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Test Results of the Modulus of Elasticity of Concretes with Various Coarse Aggregates and Standard Recommendations

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ABSTRACT

The aim of this article is to compare the modulus of elasticity recommended in the standards and the results of tests of the modulus of elasticity of normal and high performance concretes with various coarse aggregates. The results of tests of the modulus of elasticity and compressive strength of concrete with a wide range of w/c ratio from 0.70 to 0.28 made with 10 types of coarse aggregates made of igneous rocks (basalt, granite, granodiorite from Polish and Ukrainian mines) and sedimentary rocks (dolomite, quartzite, gravel). Concrete was made with CEM I 42.5R and fine natural aggregate (quartz sand) were used. In the compared concretes, the principle of keeping the same volume of coarse aggregate was applied. In order to determine the value of modulus of elasticity, the elastic deformation of the concrete was investigated with the use of electrofusion strain gauges. The results of own research were compared with the modulus of elasticity determined on the basis of compressive strength classes according to Eurocode 2. Inconsistencies were found between the compared values in concrete with basalt and granite aggregate, and the differences reach up to 20%. Only in the case of concretes with dolomite aggregate, compliance with the values specified in the Eurocode 2 standard was obtained. In addition, the physical and mechanical properties of the aggregates used were determined. The crushing strength is of the greatest importance, as measured by the aggregate crushing value according to British Standard BS 812 and Polish Standard PN-B-06714-40. It was found that there is a correlation between the aggregate crushing value and the modulus of elasticity of concrete, which is stronger than the correlation between the modulus and compressive strength.

Keywords: concrete, coarse aggregate, modulus of elasticity, compressive strength, aggregate crushing value.

INTRODUCTION

In the standard regulations, the deformability of concrete under a temporary compressive load is analyzed primarily on the basis of the values of the elasticity modulus E_c, the ultimate strain ε_{c1} at maximum stress, and the lateral strain coefficient ν_c. The standard values of these properties depend primarily on the compressive strength class. Only when considering the elasticity modulus E_{cm}, the influence of the aggregate type is taken into account. This recommendation was introduced only in 2008 [1]. The following is provided how the rules for considering the E_{cm} values have changed in Polish standards starting in 1984, i.e., for the last more than 30 years.

In the PN-B-03264:1984 [2], the values of the modulus of elasticity corresponding to individual classes of concrete were determined according to the relation E_b = 10000/(0.18 + 2.85R_{bk}), where R_{bk} = (0.77 – 0.001R_b^G)R_b^G. The given values of E_b can also be taken on the basis of experimental data. In such cases, the test methodology should be adapted to the expected loading conditions of the structure, and the E_b value should be determined for the average strength of concrete = 1.3R_b^G [2].

After the standard was revised in 2002, it was clarified that the values of E_{cm} (formerly E_b) given in the table of the standard correspond to the average secant modulus of elasticity of concrete with quartzite aggregate, determined in the range of stresses from 0 to $0.40f_{cm}$ and assigned to individual classes of concrete can be calculated from the formula $E_{cm} = 11000(f_{ck} + 8)^{0,3}$, where $f_{ck} = 0,8\ f_{c,cube}{}^{G}$, and $f_{cm} = f_{ck} + 8$ [3].

Currently, the rules for determining the modulus of elasticity are given in the PN-EN 1992-1-1:2008 [1]. They have been expanded compared to the previous standard [3] with the following information and recommendations: that the structure is sensitive to deviations from the given values, then they should be estimated taking into account its specific behavior:

- the modulus of elasticity of concrete depends on the modulus of elasticity of its components,
- the table gives approximate values of the modulus of elasticity E_{cm} (a secant value between $\sigma_c = 0$ and $0,4f_{cm}$) of concretes with quartzite aggregates,
- for limestone and sandstone aggregates, these values should be reduced by 10% and 30%, respectively, and for basalt aggregates it should be increased by 20%,
- the values given in the table of the standard were determined according to the relationship $E_{cm} = 22(0.1f_{cm})^{0,3}$, where $f_{cm} = f_{ck} + 8$.

Observing, for more than 30 years, changes in the approach to the adoption and determination of the value of the modulus of elasticity, the influence of aggregate on its value was only strongly emphasized in the PN-EN 1992-1-1:2008 [1]. It is puzzling that earlier the Polish standards did not pay attention to the possible influence of coarse aggregate on the values of modulus of elasticity, when this issue was studied and known much earlier. It is a fact that for a given type of aggregate there is a variation in the deformability of the rock from which the aggregate is produced, depending on the deposit. However, the number of deposits from which aggregates for concrete are obtained is limited in Poland, and research has been carried out for years using aggregates from available deposits.

EFFECT OF THE COARSE AGGREGATE TYPE ON THE MODULUS OF ELASTICITY OF CONCRETE

For example, as early as 1977, the effect of the type of coarse aggregate on the value of the modulus of elasticity was described by Neville [4]. He points out that the properties of the aggregate affect the modulus of elasticity, although they do not generally affect the compressive strength, whereby the higher the modulus of elasticity of the aggregate, the higher the modulus of elasticity of the finished concrete. He also states that the shape of larger aggregate grains and their surface characteristics can also affect the value of the elasticity modulus of concrete [4]. Also, Jiang at al. states that the modulus of elasticity of concrete with gravel aggregate is lower, considering the inferior adhesion of paste to gravel aggregate grains, as the determining factor. Among concretes with crushed aggregates, the highest E_{cm} values were obtained for a concrete with

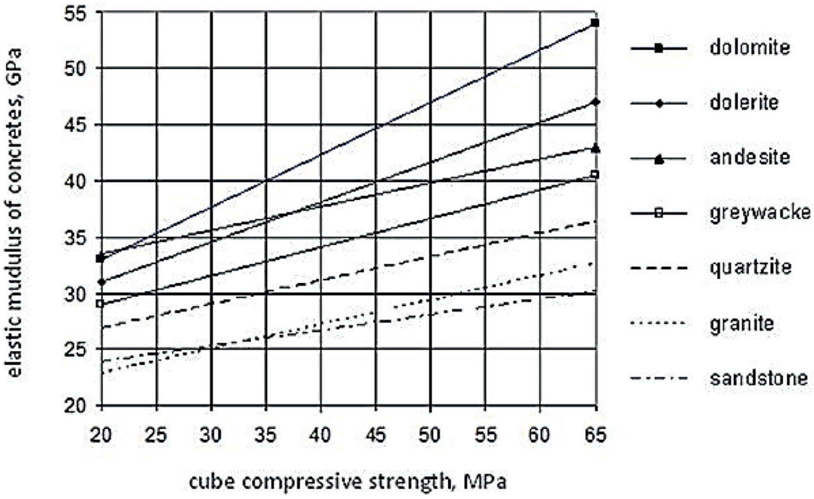

Fig. 1. Effect of aggregate type on the elasticity modulus of concrete according to Alexander [7]

basalt aggregate, lower value by about 10% was obtained with diabase, dolomite and limestone aggregate, and even lower (by about 20%) with granite and porphyry aggregate [5]. On the other hand, Deja [6], referring to the results of foreign studies of the ultimate deformability of concrete depending on the mineral composition of the aggregate (granite, porphyry, diabase, basalt, limestone, quartz, gravel) in 1972, reported that at the highest tensile strength of concrete with limestone aggregate has the lowest elongation. In contrast, the highest elongation is indicated for concrete with the porphyry aggregate.

Subsequent research results, presented in later years in both domestic and foreign literature, confirmed the influence of the type of coarse aggregate on the deformability of concretes. The differences in the values of the modulus of elasticity depending on the type of coarse aggregate can be quite significant (Figure 1) [7, 8].

They are largely the result of differences in the mineral composition and modulus of elasticity of the rocks from which the aggregates are obtained (Figure 2), as well as the properties of the aggregate grains that determine their adhesion to the cement paste [9].

According to Ajdukiewicz and co-authors [10, 11], the actual modulus of elasticity of concretes can deviate from the given standard design values by up to ±25% depending on the type of aggregate used. Among the concretes of the higher classes, the highest values of the modulus of elasticity are characterized by concretes with basalt aggregate (Figure 3), lower values by a few to several dozen percent are those with quartzite or dolomite aggregate, and even lower values (even more than 20%, although with large distribution of results) are those with granite aggregate. According to the authors [11], crushed granite aggregates available in Poland are of relatively low strength, and the modulus of elasticity of concretes with these aggregates is lower than the values given in the PN-B-03264:2002 [3]. The value of E_{cm} was calculated from the formula $E_{\mathrm{cm}} = 11000 \cdot (f_{\mathrm{ck}} + 8)^{0,3}$, where E_{cm} and f_{ck} are expressed in MPa. Based on this formula, the values of E_{cm} corresponding to the different classes of concrete were determined and are given in the PN-B-03264:2002 in Table 2 [3]. In Figure 3, the dashed line shows the course of the function plotted on the basis of the above expression. The claim that the E_{cm} modulus values calculated in this way apply to a concrete with quartzite aggregate indicate that they can be used more cautiously in the case of structural concretes, which is confirmed by the experimental results (Figure 3) [11].

In the standards [1, 3] the phrase is used – "the values of modulus of elasticity given in the table apply to concretes with quartzite aggregate". It should be strongly emphasized that this term is imprecise. What do the authors of the standards have in mind? Aggregate obtained from sedimentary rock? Rather not, both this rock and concrete made with aggregate obtained from it, despite its high strength and hardness, is also characterized by high deformability. Is aggregate

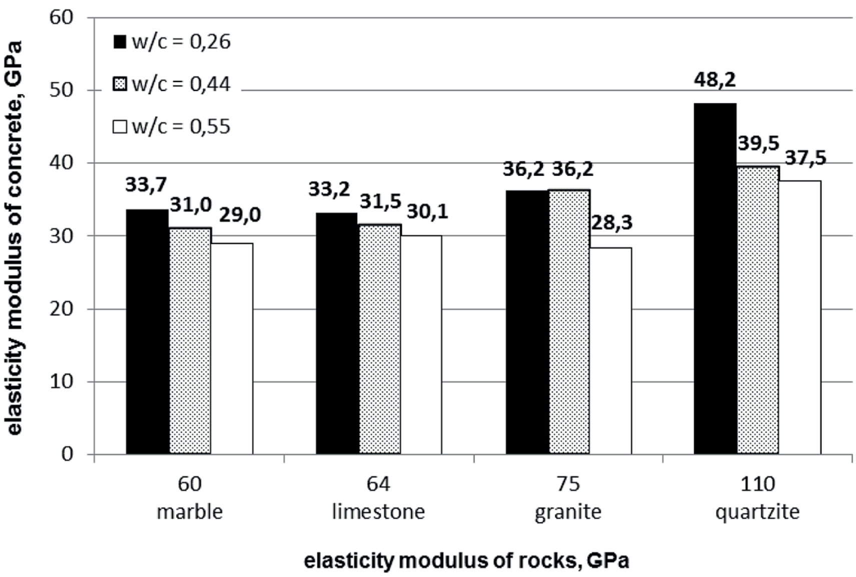

Fig. 2. Relationship between the modulus of elasticity of concretes and rocks from which crushed aggregates were obtained at different w/c values [9]

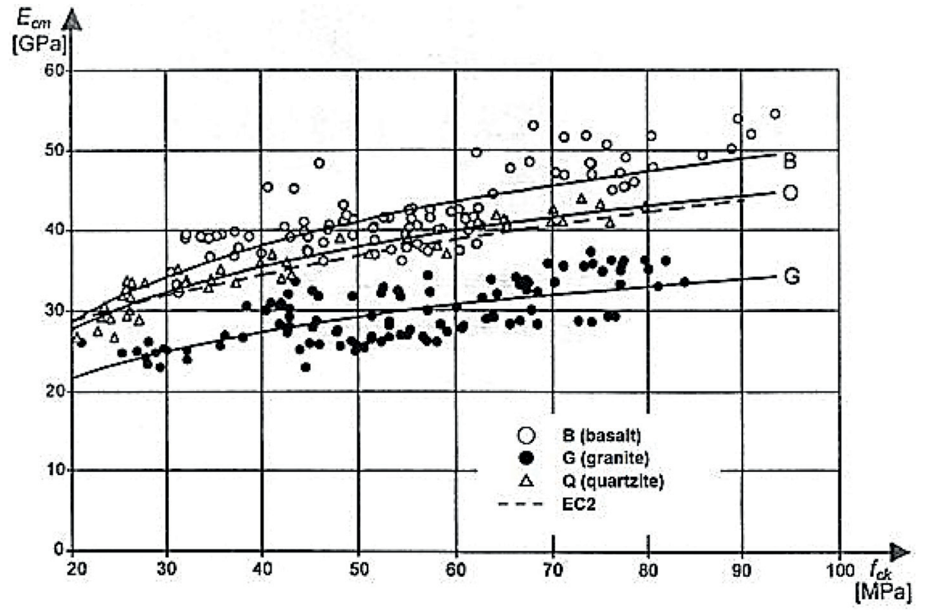

Fig. 3. Results of tests of the secant modulus of elasticity E_{cm} of ordinary and high performance concretes depending on the type of aggregate [11]

from metamorphic rock – quartzite (proper), or natural quartzite gravel? In own study of the strength and deformation properties of rocks and concretes made with aggregates from these rocks (basalt, granite, dolomite, quartzite, and gravel) [12], ordinary and high-strength concretes with crushed quartzite aggregate obtained significantly lower values of the modulus of elasticity than those given in the standard [1]. The interpretation regarding the type of quartzite aggregate with which the concretes were made, for which the values of elasticity modulus are given in the table of the standard [1], can be found in a few studies, but unfortunately not in the standard. According to the author, it is in the standard that this should be clearly resolved. Ajdukiewicz [10] and Mosley et al. [13] state that the modulus of elasticity given in the table of the standard [1] apply to concretes with quartzite gravel aggregate, which was confirmed by the test results presented in the commentary to the PN-B-03264:2002 (Figure 3) [11]. The recommendation to increase the modulus of elasticity of concrete with basalt aggregate by 20% [1] is also debatable. Despite the correct common opinion about the very good quality of this rock in a wide range of properties, it should be noted that basalt deposits are also characterized by a rather high variability of parameters, sometimes even within a single deposit. The modulus of elasticity of Polish basalts are equal to 56-115 GPa, depending on the deposit [5, 14]. In addition, some of the basalts and concretes made with them are characterized by deterioration of properties due to the sunburn and weathering [15, 16, 17].

As the hardening process progresses and the strength increases, the cement paste and concrete show less and less plastic deformation and become more elastic. The increase in the modulus of elasticity of paste and concrete over time is very similar to the change in strength. Among the factors of the greatest importance for the elasticity of paste are the w/c ratio and the degree of hydration of the cement, i.e. the basic quantities that determine the porosity and microstructure of the pores, on which the strength directly depends.

Although in concrete the importance of these factors is undisputed and primary, the coarse aggregate has a very important influence on the deformation and modulus of elasticity of concrete. The dependence of the deformation of concrete under load (as well as shrinkage) on the aggregate has a wide range. Influencing factors are the properties of the aggregate understood as filler, among them the shape and size of the grains, their texture, grain composition and the volume ratio of the coarse aggregate to the volume of the concrete. Also decisive are the properties of the material itself, i.e. the modulus of elasticity and strength of the rock, the texture of the rock or, with regard to the aggregate grains of the rock, the crushing ratio.

With regard to the deformation value and the elastic modulus of the concrete, the importance of the adhesion of the coarse aggregate grains to the cement paste must be further emphasised. In addition to the shape and size of the grains, the adhesion significantly depends on the mineral composition affecting the surface properties of the grains, but also on the reactivity of the minerals with the cement paste in the contact layer, which is the weakest in the entire concrete microstructure.

The ad hoc deformability and modulus of elasticity of concretes with fractured coarse carbonate dolomite aggregate are similar to, or even better than, the deformability and modulus of elasticity of concretes with basalt aggregate. Due to the presence of the two main components magnesium and calcium carbonate (dolomite and calcite) in the dolomite aggregate, there may be a beneficial aggregate-cement reaction for the concrete, which reduces porosity and increases adhesion, with a consequent increase in modulus and strength.

MATERIALS

Within the framework of the research program, five types of Polish aggregates were tested, as well as ordinary concretes with w/c ratios of 0.70, 0.58, 0.45 and high performance concrete (HPC) with a w/c of 0.28 with these aggregates. In addition, concretes with w/c = 0.55 were tested with aggregates from Polish and Ukrainian deposits.

The particle size gradation of sand and gravel aggregate is presented in Table 1. In the case of other coarse aggregates, the principle of the same grain volume was adopted by converting the volume proportion on the basis of the bulk densities of the aggregates: gravel – 2.64 kg/dm^3, basalt Winna Góra – 2.96 kg/dm^3, basalt Gracze – 2.97 kg/dm^3, basalt Iwaniczi – 2.84 kg/dm^3, granite Graniczna – 2.64 kg/dm^3, granite Siedlimowice – 2.63 kg/dm^3, granite Vyrivskij Karjer – 2.64 kg/dm^3, granodiorite – 2.64 kg/dm^3, dolomite – 2.79 kg/dm^3, quartzite Wiśniówka – 2.66 kg/dm^3.

Natural washed quartz sand (the Suwalki Mine) was used to make the concretes. The ordinary Portland cement CEM I 42.5 R with properties in accordance with the PN-EN 197-1 [18] was used for concretes with all the aggregates. In order to expose the influence of coarse aggregate as one of the variable factors analysed, the use of any concrete additives was abandoned. In mixtures with w/c = 0.28, a superplasticizer (a mixture of polycarboxyl ether and calcium lignosulfonate) was used to maintain a similar consistency. The composition of HPC concretes is also given in Table 2. The slump of concrete mixes was 12 ± 3 cm.

The volumes of cement, sand and water were the same in mixtures with identical w/c. Thus, the volume of cement paste was the same in all concretes.

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Table 1. Grain size distributions of the fine and coarse aggregates, %

Sieve size, mm	Sand	Gravel
16	100	100
8	100	74
4	100	49
2	95	26
1	57	8
0.5	40	1
0.25	10	–
0.125	1	–

Table 2. Composition of concrete mixture at w/c = 0.28

Concrete constituents	Mix designation				
	Basalt	Granite	Dolomite	Quartzite	Gravel
Cement, kg/m^3	479	479	479	479	479
Aggregate 2÷16 mm, kg/m^3	1258	1151	1229	1151	1151
Sand, kg/m^3	699	699	699	699	699
Water, dm^3/m^3	128	128	128	128	128
Superplasticizer, kg/m^3	10.5	10.5	10.5	10.5	10.5

accordance with the PN-EN 197-1 [18] was used for concretes with all the aggregates. No mineral additives were used in the concrete mixtures. In mixtures with w/c = 0.28, a superplasticizer (a mixture of polycarboxyl ether and calcium lignosulfonate) was used to maintain a similar consistency. The composition of HPC concretes is also given in Table 2. The consistency index of all made concrete mixtures, determined by the slump method, was 12 ± 3 cm.

In order to be able to reliably compare the strengths of the effects of aggregate type on the properties of concretes in the same w/c ratios, the principle of maintaining the same volume of cement paste in 1 m^3 of mixture was adopted. It is very common in research to find a situation where concretes with the same component weights are compared. This is not correct, as the different volumetric densities of the components mean that the tightness condition is not met, and this should be the first consideration. In these tests, the sum of the volumes of all the components in each concrete is 1 m^3. This is why, the content of cement, water and sand in mixtures with the same w/c ratio was constant.

TESTING METHODS

Aggregate testing methods

The crushing strength of aggregates was determined using the so-called aggregate crushing value (ACV) according to the PN-B-06714-40 [19], analogous to the British Standard BS 812 [20] for determining aggregate crushing value (ACV), but with some slight differences. A sample of aggregate in a steel cylinder with an inner diameter of 150 mm was loaded with a force of 200 kN. For the test, 4÷8 mm, 8÷16 mm and 16÷31.5 mm fractions should be separated from the aggregate. The crushing value of a given aggregate fraction is determined as the percentage of grains crushed into grains smaller than ¼ of the lower sieve dimension of the tested fraction. It should be noted that in this test the aggregate sample is loaded statically, which reflects well the working of the concrete in the structure. In contrast, in the currently recommended Los Angeles drum test, the aggregate is subjected to two destructive factors simultaneously – abrasion and impact by steel balls placed in the drum. Such impacts better represent the work of concrete in road pavements, while in structures concrete is mainly subjected to static impacts. For this reason, the authors decided that the tested aggregate should be statically loaded. This is particularly important as the compressive strength is tested in addition to the modulus of elasticity. An additional advantage of the adopted method is the fact that the crushing value can be used to classify aggregate and assess its suitability for concrete, such recommendations are in the PN-B-06712 [21].

Concrete testing methods

Cylindrical specimens with a base diameter of 150 mm and a height of 300 mm were used to test the compressive strength, modulus of elasticity and $\sigma - \varepsilon$ relationship of the concretes. The specimens were cured in water at 20 ± 2 °C and tested at the age of 28 days. The top surfaces of the specimens were grounded so that their bases were parallel. To determine the deformation characteristics of the concretes (modulus of elasticity E_c), 60 mm long electrical resistance strain gauges were used. The use of electrofusion strain gauges to determine the modulus of elasticity enables the examination of longitudinal strains in the full load range, up to the destruction of samples at peak stress. Thanks to this, it is possible to determine such additional properties as σ-ε relationship and the ultimate compressive strain at the peak stress ε_{c1}. The simultaneous measurement of transverse deformations also allows the determination of Poissons ratio. The use of electrical resistive strain gauges to determine the elastic modulus makes it possible to simultaneously investigate the longitudinal deformation over the full load range up to the failure of the specimens. Three strain gauges were taped to each specimen to measure longitudinal strains. The points for strain measurement were placed symmetrically with respect to the bases at 120° intervals. A stress range of 0.5 MPa to $0.4 \cdot f_{cm}$, according to the requirements of the PN-EN 1992-1-1 [1], was assumed in the E_c measurement. The rate of stress increase was 0.5 MPa/s. The concretes compressive strength tests were conducted in accordance with the PN-EN 12390-3 [22]. Each property was determined on 6 cylindrical specimens.

Concrete testing was carried out in a computer-controlled testing machine (this ensures, among other things, that the stress increment is kept constant and that stress and strain readings are taken at the right frequency).

RESULTS

The results of tests of high stregth concrete and ordinary concrete with basalt aggregate [12] (Tables 3–6) showed that the values of modulus of elasticity recommended in the PN-EN 1992-1-1:2008 [1] are 10–20% higher.

The values of modulus of elasticity of concretes recommended by the EC2 standard for design calculations are higher than the values of modulus of elasticity known from the literature and higher than the test results of the authors of the paper. The modulus results obtained are lower, some significantly, than the standard values of the modulus of elasticity of concretes.

The lowest values were found in all concretes with granite and quartzite aggregate – their modulus of elasticity values were lower than the standard ones by about 20% and 15%, respectively. Concretes with dolomite

Table 3. Test results for concretes with w/c = 0.70

Properties	Coarse Aggregate				
	Basalt Gracze	Granite Graniczna	Dolomite Laskowa	Quartzite Wiśniówka	Gravel KSM Suwałki
Mean values of the test results					
ACV, %	4.1	15.1	6.9	5.5	9.0
$f_{cm,cyl}$, *MPa* (coefficient of variation, %)	34.5 (3.1)	28.7 (3.3)	36.1 (2.5)	36.3 (2.9)	32.0 (3.1)
Concrete class	C30/37	C20/25	C30/37	C30/37	C25/30
E_{cm}, *GPa* (coefficient of variation, %)	30.9 (2.8)	24.0 (4.0)	33.9 (2.7)	26.3 (6.2)	26.9 (3.5)
Standard values based on concrete strength classes according to EC2					
$E_{cm,EC2}$, *GPa*	38.4	30.0	32.0	32.0	31.0

Table 4. Test results for concretes with w/c = 0.58

Properties	Coarse aggregate				
	Basalt Gracze	Granite Graniczna	Dolomite Laskowa	Quartzite Wiśniówka	Gravel KSM Suwałki
Mean values of the test results					
ACV, %	4.1	15.1	6.9	5.5	9.0
$f_{cm,cyl}$, *MPa* (coefficient of variation, %)	47.5 (1.1)	36.9 (3.0)	44.9 (4.6)	46.4 (3.8)	41.8 (3.3)
Concrete class	C40/50	C30/37	C40/50	C40/50	C35/45
E_{cm}, *GPa* (coefficient of variation, %)	34.8 (4.5)	25.0 (6.2)	35.3 (2.0)	28.7 (4.1)	31.0 (2.2)
Standard values based on concrete strength classes according to EC2					
$E_{cm,EC2}$, *GPa*	42.0	32.0	35.0	35.0	34.0

Table 5. Test results for concretes with w/c = 0.45

Properties	Coarse aggregate				
	Basalt Gracze	Granite Graniczna	Dolomite Laskowa	Quartzite Wiśniówka	Gravel KSM Suwałki
Mean values of the test results					
ACV, %	4.1	15.1	6.9	5.5	9.0
$f_{cm,cyl}$, *MPa* (coefficient of variation, %)	61.2 (3.0)	54.3 (3.5)	60.3 (2.7)	65.0 (3.4)	54.5 (4.3)
Concrete class	C55/67	C45/55	C55/67	C60/75	C50/60
E_{cm}, *GPa* (coefficient of variation, %)	42.9 (4.4)	29.0 (5.5)	40.8 (2.0)	32.1 (4.4)	31.6 (1.0)
Standard values based on concrete strength classes according to EC2					
$E_{cm,EC2}$, *GPa*	45.6	36	38	39	37.0

Table 6. Test results for concretes with w/c = 0.28

Properties	Coarse Aggregate				
	Basalt Gracze	Granite Graniczna	Dolomite Laskowa	Quartzite Wiśniówka	Gravel KSM Suwałki
Mean values of the test results					
ACV, %	4.1	15.1	6.9	5.5	9.0
$f_{cm,cyl}$, *MPa* (coefficient of variation, %)	93.2 (3.6)	78.3 (6.2)	89.0 (5.5)	103.6 (5.0)	82.6 (3.7)
Concrete class	C80/95	C70/85	C80/95	C90/105	C70/85
E_{cm}, *GPa* (coefficient of variation, %)	47.1 (3.5)	33.2 (4.1)	48.5 (3.0)	39.9 (1.8)	40.0 (2.6)
Standard values based on concrete strength classes according to EC2					
$E_{cm,EC2}$, *GPa*	50.4	41.0	42.0	44.0	41.0

Note: Designations in the tables: *ACV* – aggregate crushing value, %, $f_{cm,cyl}$ – cylindrical compressive strength, *MPa*, E_{cm} – elastic modulus. GPa.

aggregate were found to have the lowest elastic deformation and therefore their modulus was the highest. Certainly, there is no need to reduce the elastic modulus values of concretes with the dolomite aggregate by 10%, and the elastic properties of concretes with quartzite and granite aggregates are no better than those with dolomite aggregate.

A remark that emerges from analyzing the results of the study, and which should be emphasized, is that the fact that granite and quartzite have high strength and hardness does not mean that they also guarantee a high elasticity modulus of concrete. In addition, quartzite and granite contain quartz and silica, which can sometimes undergo a harmful alkali-silica reaction [15].

From the regression lines shown in Figure 4, it can be concluded that there is a relationship between the E_{cm} elasticity modulus and the relative crushing resistance values of aggregates (100-ACV), i.e., the percentage mass of uncrushed grains. The strength of the correlation between these properties increases as the value of the w/c ratio decreases.

In recent years, Ukrainian aggregates from magmatic rocks have been imported into the Polish market. The results of standard tests required for the introduction of aggregates into commerce are available, while information on the properties of concretes made with these aggregates is marginal. Hence, such a topic was taken up and both the properties of selected

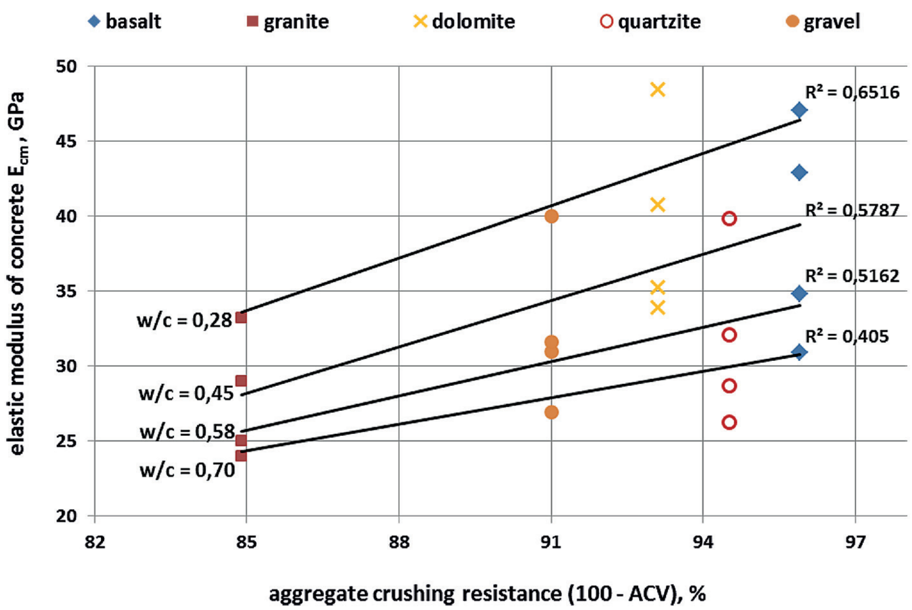

Fig. 4. Regression lines of the dependence of the elasticity modulus of concretes on the crushing resistance values of aggregate at different values of w/c ratios

Table 7. Properties of concretes with Polish and Ukrainian aggregates

Properties	coarse aggregate							
	Basalt PL Winna Góra	Basalt PL Gracze	Basalt UA Iwaniczi	Granite PL Siedlimowice	Granite PL Graniczna	Granite UA Vyrivskij Karjer	Granodiorite UA Klesov	Gravel PL KSM Suwałki
Mean values of the test results								
ACV, %	4.6	4.0	6.6	15.1	14.8	8.0	6.0	9.3
$f_{cm,cyl}$, *MPa* (coefficient of variation, %)	44.2 (2.8)	48.8 (3.1)	40.8 (2.9)	39.7 (3.5)	39.1 (4.9)	40.1 (3.9)	37.9 (5.0)	38.0 (3.7)
E_{cm}, *GPa* (coefficient of variation, %)	34.9 (4.0)	35.0 (1.7)	27.7 (3.3)	23.6 (6.2)	26.2 (4.2)	30.7 (2.8)	33.0 (3.6)	31.3 (4.0)
Standard values based on concrete strength classes according to EC2								
Concrete class	C40/50	C40/50	C35/45	C35/45	C35/45	C35/45	C30/37	C30/37
$E_{cm,EC2}$, *GPa*	42.0	42.0	40.8	34.0	34.0	34.0	32.0	32.0

Ukrainian aggregates available on the Polish market and concretes with these aggregates were studied. Analogous tests, for comparison, were carried out with Polish aggregates. Tests were carried out on the crushing values of aggregates and concretes with these aggregates in terms of compressive strength and modulus of elasticity (Table 7). The values of $E_{cm,PN}$ for each class of concrete given in Table 7 refer to the concrete with the quartzite gravel aggregate.

Figure 5 compares the relative proportions of the uncrushed grains (100 – ACV), f_{cm} strengths and the E_{cm} elasticity modulus of concretes with individual magmatic aggregates in proportion to the corresponding properties of concrete with gravel. The values of f_{cm} and E_{cm} of concrete with gravel aggregate and (100 – ACV) of the gravel aggregate were taken as a reference level (100%), as in the standard [1] when determining the values of correction factors for the modulus of concretes with different aggregates.

The best deformation and strength parameters of the concretes were found for Polish basalts, while by far the worst were found for both concretes with the Polish granite aggregates. In the same way, the susceptibility of Polish aggregates

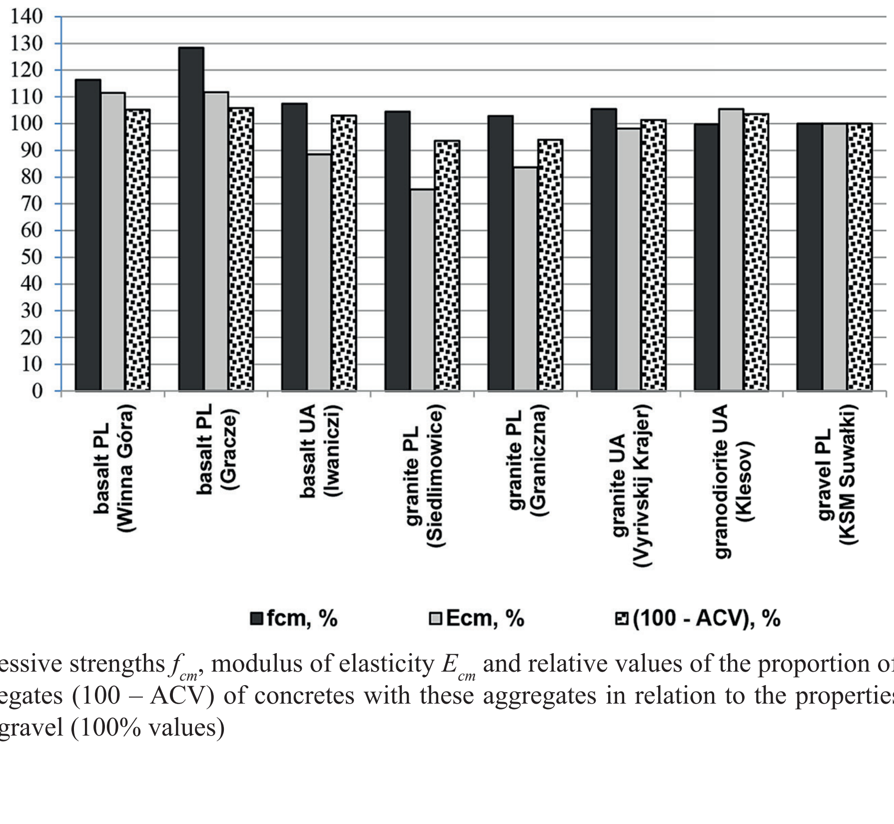

Fig. 5. Compressive strengths f_{cm}, modulus of elasticity E_{cm} and relative values of the proportion of the uncrushed grains in aggregates (100 – ACV) of concretes with these aggregates in relation to the properties of gravel and concrete with gravel (100% values)

to crushing should be evaluated, which is consistent with the properties of the concretes.

The values of the modulus of elasticity of the tested concretes with aggregates from magmatic rocks, with the exception of concrete with granodiorite aggregate, are smaller than those recommended on the basis of strength classes in the PN-EN 1992-1-1:2008 [1], and the differences reach up to 30%. The modulus of elasticity of concretes with Polish granite aggregates from the Strzegom Massif are 25% and 16% lower than the modulus of concrete with gravel aggregate. When using Ukrainian granite aggregate, the difference is only 2%.

Additional interpretation of the test results was carried out to evaluate the nature and significance of changes in the modulus of elasticity as a function of the crushing value of aggregates and as a function of the compressive strength of concretes with these aggregates. For this purpose, the linear regression was used. Correlation analysis, on the other hand, was used to compare how strong and significant is the effect of the strength of the concretes and the type of aggregate – represented by the crushing value, on the modulus of elasticity. The regression lines, estimated by the least squares method, characterizing the dependence of the elasticity modulus of concrete on the crushing value of the aggregate and the modulus on the compressive strength, are shown in Figures 6 and 7. In both cases, clear trends in the change of modulus were revealed – decreasing for the crushing value, and increasing for the strength. The coefficients of determination R^2, which determine the extent to which the total variation in the elasticity modulus of concrete is explained by the corresponding regression model, differ significantly and is

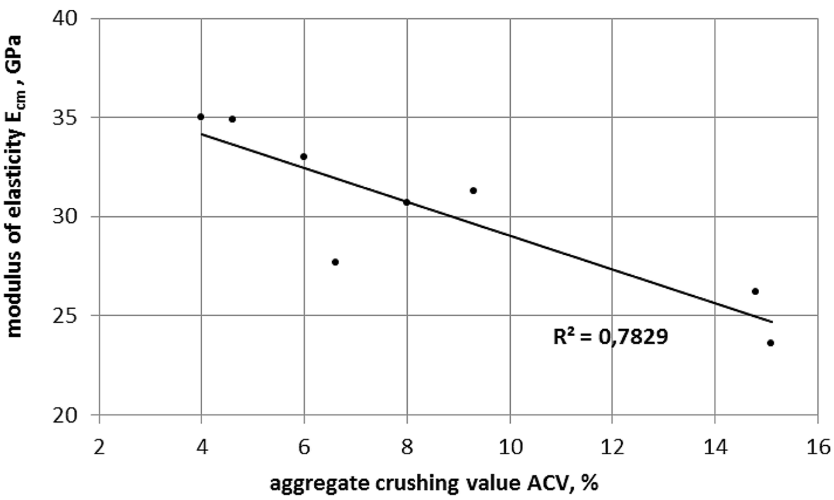

Figure 6. Regression line of the dependence of the modulus of elasticity of concrete on the crushing value of aggregate

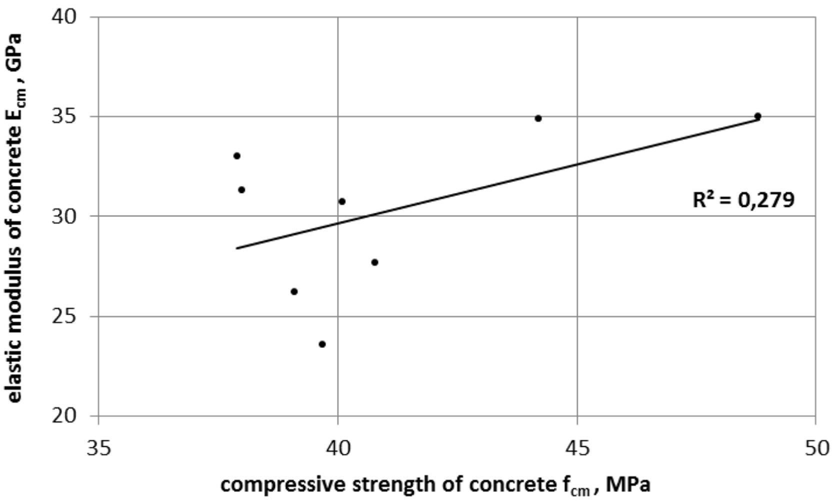

Figure 7. Regression line of the dependence of the elasticity modulus and the compressive strength of concrete

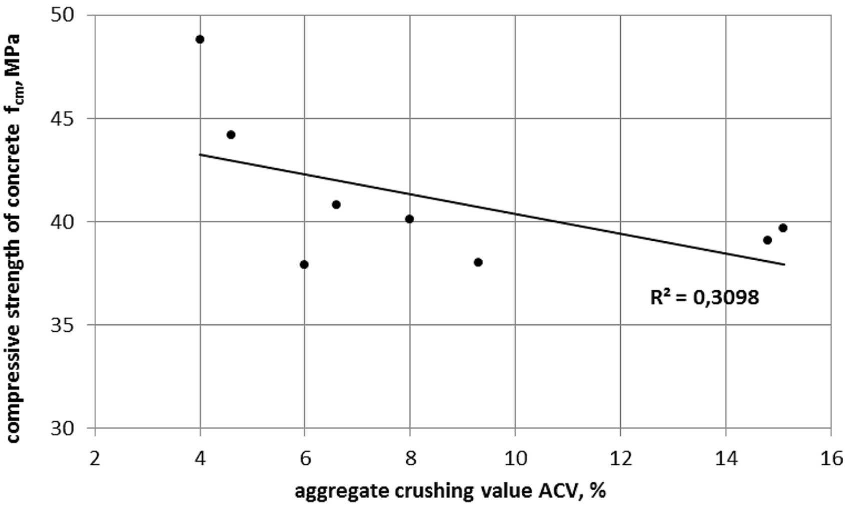

Figure 8. Regression line of the dependence of the compressive strength of concrete and the crushing value of the aggregate

equal to 78.3% for the crushing value and 27.9% for the compressive strength, respectively. The correlation coefficient between the value and modulus is -0.885, and the test probability is p = 0.0035 < 0.05, i.e., the correlation is significant. The correlation coefficient between the strength and modulus is 0.528, and the test probability p = 0.1784 > 0.05, that is, there is no basis for rejecting the null hypothesis that the correlation coefficient $R^2 = 0$, so the correlation in the statistical sense is insignificant. It follows that the effect of aggregate type on the modulus of elasticity of the studied population of concretes with magmatic aggregates (with equal w/c ratio = 0.55) is significant and stronger than the strength effect.

In addition, the same analyses were carried out to evaluate the dependence of the strength of concretes (dependent variable) on the crushing value (independent variable). Figure 8 shows a simple regression line confirming the decreasing trend of changes in the compressive strength of concretes depending on the crushing value of the aggregate. The coefficient of determination R^2 is equal to 0.310, and the correlation coefficient between the value and strength is -0.557 with a test probability p = 0.152 > 0.05, so there is no basis for rejecting the null hypothesis, so the correlation is statistically insignificant.

Statistical analyses of the crushing value of the magmatic aggregates and properties of concretes with w/c ratio = 0.55 (E_{cm}-X_{rm}, f_{cm}-X_{rm}) show that the effect of the crushing ratio on the modulus is statistically significant in contrast to its effect on strength.

It should be noted that in the case of the tested basalt aggregates, the recommended increase of 20% in the standard values of the modulus of elasticity is not necessary. On the other hand, the modulus of elasticity of concretes with the Polish granite aggregates are significantly lower than the values of $E_{cm,EC2}$ given on the basis of compressive strength classes.

It is right that the PN-EN 1992-1-1:2008 [1] emphasizes the influence of the type of coarse aggregate on the modulus of elasticity of concrete. However, the recommendations for correcting the values of the modulus of elasticity of concrete depending on the coarse aggregate used remain debatable. According to the author, these recommendations should be introduced in the form of a national annex.

As can be seen from the cited results of own tests of concretes made with the basalt aggregate, increasing the modulus of elasticity by 20% proves to be inexpedient, yet basalts from currently exploited deposits were used and these are aggregates commonly available in the country. It seems safer to take the modulus value without increasing it by 20%. However, it is more glaring that there is a lack of information and recommendations for reducing the standard modulus values when using granite aggregate. It is clear from own research, as well as from the examples cited domestically [5, 10, 11, 12] and abroad [7, 8], that the deformability of concrete with granite aggregate is significant, and the values of modulus of elasticity given in the standard are greater than the actual ones, which was confirmed by the tests results. It seems that this should be taken into account in the form of a national annex to the standard, while it is advisable to conduct more extensive studies in advance on the most commonly exploited Polish granite deposits.

CONCLUSIONS

Based on the results of own research and a comparison with the standard recommendations, it was found that the modulus of elasticity of concretes with most Polish aggregates found by the authors in many studies are lower than the modulus of elasticity of concretes recommended by the Eurocode 2. Inconsistencies were found between the compared modulus values of concretes with basalt and granite aggregates and the values in the Eurocode 2. Differences between the test results and the standard values reach up to 20%. Only in the case of all tested concretes with the dolomite aggregate, compliance with the values specified in Eurocode 2 was always obtained. In view of the lower modulus of elasticity of concretes with most Polish aggregates than the values required by the Eurocode 2 it is advisable to supplement the standard(s) with a national annex, adapted to local aggregates (or depending on the properties of aggregates). The significant influence of aggregates on the values of the elasticity modulus of concretes was first explicitly emphasized in the Eurocode 2.

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