits from three different geological units. The obtained results were subjected to static analysis to fit the best mathematical function describing the relationship between the two parameters. The obtained results may in the future be used to estimate a given coefficient when the results of only one of these two parameters are available. When it is impossible to carry out research for technical reasons, this method can be applied.

2 Description of the tested materials

The test samples were prepared as a result of crushing rocks, originating from three Carpathian sandstones of the south-eastern part of Poland. The Los Angeles and Micro-Deval tests were performed on aggregates produced from Magura sandstone (Klęczany, Osielec, Wierchomla and Męcina Mines), Cergos sandstone (Lipowica and Komańcza-Jawornik Mines) and Krosno sandstone (mainly Barwałd and Porąbka Mines). Carpathian sandstone deposits are among the most common rock formations in the southern and south-eastern parts of Poland (Fig. 1). They were formed as a result of deep-water flysch sedimentation, diagenetic processes and significant tectonic disturbances. A characteristic feature of these sandstones is their grey colour, sometimes with shades of yellow, green or blue. The main mineral component of the grains is quartz (30%–50%). In addition to quartz, there are secondary components such as feldspar, plagioclase, mica and lithoclasts, glauconite and others, which constitute several to several dozen percent of the total volume. Sandstone cement consists mainly of silica and various proportions of argillaceous and carbonate substances [3].

The Cergos sandstones are found in the Dukla and pre-Dukla units of the outer Carpathians (Fig. 1). Quartz grains in the Cergos sandstones account for 20%–36%, while foreign rock chips account for 25%–58% of all components. The most represented group is chips of carbonate rocks, mainly limestones and dolomites. The other components are represented by sandstones and siliceous rocks, argillaceous rocks, granitoids and vulcanites or metamorphic rocks. The average share of individual components in the Cergos sandstones allows us to classify them as greywacke. Among Cergos sandstones, strata of undefined structure, normally fractionated with lamination can be distinguished [19].

Krosno sandstones belong to the Silesian unit. In the mineral and petrographic composition of the samples of Krosno sandstones, among the components of the rock skeleton are quartz (23%–36%), metamorphic and magna rock grains as well as micas and feldspars. The binder, on the other hand, is mainly carbonate, quartz or argillaceous cement [10].

Magura sandstones (Magura unit) are most often found in the form of fine- and medium-grained rocks. Sorted large quartz grains, muscovite plates, shale fragments and glauconite grains are also found within Magura sandstones. There can be clay and limestone or silica and clay binders [20].

Carpathian sandstones are very diverse in mineralogical and phase terms, which translates directly into the physico-mechanical properties of the rocks themselves and their aggregates. Table 1 shows selected physico-mechanical properties of rocks, from

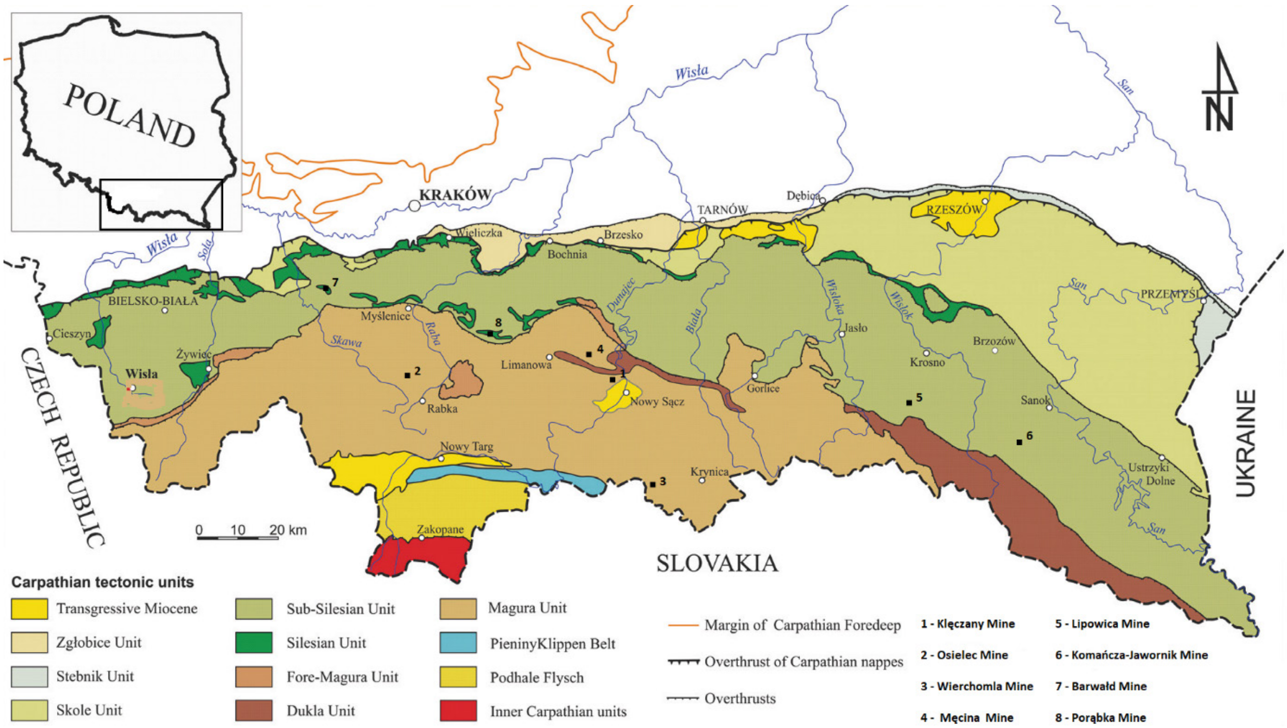


Figure 1: A simplified geological and structural map of the Polish Carpathians [5, 16, 23, 30].

Table 1: Physico-mechanical properties of sandstones [12].

Rock type	Bulk density [Mg/m^3]		Absorbability [%]		Dry condition compressive strength [MPa]		Compressive strength after water absorption [MPa]	
	min–max	on average	min–max	on average	min–max	on average	min–max	on average
Krosno sandstone	2.31–2.71	2.64	0.25–3.70	1.50	57–178	122	40–153	89
Magura sandstone	2.50–2.69	2.62	0.30–2.47	1.12	91–207	164	59–194	125
Cergos sandstone	2.48–2.77	2.63	0.52–2.94	1.33	115–207	170	94–173	134

which aggregate samples were prepared for testing of fragmentation and abrasion resistance.

Bulk density and absorbability for the analysed sandstones are in a very similar range, but differences can be observed in compressive strength values. Cergos and Magura sandstones are characterised by quite high mechanical properties and average dry condition compressive strengths of about 170 MPa and 164 MPa, respectively, while in the case of Krosno sandstones, the compressive strength is about 120 MPa. The compressive strength values after water absorption by the samples are similar with an indication that the lower the dry condition compressive strength, the greater the reduction of its value. After water absorption, a decrease of 27% in compressive strength was noted for Krosno sandstone, a 24% decrease for Magura sandstone and a 21% decrease for Cergos sandstone. The percentage is small; however, the results themselves vary by up to several tens of megapascals. Presentation of the results of strength tests of dry samples and those saturated with water was intended to show how their strength changes, which can translate into resistance to abrasion.

3 Description of tests

All the performed tests were carried out in a certified laboratory in accordance with the required standards. Testing aggregate resistance to fragmentation in the Los Angeles drum was carried out in accordance with the applicable standard PN-EN 1097-2 [18], which is part of a number of standards on testing mechanical and physical properties of aggregates. The test was carried out on a sample of aggregate passing through a 14 mm mesh sieve and remaining on a 10 mm sieve, with a 60%–70% content of aggregate with a 12.5 mm grain size. It is also possible to prepare a sample in which grains up to 11.2 mm will constitute 30%–40% of the total sample. The obtained 5000 g sample was placed together with steel balls in the Los Angeles drum (Fig. 2), which is rotated at the speed of 31–33 rpm, thus making 500 rotations. After a full rotation cycle, the aggregate was sieved on a 1.6 mm mesh sieve, checking the mass remaining on the sieve. The Los Angeles (LA) fragmentation resistance coefficient of the aggregate is calculated according to formula (1). The higher the coefficient value, the more the aggregate that is crushed, which means a lower resistance to fragmentation. Figure 3 shows a picture of an aggregate sample after the fragmentation resistance test in the Los Angeles drum.

Figure 2: Los Angeles drum.

$$LA = \frac{5000-m}{50} \quad , \tag{1}$$

where m is the aggregate mass remaining on the 1.6 mm sieve.

Preparation of a sample for the determination of abrasion resistance in the Micro-Deval drum was similar to that in the Los Angeles drum. The aggregate mixture was sieved through a set of sieves with mesh sizes of 14 mm, 12.5 mm (or 11.2 mm) and 10 mm. However, in accordance with the PN-EN 1097-1 [17] standard, the sample mass was much smaller and amounted to 500 g. The idea of the test is quite similar. The aggregate sample is also subjected to a full rotation cycle; however, it takes place in the Micro-Deval drum (Fig. 4). In the case of determining abrasion resistance, the drum is much smaller and the steel balls have a diameter of 10 mm with a total mass of 5000 g. Additionally, 2.5 l of water is poured into the drum to achieve an abrasive effect, and the drum performs 12,000 rotations at 100 rpm. The effect of the test was the aggregate mass remaining on the 1.6 mm sieve. The Micro-Deval (M_{DE}) abrasion resistance coefficient is calculated from formula (2) and, as in the case of LA, a higher coefficient value means a lower wear resistance due to abrasion. A sample of crushed-stone aggregate after testing in the Micro-Deval drum is characterised by gently rounded edges similar to gravel or river pebbles (Fig. 5).

(a)

(b)

Figure 3: Sample before (a) and after (b) fragmentation test.

Figure 4: Micro-Deval drum.

(a)

(b)

Figure 5: Sample before (a) and after (b) abrasion test.

$$M_{DE} = \frac{500 - m}{5}, \tag{2}$$

where m is the aggregate mass remaining on the 1.6 mm sieve.

4 Relationship between fragmentation and abrasion resistance

The Magura sandstone was tested on 46 samples, the Cergos Sandstone on 30 and the Krosno Sandstone on 13. A total of 89 resistance to fragmentation results and the same on abrasion results of sandstone aggregates were statistically analysed. Figure 6 presents histograms for individual types of aggregate and for all tested samples, taking into account the values of M_{DE} and LA coefficients. The beta distribution was used for matching as the domain of this distribution is closed as are the possibilities of the results of the analysed coefficients. It should be noted, however, that the beta distribution is described in the field {0, 1}. Therefore all the results analysed were directly divided by 100 to obtain such a range. It can be noted that a larger spread of values is characteristic for resistance to abrasion, while a distribution close to symmetrical is more often achieved for resistance to fragmentation. In Figure 6d, on the other hand, which shows the distribution of results obtained for all samples, it can be observed that the most numerous group (28 cases) was characterised by LA coefficients between 0.2 and 0.3 (original results 20–30). In the case of resistance to abrasion, the most numerous group, i.e. 29 cases, was in the 0.3–0.4 range (original results 30–40). It should also be added that the highest value of the LA coefficient was 66, while the highest value of the M_{DE} coefficient was 84.2. On this basis, it can be concluded in a very general way that the tested sandstones have a much higher resistance to fragmentation than to abrasion. This conclusion is supported by the statistical parameters presented in Table 2. Both the average and the maximum values of the abrasion resistance coefficient are significantly higher than the fragmentation resistance coefficient.

In order to carry out the statistical characteristics of the sandstones tested in terms of fragmentation and abrasion resistance, an attempt was made to fit the best function describing the relationship between the two parameters. Figure 7 shows three functions describing the relationship

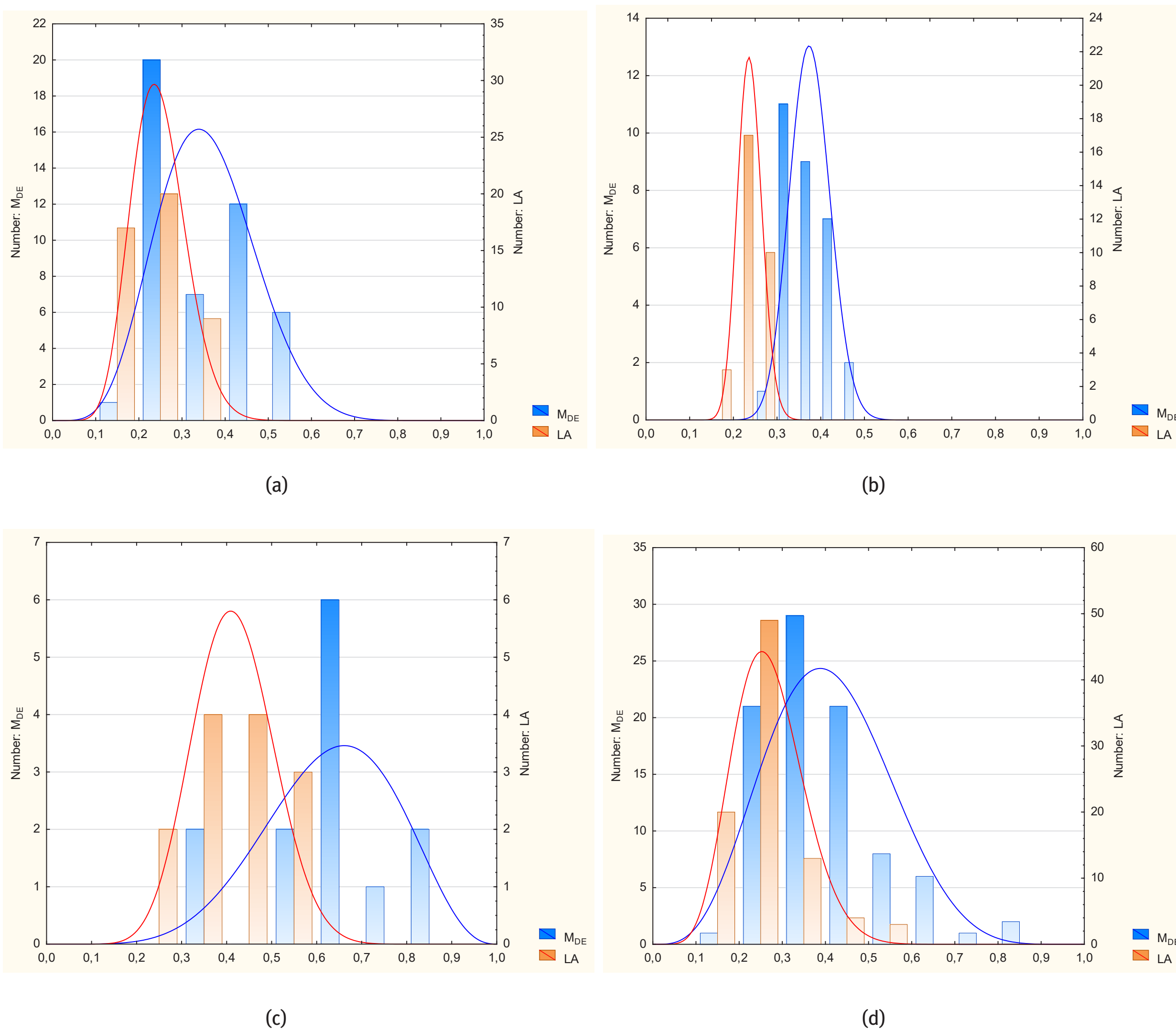
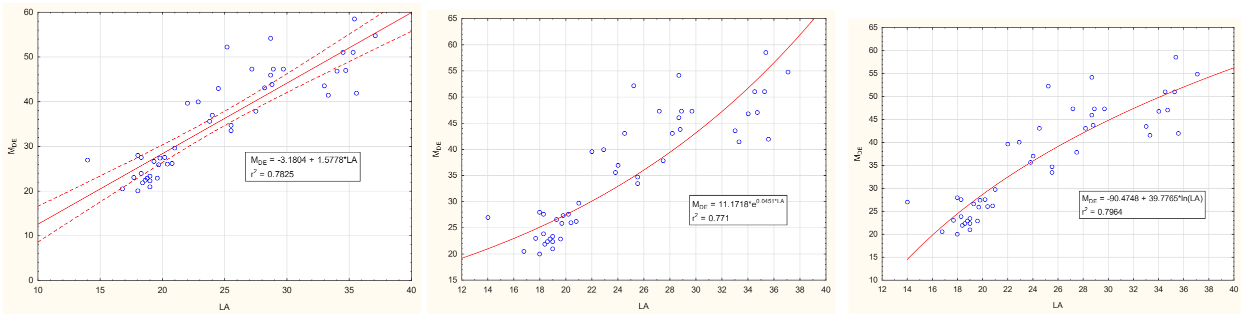


Figure 6: Histogram of beta distribution of resistance to fragmentation and abrasion: (a) Magura sandstone, (b) Cergos sandstone, (c) Krosno sandstone and (d) overall.

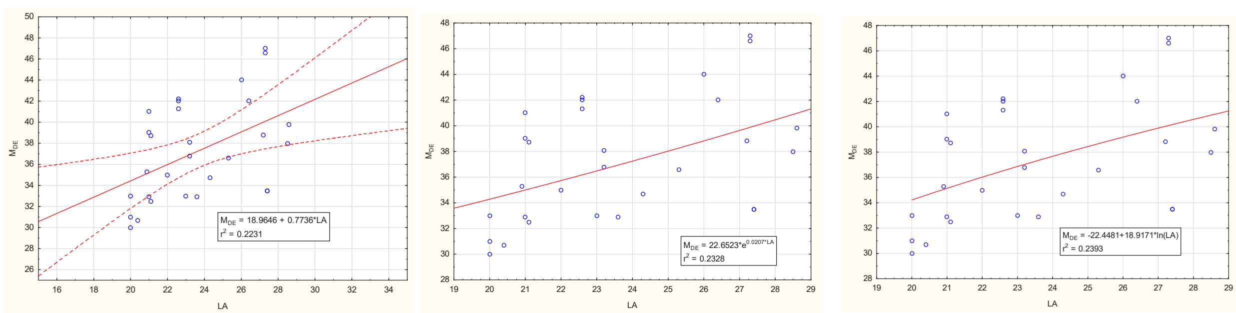
Table 2: Statistical values of *LA* and M_{DE} coefficients for Carpathian sandstone aggregates.

Value	***LA* coefficient**				**M_{DE} coefficient**			
	Overall	**Magura sandstone**	**Cergos sandstone**	**Krosno sandstone**	**Overall**	**Magura sandstone**	**Cergos sandstone**	**Krosno sandstone**
Average	26.69	24.54	23.67	41.32	40.15	35.53	37.36	62.95
Minimum	14.00	14.00	20.00	24.30	20.00	20.00	30.00	35.20
Maximum	56.00	37.10	28.60	56.00	84.20	58.50	47.00	84.20
Standard deviation	8.47	6.38	2.83	9.08	13.97	11.39	4.67	15.15
Median	24.30	23.35	23.10	41.00	38.10	35.15	37.40	66.00
Coefficient of variation	31.76	26.01	11.96	21.99	34.80	32.04	12.50	24.07



(a) (b) (c)

Figure 7: Function fitting for Magura sandstone: (a) linear, (b) exponential and (c) logarithmic.



(a) (b) (c)

Figure 8: Function fitting for Cergos sandstone: (a) linear, (b) exponential and (c) logarithmic.

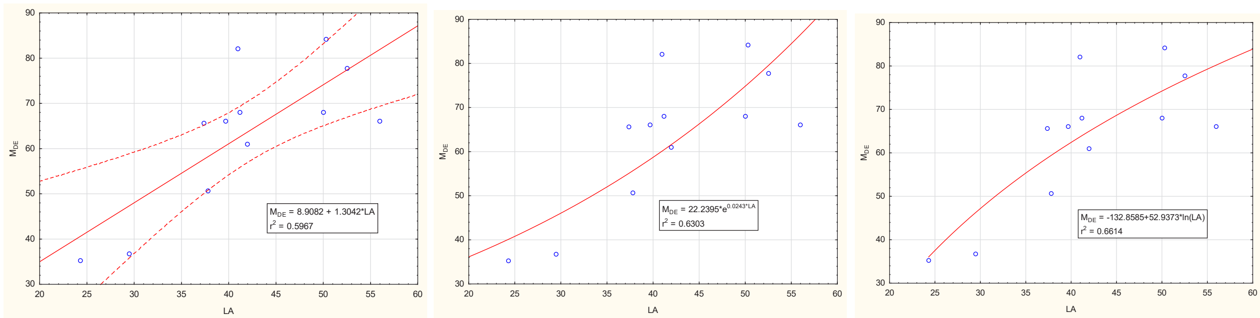
between M_{DE} and LA for Magura sandstone. For the linear function, a 95% confidence interval is additionally shown for the average value. However, it can be seen that the logarithmic function was the best fit (Fig. 7c), for which the determination coefficient was r^2 = 0.7964, while the determination coefficient for the linear and exponential functions was slightly smaller (r^2 = 0.7825).

In the case of Cergos sandstone, the best fit describing the relationship between M_{DE} and LA was demonstrated by the logarithmic function. The value of the determination coefficient was much lower and in this case amounted to r^2 = 0.2393 (Fig. 8c). It can be noted that for all three functions, the fit is at a very low level of only 0.2, which, statistically speaking, does not give much credibility. The scattering of points and the low r^2 value demonstrate a lack of relationship between abrasion resistance and fragmentation resistance.

Despite the smallest number of tests for the Krosno sandstone, the fitting of the function describing the relationship between abrasion resistance and fragmentation resistance was at a good level (Fig. 9). In this case, as in the previous ones, the highest value of the determination coefficient equal to r^2 = 0.6614 was obtained for the logarithmic function.

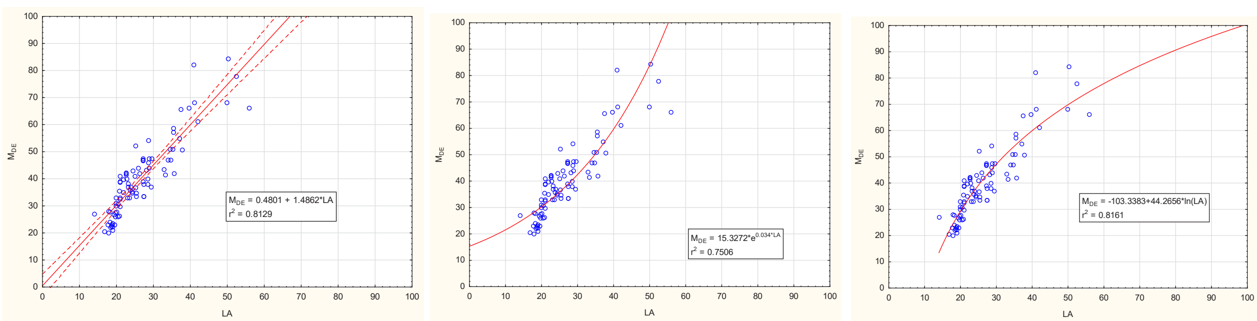
Figure 10 shows the fit of three functions for all samples without division into sandstone type. After analysing the function fit for individual sandstones, it appeared that the logarithmic function describes the relationship between M_{DE} and LA best also for the overall of the tested sandstones. The r^2 coefficient turned out to be high and amounted to 0.8161. Additionally, for the analysis of all tested sandstone samples, the domain of functions describing the relationship between abrasion resistance and fragmentation resistance is presented in its full range, i.e. {0, 100}. This intentional action showed whether the tested sandstones have greater resistance to abrasion or fragmentation. It turned out that there is no clear answer to this question. In the case of the linear and exponential functions, the sandstone will be more susceptible to abrasion than fragmentation. By contrast, the logarithmic function that best describes this relationship shows almost the same abrasion and fragmentation resistance.

The analysis of the residuals is shown in Figure 12. From this analysis, it can be seen that the smallest range of residuals concerns the logarithmic function and was in the interval {–12.86, 20.95}. However, the range of residuals for the linear function was {–17.70, 20.58} and for the exponential function {–27.5, 23.34}. It can therefore be



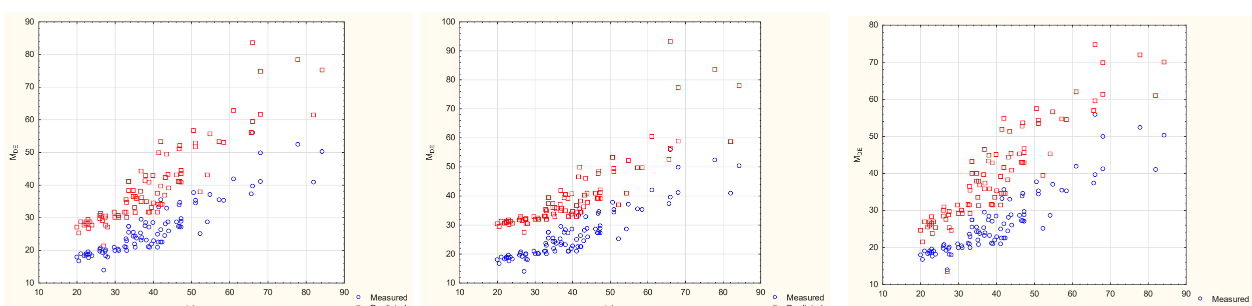
(a) (b) (c)

Figure 9: Function fitting for Krosno sandstone: (a) linear, (b) exponential and (c) logarithmic.



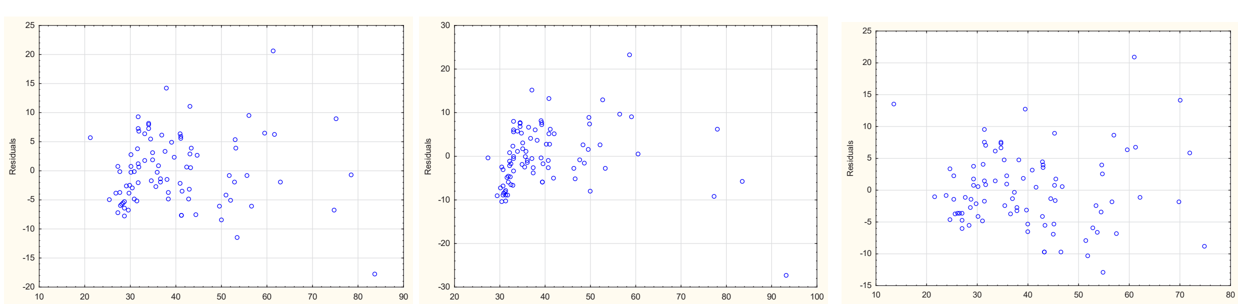
(a) (b) (c)

Figure 10: Function fitting for all tested sandstones: (a) linear, (b) exponential and (c) logarithmic.



(a) (b) (c)

Figure 11: Regression analysis results: (a) linear, (b) exponential and (c) logarithmic.



(a) (b) (c)

Figure 12: Residuals for all tested sandstones: (a) linear, (b) exponential and (c) logarithmic.

Table 3: Regression statistics.

	Coefficients	R square	Standard error	t Stat	p-value	Lower 95%	Upper 95%
Linear function							
Intersection	0.480	0,8129	2.139	0.224	0.822	−3.773	4.733
LA	1.486		0.076	19.444	2.02E-33	1.334	1.638
Exponential function							
Intersection	6.634	0,7426	2.246	2.952	0.004	2.168	11.099
exp^(0.034*LA)	12.904		0.814	15.845	2.24E-27	11.285	14.522
Logarithmic function							
Intersection	−103.338	0,8161	7.330	−14.097	3.49E-24	−117.908	−88.768
ln(LA)	44.265		2.252	19.649	9.59E-34	39.788	48.743

concluded that statistically the logarithmic function best describes the relationship between LA and M_{DE}.

5 Conclusions

A thorough analysis of the results obtained led to the following conclusions:

1. Aggregates from Carpathian sandstone deposits are more resistant to fragmentation than abrasion. The average value of the fragmentation resistance coefficient was LA = 27, whereas the average value of the abrasion resistance coefficient was M_{DE} = 40. Among the tested samples, the LA value was the most numerous in the 20–25 range, while the M_{DE} value was the most numerous in the 30–40 range. Therefore, it can be concluded that the Carpathian sandstone aggregates will be better suited for the construction of elements subjected to dynamic loads.
2. The average values of LA and M_{DE} coefficients are LA = 24.5 and M_{DE} = 35.5 for the Magura sandstone, LA = 23.7 and M_{DE} = 37.4 for the Cergos sandstone, and LA = 41.3 and M_{DE} = 62.9 for the Krosno sandstone, respectively. The average values for the Magura and Cergos sandstone are very similar, whereas the Krosno sandstone is characterised by much higher coefficients. There is also a certain analogy between these values and compressive strength.
3. The logarithmic function turned out to be the best fitting function to describe the relationship between LA and M_{DE} coefficients. The highest determination coefficient r^2 = 0.7964 was obtained for samples of Krosno sandstone. The lowest determination coefficient r^2 = 0.2231, on the other hand, was attributed to the linear function, describing the relationship of the analysed coefficients for Cergos sandstone.
4. For the analysed Carpathian sandstones, the best matching of the relationship between LA and M_{DE} was obtained for both logarithmic (r^2 = 0.8161) and linear (r^2 = 0.8129) functions. The coefficient of determination for a linear function coincides with the coefficients obtained in similar tests performed for basalt and andesite [27].
5. The performed statistical analysis of the three functions showed slight differences in the fit factor. However, analysis of the residuals shows that the smallest range of the obtained residues concerns the logarithmic function and is {–12.86, 20.95}.
6. The above analysis may be used to estimate a given coefficient using one of them. In particular, this may apply to the construction site, where it is not possible to carry out specialised laboratory tests. Additionally, the obtained results of the analysis could be used to optimise the aggregate to the direction of its destination. The relationship between LA and M_{DE}, with additional consideration of the strength properties, may be useful when a given raw material can be used as an element of a structure exposed to, for example, flowing water, traffic car or dynamic loads.

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