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THE RELATIONSHIP BETWEEN THE MECHANICAL PROPERTIES OF AGGREGATES AND THEIR GEOMETRIC PARAMETERS ON THE EXAMPLE OF POLISH CARPATHIAN SANDSTONES

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The basic tests that allow the mechanical properties of grained material to be evaluated are tests of an aggregate's resistance to crushing - the Los Angeles coefficient, and resistance to abrasion - the micro-Deval coefficient. These parameters primarily depend on the physical and mechanical properties of the raw material from which they are produced. The available literature widely describes the relationship between these parameters and bulk density, porosity, ultrasonic wave velocity, compression strength, tensile strength and point strength. This paper presents the relationship between the mechanical properties of aggregates and their geometrical properties. The analysis was carried out for the relationship between the Los Angeles and micro-Deval coefficients and the flatness and shape indices. As a result of the conducted considerations, the influence of the aggregate assortment on the analysed coefficients was also noted. All of the tests were carried out for aggregates (arch stones and mixtures) produced from sandstones from the Magura, Cergo and Krosno layers.

Keywords: aggregates, Los Angeles *LA* coefficient, micro-Deval M_{DE} coefficient, geometric properties of aggregates

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1. INTRODUCTION

Aggregate is one of the materials that are used in construction; depending on the type of raw material and the method of production, aggregates are divided into natural (gravel-sandy and crushed stone), recycled and artificial. The quality of the aggregate is influenced by the type and properties of the rock, its production, and the mechanical and geometrical properties of the aggregates themselves. for the quality of aggregates used in construction and the scope of the required tests have been defined in binding European standards, e.g. PN-EN 13242 [20], PN-EN 12620 [21], PN-EN 13043 [22], PN-EN 13450 [19], PN-EN 13383 [23]. The most important parameters that describe the mechanical properties of aggregates are the Los Angeles and the micro-Deval coefficients.

These two methods of assessing the mechanical properties of aggregates are used worldwide [3], [4], [5], [6], [7], [24], [25]. They differ in details such as grain size (fraction), sample mass or mass and type of abrasive charge. In general, the methods of these mechanical tests are empirical and are adapted to a given region of the world. They express resistance to fragmentation or abrasion; this has been confirmed in the literature [12], in which the grain compositions of aggregates were analysed after testing in micro-Deval and Los Angeles drums. It has been shown that these two methods of testing the mechanical properties of aggregates have quite different characters. After testing in the micro-Deval drum, the grain size is significantly smaller than the grain size after testing in the Los Angeles drum. The micro-Deval test is an abrasive resistance test [24], [6], [7], whereas the Los Angeles test is called a fragmentation resistance test [25]. However, some test methods using the Los Angeles drum indicate that this is an abrasion resistance test [3], [4], [5], [18].

Lithology and the structural and textural properties of aggregates [2], [8], [29], [35] have a significant influence on the abrasion and fragmentation of aggregates. Depending on the type of rock, the aggregate in the micro-Deval and Los Angeles drums will have a different shape and a different degree of roundness after abrasion. For carbonate aggregates, the relationship between the Los Angeles coefficient and the textural coefficient developed in the literature [1] showed a considerably good match. The way the grains are rounded and the texture of their surface after abrasion in the micro-Deval drum is often the basis for the assessment of the polarity of aggregates. This is a very important parameter that is used in the selection of granular material for concrete and bituminous mixtures used for road surfaces [11], [13]. The values of the Los Angeles and micro-Deval coefficients are also influenced by the size of the tested grains. The results presented by

Kukielska [16] indicate that, for aggregate with a 2-8 mm fraction, the values of these coefficients are much higher than for a 10-14 mm fraction; similar results were presented in the literature [2]. This indicates that special attention should be paid to the size of the tested aggregates when interpreting the results.

Very interesting studies were conducted using the micro-Deval drum [31]; the influence of the mass of the abrasive charge and the number of rotations of the drum on the value of the aggregate's mass loss after the test was investigated for seven types of rocks (diabase, andesite, slate, coarse-marble, fine-marble, tuff and limestone). Loss of mass after abrasion is directly proportional to the number of drum rotations. However, in the case of an abrasive charge mass, this dependency is much more complicated. It has been observed that the loss of mass only increases up to a certain limit of the mass of the abrasive charge, about 5000 g, and after this value is exceeded, the abrasion index decreases. The results of these tests will accurately justify the standardized amount of abrasive charge in the drum for the abrasion test.

It has been proved in the literature [15], [30], [32], [34] that there is a close correlation between the resistance to fragmentation (abrasion) of aggregate in the Los Angeles drum and the mechanical properties of the rock. In these papers, the results of research on rocks representing both sedimentary, igneous (intrusive and volcanic) and metamorphic rocks were analysed. The aggregate mass loss after the drum test was compared with the properties obtained from the bulk density, the porosity and the Schmidt hammer and ultrasound tests, as well as compression strength, tensile strength and point strength. The values of the coefficients ranged from a few to several dozen percent. For the most part, the matching regression curves are exponential or linear with fairly good matching (R^2=(0.72-0.90)) [15], [28], [30]. However, in the literature [31], a logarithmic regression with a correlation coefficient at the level of R^2=(0.51-0.80) was proposed.

Similar relationships were determined for the abrasiveness of aggregates in the micro-Deval drum [9], [33]. In this case, the dependence of the abrasion resistance on the compressive and tensile strength, the ultrasonic wave velocity and the number of Schmidt hammer strokes was correlated by means of exponential regression where the determination factor R^2 ranged from 0.59 to 0.67 [9]. In the literature [33], the determination coefficient R^2 correlated with the compressive strength even reached 0.84 for selected andesites.

The literature lacks publications on the dependence of the mechanical properties of aggregates on their physical and geometric properties. Only studies related to salt crystallization resistance [10], [17], [28] are available.

2. AIM OF THE STUDY

aim of this study was to determine the empirical relationships between the mechanical properties of aggregates represented by the Los Angeles *LA* coefficient and the micro-Deval M_{DE} coefficient and geometric properties, i.e. the shape index and the flatness index.

3. LABORATORY TESTS

3.1. TESTING MATERIAL

In order to conduct the experiments, aggregate samples were prepared from three types of Carpathian sandstones from the south-eastern region of Poland, i.e. Magura sandstone, Cergo sandstone and Krosno sandstone. These types of sandstone are a popular material that is often used in local road construction and hydrotechnical works. Cergo and Magura sandstones are characterized by quite high mechanical properties, with an average compression strength of about 170 MPa, while in the case of Krosno sandstones the compression strength is about 120 MPa [14].
From each type of sandstone, their aggregate was analysed in the form of arch stones of 5-20 mm and 5-31.5 mm grain size and mixtures of 0-31.5 mm and 0-63 mm continuous granulation. Arch stone is a broken aggregate, resulting from a single crushing and with controlled grain composition. Continuous granulation aggregate mixtures are a multi-fractional material resulting from mixing fine and coarse fractions, which are often waste. In order to perform fragmentation and abrasion resistance tests for each aggregate type, samples of aggregates with a grain size of 10-14 mm were prepared using the screening method, in accordance with the requirements of the standards (PN-EN 1097-2:2010 [25], PN-EN 1097-1:2011 [24]). The grain composition of the analysed samples additionally included 35% of grains with 10-11.2 mm fractions and 65% of grains with 11.2-14 mm fractions. However, the remaining tests, i.e. the shape index [26] and the flatness index [27] were performed on aggregate with a basic fraction (arch stone or mixture). For Magurian sandstone, the results for 28 arch stones and 18 mixtures were analysed; for Cergo sandstones, 20 arch stones and 10 mixtures were analysed; and for Krosno sandstone, 3 arch stones and 10 mixtures were analysed. All of the aggregates were delivered from private quarries and, in accordance with the privacy policy, the exact names and locations of the suppliers of samples and materials have not been presented here. For each sample, the type of sandstone and the aggregate assortment were given. All of the analysed results are the average of two determinations of a given property.

3.2. TEST METHOD

3.2.1. LOS ANGELES FRAGMENTATION RESISTANCE

The Los Angeles fragmentation resistance test was performed in accordance with the guidelines of the PN-EN 1097-2:2010 standard [25]. The test consisted of determining the percentage loss of the mass of a sample during tumbling with steel balls in a rotating drum (Fig. 1a). After completion of the full 500 rotations, the mass of the material remaining in the 1.6 mm sieve was determined. The loss of mass was caused by the wear and tear of the aggregate grains, caused mainly by crushing. The Los Angeles drum is equipped with a shelf that gathers the aggregate with the balls and when it reaches a certain height, the material is dropped and destroyed by the balls. The load consists of 11 steel balls with a diameter of 45-59 mm. All tests were performed on two test samples with a mass of 5000±5 g. The tests were carried out using the "dry" method. The Los Angeles *LA* coefficient was determined from formula (3.1):

$$LA = \frac{5000 - m}{50} \tag{3.1}$$

where:
m - mass fraction remaining in the 1.6 mm sieve (g).

3.2.2. MICRO-DEVAL ABRASION RESISTANCE

The micro-Deval abrasion resistance test was performed in accordance with the guidelines of the PN-EN 1097-1:2011 [24] standards. The test consisted of determining the percentage loss of the mass of a sample that is smaller than 1.6 mm during the abrasion process. The loss of mass is caused by the wear of the aggregate grains caused by friction between the aggregate and the abrasive material in the rotating drum (Fig. 1b). The abrasive material consisted of 2 kg of steel balls with a diameter of 10±5 mm. All of the tests were performed on two test samples with a mass of 500±2 g. The mass loss was determined after 12 000 drum rotations. The studies were performed with the addition of 2.5 l of water. The micro-Deval coefficient M_{DE} was determined from the formula (3.2):

$$M_{DE} = \frac{500 - m}{5} \tag{3.2}$$

where:

m - aggregate mass remaining in the 1.6 mm sieve (g).

3.2.3. THE SHAPE INDEX

The shape index was tested in accordance with the requirements of the PN-EN 933-4:2008 standard [26]. The test consisted of segregation of the coarse aggregate on the basis of the ratio of its length L (maximum aggregate grain size) to thickness E (minimum grain size) by means of the so called Schultz caliper (Fig. 1c). The shape index is calculated as the percentage of the mass of the grains with an L/E ratio greater than 3 (3.3):

$$SI = \frac{\sum M_2}{\sum M_1} \cdot 100 \tag{3.3}$$

where:

SI - shape index (%), $\sum M_1$ - sum of the masses of the tested fractions (g), $\sum M_2$ - sum of the masses of the irregular grains (g).

Fig. 1. The laboratory equipment used to perform the laboratory tests: a) Los Angeles drum, b) micro-Deval drum, c) Schultz caliper, d) rod sieves

3.2.4. THE FLATNESS INDEX

The determination of the flatness index was carried out in accordance with the guidelines contained in the PN-EN 933-3:2012 [27] standard. This test consisted of two screening stages; first of all, the sample was separated using square mesh sieves into fractions of grains of dimensions d_i/D_i according to the aforementioned standard. Each fraction was then sieved on suitable rod sieves with a slot width equal to $D_i/2$ (Fig. 1d). The flatness index was calculated as the mass of the grains passing through the rod sieves in relation to the total mass of dry grains (4):

$$FI = \frac{M_2}{M_1} \cdot 100 \tag{3.4}$$

where:

FI - flatness index (%), M_1 - sum of the mass fraction with grain size d_i/D_i (g), M_2 - sum of the mass fraction of the grain size passing through the appropriate sieves with slot width $D_i/2$ (g).

4. ANALYSIS OF RESULTS

The mean values of the Los Angeles and the micro-Deval coefficients, depending on the deposit, were characterized by a considerable scattering of the results. In the diagrams (Fig. 2), the variances of the data sets were presented for the individual types of sandstones and for the overall results of the tested sandstones, divided into the Los Angeles and the micro-Deval coefficients, as well as for the aggregate assortment.

For the Magura and Cergo sandstones, regardless of whether the samples were prepared from arch stones or mixtures, the average values of the analysed coefficients were very similar and amounted to: 24-25 for the Los Angeles coefficient, and about 34-38 for the micro-Deval coefficient. A clear difference can only be seen when the results are scattered. The Krosno sandstone is much more susceptible to fragmentation and abrasion, as evidenced by the results of the analysed coefficients; the *LA* was 32 for the arch stones on average and 44 for the mixture. There was an even greater difference in the M_{DE}, 48 for the arch stones and 67 for the mixtures. In addition, the scattering of the results was much greater than in the case of the other sandstones. The average coefficient values for all of the sandstones, according to the assortment, were as follows: for the arch stones: *LA* 24 and M_{DE} 36, while for the mixtures they were 30 and 45 respectively. Comparing these results to the requirements of the PN-EN 13242 standard, the arch stones met the requirements of categories LA_{25} and M_{DE40} on average, while the mixtures categories LA_{30} and M_{DE50}.

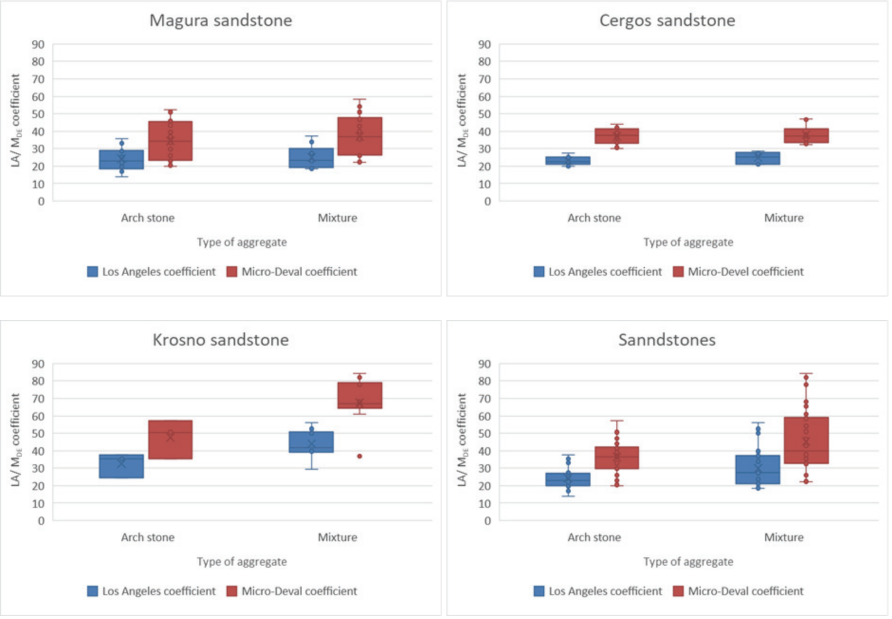

Fig. 2. Variations in the results of the Los Angeles and micro-Deval coefficients due to the assortment of the aggregates and the type of sandstone from which it was made

When analysing the mean values of the Los Angeles and the micro-Deval coefficients for the arch stones and the mixtures, it was found that in all cases the values of these coefficients were lower for the arch stones. This indicates that the method of production, and thus the shape and form of the grains, are significant. Figure 3 presents the variances in the results of the shape and flatness indices due to the aggregate assortment and sandstone type.

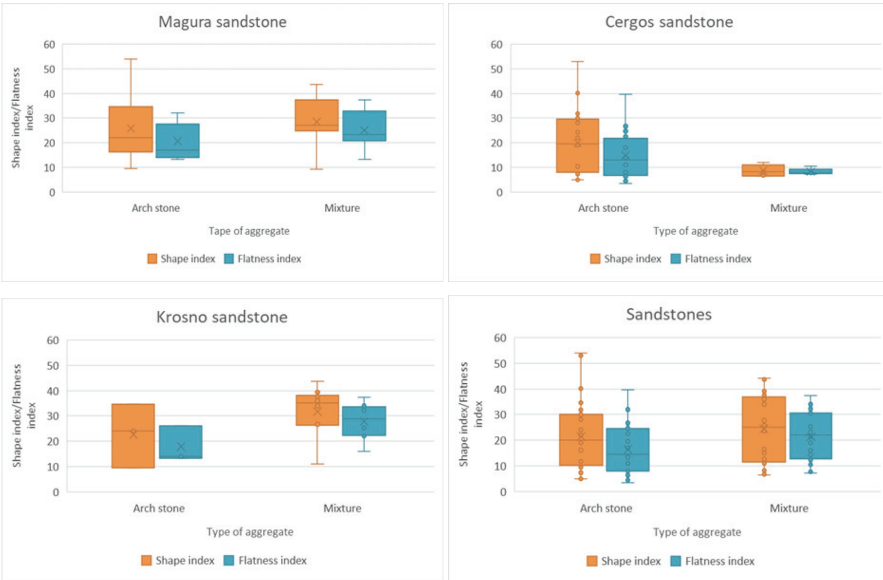

Fig. 3. Variants of the results of the shape and flatness indices due to the assortment of the aggregate and the type of sandstone from which it was made

In the case of Magura sandstone, the differences between the average values of the analysed geometrical indices for the particular aggregate assortments were small, with a maximum of 3% for the flatness index. For the aggregates from Cergo sandstone the differences were as follows: for the flatness index it was also about 3%, while for the shape index it was about 5%. The biggest differences could be observed for aggregates from Krosno sandstone, and in both cases they were about 10%.

Due to an insufficient amount of data, the results for all of the analysed sandstones have been summarized in Figures 4-7 by aggregate assortment for each type of sandstone. Figures 4 and 5 show the correlation between the Los Angeles coefficient and the shape index, and the Los Angeles coefficient and the flatness index, respectively. Similarly, Figures 6 and 7 show the relationship between the micro-Deval coefficient and the shape and flatness indices.

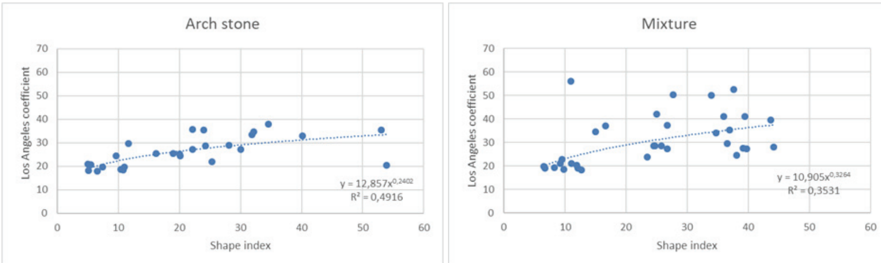

Fig. 4. Correlation between the Los Angeles coefficient and the shape index depending on the aggregate assortment

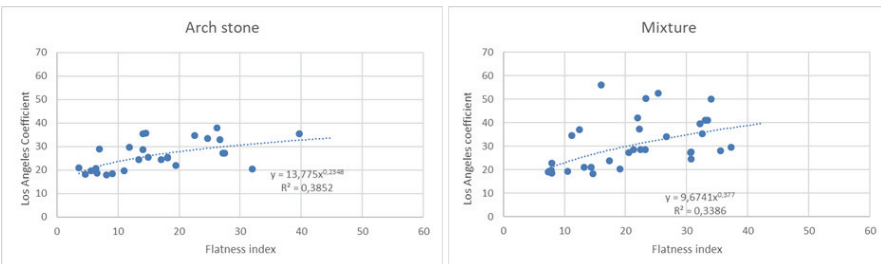

Fig. 5. Correlation between Los Angeles coefficient and shape index depending on the aggregate assortment

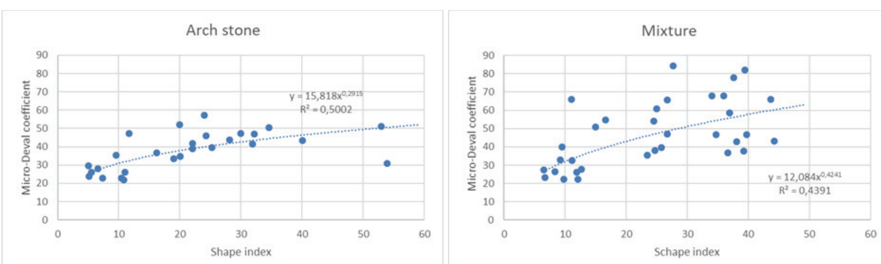

Fig. 6. Correlation between the micro-Deval coefficient and the shape index depending on the aggregate assortment

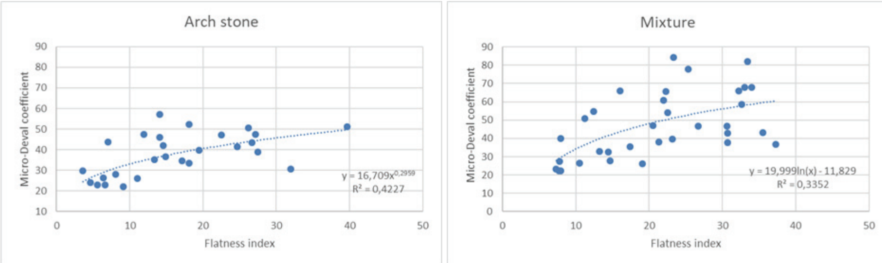

Fig. 7. Correlation between the micro-Deval coefficient and the flatness index depending on the aggregate assortment

From analysing the graphs presented in Figures 4–7, a certain trend can be noticed in the dependence of the mechanical properties of the aggregates on the content of the flat and irregular grains. The best match was obtained by using the power function. The determination factor R^2 for all of the analysed cases ranged from 0.33 to 0.50 with a clear difference between the individual correlations for the arch stones and the mixtures. The regression match was slightly more accurate for the arch stones than for the mixtures. This may be due to the fact that the grain composition of the mixtures was more varied. Also, the preparation of the sample for the fragmentation and abrasive tests on the aggregate with a wide range of fractions, as in the case of the arch stones or the mixture, resulted in the fact that a narrow range of fractions (10-14 mm) is not always characterized by the same shape and flatness indices. Moreover, the trend lines for the arch stones appear to be flatter, which may indicate that when the aggregate contains a significant amount of flat and/or irregular grains, it will no longer have a significant impact on the degradation of the aggregate grains as a result of either fragmentation or abrasion.

4. CONCLUSIONS

The Los Angeles and the micro-Deval coefficients can be used to describe the mechanical properties of aggregates. They are the basic parameters that are necessary when assessing the quality of aggregates in terms of their resistance to mechanical damage caused by fragmentation and abrasion. On the basis of the literature analysis, it was found that the value of these coefficients is influenced by factors mainly related to lithology, as well as the structure and mechanical properties of the rocks from which the aggregate is produced. The research conducted for aggregates from selected Carpathian sandstones proved that the value of the Los Angeles and the micro-Deval coefficients is also influenced by geometric properties and the way the aggregates are produced.

The Los Angeles and the micro-Deval coefficients of the aggregates from Carpathian sandstones are classified as being quite high in terms of fragmentation resistance, while in terms of abrasion resistance they are usually classified in the last or penultimate category. There is also a visible difference between the values of the analysed coefficients when dividing them into aggregate assortment. Aggregate mixtures are less resistant to fragmentation and abrasion than arch stones; one of the reasons for this is the higher content of irregular and flat grains than in the arch stones.

Based on the correlation between the mechanical and geometrical properties of the aggregates, a certain correlation between these parameters can be deduced; the highest determination coefficients R^2 were obtained for an exponential regression. From analysing the course of these curves, it can be stated that the values of the *LA* and M_{DE} coefficients aimed at a certain asymptote, which may mean that after a certain content of irregular and flat grains is exceeded, the values of these coefficients will not increase any further.

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OPRACOWANIE ZWIĄZKU POMIĘDZY WŁAŚCIWOŚCIAMI MECHANICZNYMI KRUSZYW A ICH PARAMETRAMI GEOMETRYCZNYMI NA PRZYKŁADZIE POLSKICH PIASKOWCÓW KARPACKICH

Słowa kluczowe: kruszywa, współczynnik Los Angeles *LA*, współczynnik mikro-Deval M_{DE}, właściwości geometryczne kruszyw

STRESZCZENIE

Najważniejszymi parametrami opisującymi właściwości mechaniczne kruszyw są współczynniki Los Angeles oraz micro-Deval. Wyrażają one odporność na fragmentację i ścieralnie. Bardzo duży wpływ na rozdrabianie i ścieralność kruszyw ma ich litologia oraz właściwości strukturalne i tekstualne. Istnieje również ścisła korelacja pomiędzy tymi parametrami a właściwościami fizycznymi i mechanicznymi skały, z której wykonano dane kruszywo. Wiele pozycji literatury zawiera zestawienia ubytków masy kruszywa po badaniu w bębnie Los Angeles i Mikro-Devala z właściwościami uzyskiwanymi z badań gęstości objętościowej, porowatości, badań z użyciem młotka Schmidta i ultradźwięków oraz wytrzymałości na ściskanie, wytrzymałości na rozciąganie, czy też wytrzymałości punktowej. Natomiast brakuje publikacji dotyczących zależności właściwości mechanicznych kruszyw od ich właściwości geometrycznych. W związku z tym, celem niniejszej pracy było ustalenie relacji empirycznych między właściwościami mechanicznymi kruszyw, reprezentowanymi przez współczynnik Los Angeles *LA* oraz współczynnik mikro-Devala M_{DE} a właściwościami geometrycznymi, tj wskaźnikiem kształtu i wskaźnikiem płaskości.

W celu przeprowadzenia eksperymentów przygotowano próbki kruszyw wykonane z trzech rodzajów piaskowców karpackich występujących w południowo-wschodniej części Polski, tj. piaskowiec magurski, piaskowiec cergowski i piaskowiec krośnieński. Próbki do badań odporności na rozdrabnianie i ścieralnie oraz do badania wskaźnika kształtu i płaskości, przygotowano z kruszyw asortymentu: kliniec o uziarnieniu 5-20 mm i 5-31,5 mm oraz mieszanka o uziarnieniu ciągłym 0-31,5 mm i 0-63 mm. Próbki analityczne uzyskano metodą przesiewania.

Uzyskane wyniki współczynników klasyfikują kruszywa z piaskowców karpackich dość wysoko pod względem odporności na rozdrabnianie (*LA*), natomiast pod względem odporności na ścieranie (M_{DE}) zwykle kwalifikują się do ostatniej bądź przedostatniej kategorii. Widoczna jest również różnica pomiędzy wartościami analizowanych współczynników przy podziale na asortyment kruszywa. Mieszanki kruszyw charakteryzują się mniejszą odpornością na rozdrabnianie i ścieranie niż klińce. Jedną z przyczyn jest większa niż dla klińców zawartość ziaren nieforemnych i płaskich.

Na podstawie korelacji pomiędzy właściwościami mechanicznymi a geometrycznymi kruszyw, można wywnioskować pewną zależność pomiędzy tymi parametrami. Najwyższe współczynniki determinacji R^2 uzyskano dla regresji wykładniczej. Współczynnik determinacji R^2 dla wszystkich analizowanych przypadków zawiera się w granicach 0,33 do 0,50 z wyraźną różnicą pomiędzy poszczególnymi korelacjami dla klińców i mieszanek. Dla klińców dopasowanie regresji jest nieco dokładniejsze niż dla mieszanek. Spowodowane może to być tym, że skład ziarnowy mieszanek jest bardziej zróżnicowany. Również przygotowanie próbki do badań odporności na rozdrabnianie i odporności na ścieralnie z kruszywa o szerokim zakresie frakcji, jak w przypadku klińca czy mieszanki, powoduje, że nie zawsze wąski zakres frakcji (10-14 mm) charakteryzuje się tożsamymi współczynnikami kształtu i płaskości. Analizując przebieg tych krzywych można stwierdzić również, że wartości współczynników Los Angeles oraz Mikro-Deval dążą do pewnej asymptoty, co może oznaczać, że po przekroczeniu pewnej zawartości ziaren nieforemnych i płaskich wartości tych współczynników nie będą już wzrastać.

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