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Flow coefficient of the aggregates as a parameter characterizing the suitability of non-cohesive soils for earthworks

Key words: flow coefficient of the aggregates, uniformity coefficient

Introduction

The introduction of European standards for the assessment of construction aggregates over 20 years ago provided a number of new testing methods previously non-existing in Poland. One of them is the flow coefficient of aggregates, popularly known as aggregate angularity. The method of determination is given in PN-EN 933-6:2014 standard, which defines the method of determining the coefficient for coarse aggregates with grain sizes between 4 and 20 mm and fine aggregates with grain sizes below 2 mm. This test is particularly important when designing mineral–asphalt mixtures (Mitchell, 2001). Aggregate angularity, particularly for fine aggregates, is the main factor influencing the workability of mixtures (Little, Button, Jayawickrama & Hudson, 2003). In the 1980s in the USA and France, it was proven that the angularity of an aggregate affects the stability and rutting resistance of mixtures (Topal & Sengoz, 2005). It is desirable to include angular fine aggregates in the composition. Rounded grains, especially natural sand, can lead to rutting of the mixture. The problem of grain angularity is also considered in concrete design (Quiroga & Fowler, 2004).

The shape of grains is a complex characteristics, determined by three parameters: sphericity, angularity and surface micro texture. The shape of grains affects the compaction of non-cohesive soils (Szerakowska, 2018). The problems of grain shape influence on parameters of non-cohesive soils in Poland was studied by (Parylak, 2000; Mamok, 2006; Chmielewski, 2008; Zięba, 2013).

The coefficient of uniformity (C_U) is still regarded as one of the basic parameters characterizing the aggregates/soils intended for embankment construction. This parameter describes the shape of the grain-size curve. Since the 1970s the requirements for subsoil for road surface constructions in Poland are given in typical surface catalogues and include (Judycki et al., 2014a; Judycki et al., 2014b):

- non-swelling of the soil,
- *CBR* ≥ 10 (after four days of water saturation); since 2014 also secondary modulus $E_2 \geq 80$ MPa,
- compaction in accordance with current standards or/and guidelines.

Non-swelling of the soil depends on the content of the dust and clay fraction and their activity – the sand equivalent (SE). In earthworks, the parameter relating to the ability to carry loads without excessive deformation is the bearing ratio or secondary modulus (E_2) determined with static load plate test (VSS). The value of the bearing ratio for non-cohesive soils depends mainly on the angle of repose.

The angle of repose depends on many factors, among others, the shape, roundness of the grain and the compaction (Hansen, Lundgren, Beuck & Rönfeldt, 2013). The influence of various factors on the angle of repose is determined by the Lundgren formula (Glazer, 1985):

$$\phi = 36° + \phi_1 + \phi_2 + \phi_3 + \phi_4 \qquad (1)$$

where:

ϕ_1 – grain shape –5° for round aggregates; +1° for angular (range 7°),

ϕ_2 – dimensions of grains 0° for sands do +2° for coarse (range 3°),

ϕ_3 – degree of compaction from –3° for $C_U < 5$ to +3° for $C_U \geq 15$ (range 7°),

ϕ_4 – density index from –6° for loose soils to +6° for compacted soils (range 13°).

The shape of the grains can cancel out the impact of grading on the angle of repose.

The paper attempts to determine if there is a strong correlation between the California bearing ratio (*CBR*) and flow coefficient of the aggregates. The strength of the correlation with other parameters determining the suitability of soil/aggregates for earthworks was evaluated. Among others those parameters were: effective grain size, coefficient of uniformity (C_U), curvature coefficient (C_C) and dry density of solid particles.

Determination of flow coefficient of aggregates

In the United States, the angularity of the aggregate is determined in accordance with AASHTO T 304 standard or ASTM C 1252. The porosity of the loose rock material passing through a standard 30 ml funnel into a cylinder is determined. In France, the test is carried out on the basis of AFNOR P18-564 standard. The time in seconds of flow (pouring) of a certain amount of aggregate through the funnel was determined as a measure of the angularity of the aggregate. Similar approach can be seen in comparative viscometers such as Engler's. The comparison of the results for above mentioned methods can be found in the study (Aschenbrener, 1994).

The same principle as in France is adopted in BS EN 933-6 standard. The flow rate of fine aggregate is determined on a 0.063/2 mm fraction. The laboratory sample is washed, dried and then reduced to reference test portion with M_1 mass according to the formula:

$$M_1 = \left(1{,}000\frac{\rho_p}{2.70} \pm 2\right) \quad (2)$$

where:
ρ_p – pre-dried particle density (EN 1097-6) [$\mathrm{Mg \cdot m^{-3}}$],
2.70 – constant, the density of reference material in dried state [$\mathrm{Mg \cdot m^{-3}}$].

A polycarbonate funnel with a 12 mm hole is used to test the 0/2 mm aggregates. The flow time (E_{csi}) is measured with a stopwatch with an accuracy of 0.1 s. Five runs are made. The aggregate flow time (E_{cs}) is calculated from the formula:

$$E_{sc} = E_{csm} + (E_{RS} - E_{cse}) \quad (3)$$

where:
E_{csm} – average flow time [s],
E_{RS} – flow time for reference material 32 s,
E_{cse} – flow time for the reference test portion (30–34 s).

The apparatus for determining the flow time is extremely simple and includes a tripod polycarbonate funnel and a measuring cylinder. The bulk density of the aggregate in the measuring funnel and the measuring cylinder has a significant influence on the obtained results. This problem has been solved by using an additional cylinder with a shutter – Figure 1.

Additional tests

Simultaneously while preparing the sample for determination of the flow coefficient of fine aggregates it is also possible to determine the grading curve of the soil. As the PN-B-04481:1988 standard was withdrawn in 2015, while the ISO/TS 17892-4:2004 technical specification was replaced in 2017 by the PN-EN ISO 17892-4:2017-01 standard, the grain composition was determined in accordance with the PN-EN 933-1:2012 standard.

The second test necessary to conduct the flow time of fine aggregates is the density determination by pycnometric method. The determination is carried out according to PN-EN 1097-6:2013 standard. Density of pre-dried grains is defined as the ratio of mass of the sample in

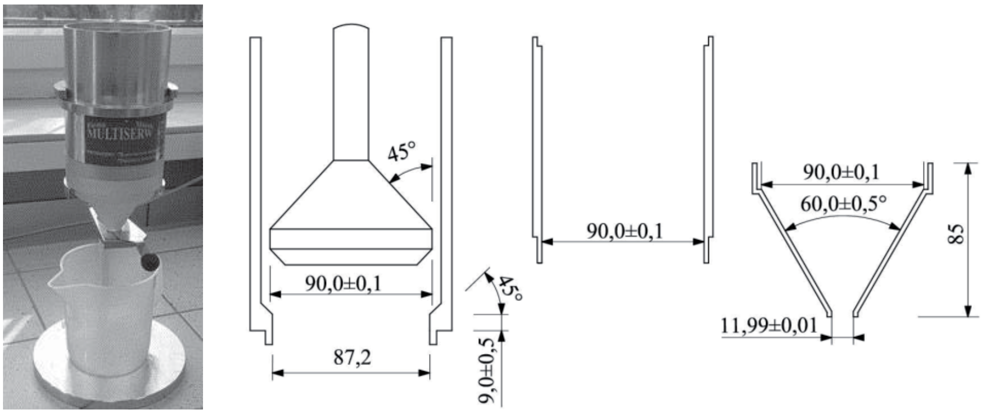

FIGURE 1. Aparatus required for the determination on the flow coefificent of fine aggragate

dry state to the volume it occupies in water. The mass is determined by weighing the sample in saturated state, surface-dried and then re-weighing. The volume is determined by weighing.

Two samples must be prepared for testing. The weight of the samples shall not be less than that given in Table 1. The first step is to wash the sample to get rid of clogged grains and to discard grains that remain on the 31.5 mm sieve and pass through the 0.063 mm sieve. The sample shall then be dried in the oven at 110 ±5°C. After drying, the aggregate shall be cooled to ambient temperature. The next step is to get a net weight M_1 of a setup with a known volume V (Fig. 2) and put the sample in to determine the total weight of the setup M_2. The pycnometer is then filled with water ($T = 22 \pm 3°C$) up to about 30 mm below the line at the neck. In order to remove the air, the sample is mixed with a glass rod. Afterwards, the pycnometer is filled with water up to 20 mm below the measuring line and placed in a water bath ($T = 22 \pm 3°C$) for 1 h. It is important that the level in the water bath reaches 20 mm below the neck of the pycnometer. After one hour, the pycnometer should be taken out of the bath, the outer surface should be dried and then weighed to obtain M_3. After the test, calculate the density using the formula:

TABLE 1. Minimum mass of samples for density testing by pycnometer method

Upper (D) aggregate size [mm]	Minimum mass of test specimen [kg]
31.5	1.5
16	1.0
8	0.5
≥ 4	0.25

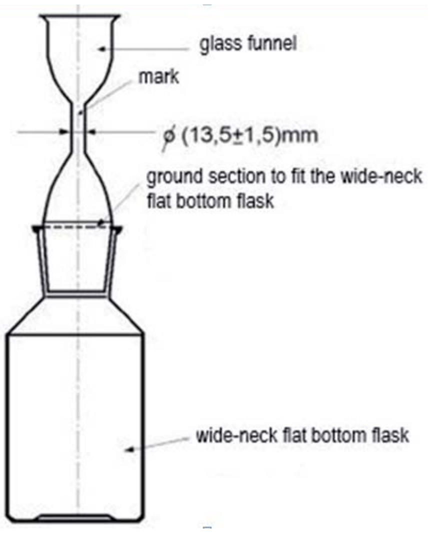

FIGURE 2. Pycnometer for determining the density of aggregates

$$\rho_p = \frac{(M_2 - M_1)}{V - \frac{(M_3 - M_2)}{\rho_w}} \tag{4}$$

where:

ρ_p – pre-dried grain density [Mg·m^{-3}],

M_1 – mass of pycnometer [g],

M_2 – mass of pycnometer with a sample [g],

M_3 – mass of pycnometer with a sample and water [g],

V – pycnometer volume [mm^3].

ρ_w – water density at set temperature [Mg·m^{-3}].

The density shall be determined to an accuracy of 0.001 Mg·m^{-3}. The accepted difference between two samples shall not exceed 0.019 Mg·m^{-3}. The final result is given as the average of two values with an accuracy of 0.01 Mg·m^{-3}.

As part of the research program, the *CBR* was additionally determined according to the procedure given in the PN-S-02205:1998 standard. The Proctor's test was included to determine the maximum dry density of solid particles (ρ_{ds}).

Test materials

The research was carried out on 19 soils (Nos 1–19 in Table 2) from the area of north-western Poland, four washed and sieved sands (20–23) and seven crushed aggregates (24, 29 – basalt, 25, 30 – granite, 26 – greywacke, 27 – granodiorite, 28 – amphibolite). The materials were categorized in accordance with the PN-EN 14688-2:2018 standard. Majority of the studied soils were evenly and gap-graded, only a few sands with gravel and one coarse sand (10) could be categorized as medium-graded. As predicted, washed and sieved aggregates (20–23) were single-graded, while crushed sands were medium-graded or, as in case of 26, gap-graded. All the soils studied in terms of *CBR* values met the requirements for the construction of road embankments and other structural layers. Natural sands are characterized by E_{cs} of 24 to 35 with an average value of 28, while crushed sands are characterized by E_{cs} of 35 to 45 with an average of 40. The aggregates and soils were listed by the *CBR* values (Table 2).

TABLE 2. Soil and aggregates parameters taken for testing

No	Type	C_C [-]	C_U [-]	d_{10} [mm]	d_{30} [mm]	d_{60} [mm]	ρ_{ds} [Mg·m^{-3}]	ρ_p [Mg·m^{-3}]	*CBR* [%]	E_{sc} [s]
23	MSa	0.9	2.1	0.25	0.34	0.53	1.76	2.66	14	29
1	FSa	1.0	1.8	0.15	0.20	0.27	1.70	2.64	15	25
16	FSa	0.9	2.6	0.11	0.16	0.28	1.65	2.62	15	25
19	MSa	1.1	2.2	0.10	0.14	0.21	1.76	2.65	15	27
3	MSa	0.9	2.0	0.25	0.34	0.50	1.81	2.66	16	24
4	FSa	1.0	2.2	0.09	0.14	0.20	1.69	2.65	16	26
22	MSa	0.9	2.3	0.25	0.36	0.58	1.81	2.55	16	27
6	FSa	1.0	2.0	0.10	0.14	0.19	1.70	2.66	17	27
21	MSa	0.9	1.9	0.26	0.34	0.49	1.77	2.65	17	28
20	MSa	1.0	2.4	0.19	0.30	0.47	1.79	2.65	19	27
5	MSa	1.0	2.4	0.12	0.19	0.30	1.72	2.65	20	26
8	MSa	0.9	3.0	0.21	0.34	0.61	2.03	2.64	20	27
7	MSa	0.9	2.4	0.21	0.32	0.51	1.76	2.67	21	25
9	MSa	0.9	3.3	0.19	0.31	0.61	1.79	2.66	21	27
11	MSa	0.9	2.3	0.22	0.32	0.49	1.76	2.67	21	25
18	grSa	0.7	4.9	0.32	0.58	1.56	1.86	2.65	21	30
14	MSa	0.9	2.2	0.16	0.23	0.35	1.71	2.66	22	25
15	MSa	1.1	3.4	0.13	0.25	0.45	1.79	2.63	22	25

TABLE 2 cont.

No	Type	C_C [-]	C_U [-]	d_{10} [mm]	d_{30} [mm]	d_{60} [mm]	ρ_{ds} [Mg·m^{-3}]	ρ_p [Mg·m^{-3}]	*CBR* [%]	E_{sc} [s]
25	CSa	1.1	6.7	0.10	0.23	0.67	1.92	2.68	24	35
10	CSa	0.9	4.5	0.18	0.35	0.81	1.78	2.69	25	32
13	grSa	0.7	6.5	0.16	0.36	1.07	1.96	2.70	25	32
12	grSa	0.6	8.6	0.16	0.35	1.38	2.00	2.69	27	35
28	CSa	1.0	10.1	0.09	0.24	0.91	2.08	2.86	27	37
2	grSa	0.4	8.9	0.15	0.29	1.33	1.95	2.67	29	34
29	CSa	1.2	6.2	0.17	0.48	1.08	2.08	3.09	30	40
17	grSa	0.8	4.9	0.18	0.36	0.88	1.99	2.64	31	35
27	CSa	1.5	9.3	0.13	0.35	1.21	1.97	2.64	33	41
30	CSa	1.0	7.7	0.14	0.40	1.09	1.81	2.65	34	39
26	CSa	0.8	4.8	0.26	0.44	1.26	1.97	2.73	35	42
24	CSa	1.7	7.1	0.17	0.37	1.20	2.23	3.13	42	45

Analysis of the relationship between the flow time and other parameters

The correlation between the parameters describing the grading curve, i.e. C_U and C_C, and the *CBR* and volumetric density of the dry density of soils was analysed. The correlations were analysed for soils and aggregates together. Pearson coefficient of linear correlation was used to measure the relationship. Table 3 presents the obtained coefficient values for relations between selected parameters. Analysing the obtained dependencies, it should be stated first of all that the C_C does not show any relation with the *CBR* or flow coefficient. For soils only there is a negative relation while for soils and aggregates together, no relation at all. However, as predicted, the C_U shows much better dependence. The flow coefficient shows the highest values of dependence in relation to the coefficient of uniformity but also to the *CBR*. This indicates the potential of this simple study. Figures 3–5 present the correlation between major parameters and the confidence interval.

TABLE 3. Impact of individual stakeholder groups on the study contract (own studies)

Parameter	Correlation coefficient	
	CBR	E_{cs}
C_U	0.76	0.81
C_C	0.29	0.33
d_{30}	0.48	0.48
d_{60}	0.76	0.78
E_{cs}	0.90	–
$\rho_{d\,\max}$	0.77	0.80

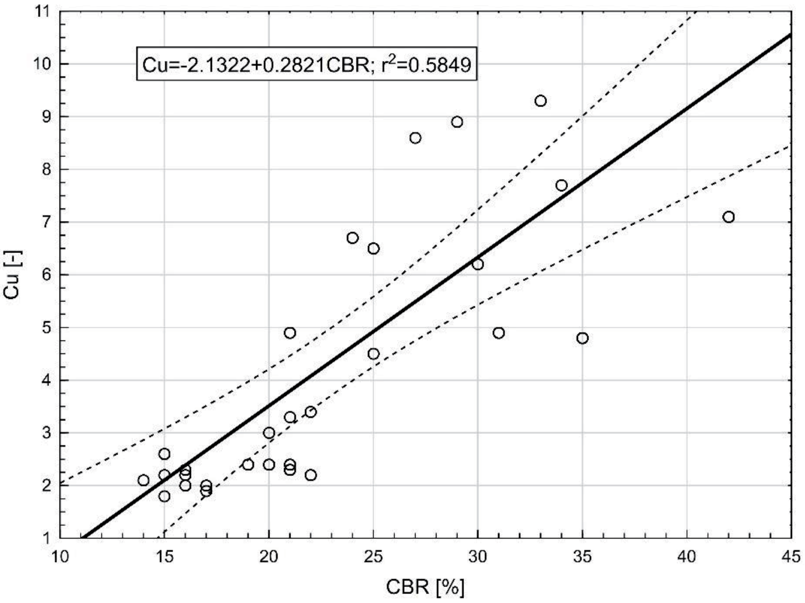

FIGURE 3. The relationship between the uniformity coefficient and *CBR*

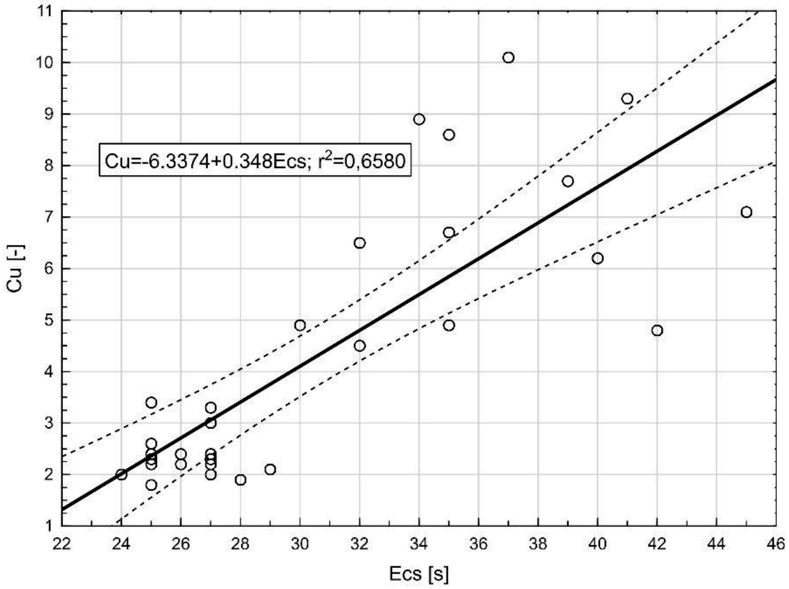

FIGURE 4. The relationship between the uniformity coefficient and flow coefficient of the aggregates

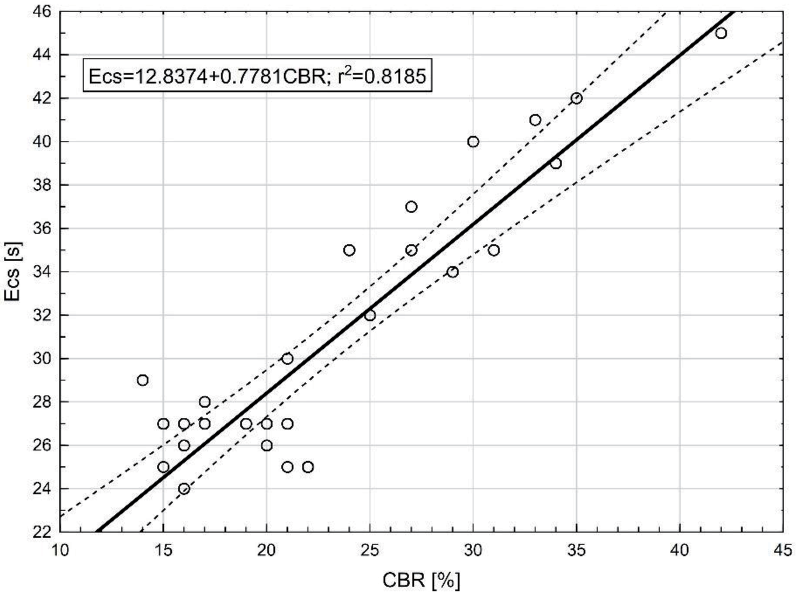

FIGURE 5. The relationship between the flow coefficient of the aggregates and *CBR*

Recapitulation

The study tried to determine the correlation between the flow coefficient E_{cs} and California bearing ratio as well as other parameters describing the non-cohesive soils. It was proven that for studied soils and aggregates the flow coefficient had the strongest correlation to the bearing ratio, which in the author's opinion is the most basic parameter for assessing the suitability of soils and aggregates for embankment's construction. Determination of soils and aggregates suitability based mainly on the coefficient of uniformity is improper. This can lead to exclusion of materials which can be safely used as subsoils for road construction. From tested materials all of them met the requirements of minimal *CBR*, some met the requirements for improved subgrade and freezing depth (≥ 20, ≥ 25).

Flow coefficient of aggregates can be tested in a simple way and can be performed in parallel with screen analysis, assuming a density of $\rho_p = 2.65\ \mathrm{Mg \cdot m^{-3}}$ for quartz sands. Natural sands were characterized by E_{cs} flow coefficient from 24 to 35 with the mean value of 28, while crushed sands were characterized by E_{cs} from 35 to 45 with the mean value of 40. However, analysing the results of the research it should be stated that for the same value of flow coefficient, e.g. 25, 27, there is a variability of *CBR* in the range of 15–22 and 15–21, respectively. Of course, this indicates that the flow coefficient is a rather simplified measure and detailed analyses of grain shape should be carried out using more precise methods and parameters, e.g. general shape index proposed by Parylak (2000).

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Summary

Flow coefficient of the aggregates as a parameter characterizing the suitability of non-cohesive soils for earthworks. The article presents the results of the flow coefficient of aggregate for 30 sands and aggregates. The introduction of European standards for the assessment of construction aggregates over 20 years ago introduced a number of new testing methods not previously used in Poland. One of them is the flow coefficient of aggregate, popularly called aggregate angularity. The method of determination is given in the standard PN-EN 933-6:2014. This standard defines the method of determining the index for coarse aggregates with grain sizes between 4 and 20 mm and fine aggregates with grain sizes below 2 mm. This test is particularly important when designing mineral-asphalt mixtures. Aggregate angularity, particularly in fine aggregates, is the main factor influencing the workability of mixtures. The flow time through the apparatus depends on the degree of roundness and form of the grain. The study determined the relationship between the flow coefficient of aggregate and *CBR* in relation to the uniformity coefficient. This indicator is still considered to be one of the main parameters that affect the suitability of non-cohesive soils in earthworks. It was proven that E_{cs} is more dependent on *CBR* than C_U.

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