ECOLOGICAL AND ECONOMIC ASPECTS OF THE IMPACT OF THE TYPE OF COARSE AGGREGATE ON STRENGTH PROPERTIES OF CONCRETE

Waldemar Budzyński, Jacek Góra

Lublin University of Technology, Faculty of Civil Engineering and Architecture
Nadbystrzycka St. 40, 20-618 Lublin, Poland
e-mail: w.budzynski@pollub.pl, j.gora@pollub.pl

Summary:
Solution proposed by authors of this paper is to change the type of coarse aggregate into the aggregate of higher quality in order to achieve better strength for a given concrete with a specific quantitative composition. Concrete classified in 3 groups was subjected to test: ordinary concrete of w/c = 0,70 and w/c = 0,58, and also high strength concrete of w/c = 0,28. In each group concrete was made using four different types of coarse aggregate. Comparing test results of strength properties it should be stressed that there is a significant effect of coarse aggregate on the values obtained, as confirmed by a statistical analysis. One can look for "concrete strength" in other sources than those consisting in a unit increase of cement content, through as shown, an appropriate choice of the type of coarse aggregate.

Keywords: concrete, coarse aggregate, strength

Introduction

Nowadays, the cement industry in Poland has become one of the most modern in Europe. This was possible due to investments, the value of which has exceeded 10 billion zloty over the last 20 years. The investments concerned not only improving technology and production efficiency, but also environmental protection. In the last five years, the expenditures on investments related to environmental protection in cement plants in Poland have exceeded the amount of 500 million zloty (Wiśniewska, 2013). Emission is nowadays much smaller than that set out in the European standards. In addition, about 50% of fuel needed for production of Portland cement clinker in all cement industry in Poland comes from combustion of alternative fuels (Wiśniewska, 2013). Despite many environmental-oriented activities and undeniably positive effects of their impact on the environment, cement plants in Poland are facing a major problem related to ecology. Currently, the CO_2 emission per ton of Portland cement clinker produced in our country is about 820 kg (Wiśniewska, 2013) and it exceeds the allowable limit of 766 kg per ton of clinker that has been set out in the European Union since 2013. In this situation cement factories must go for new investments or purchase licenses for the CO_2 emission. In both cases, production costs of clinker and cement are increased despite using alternative fuels and mineral supplements as a substitute for clinker. Additional costs will have to be somehow compensated by an increase of cement price, which in turn will affect the price of concrete. Basically, the production of clinker (cement) is not ecological, therefore it would be advisable to obtain high quality concrete at a minimum consumption of cement.

With regard to concrete, important parameters considered in quality assessment are compression and tensile strength. As usual, the value of these properties is primarily conditional on the value of the w/c ratio. Thus, in order to achieve better strength for a given concrete with a specific quantitative composition, it is necessary to decrease the w/c value which means an increase of cement content in a volume of $1m^3$, thus its bigger use in the production of concrete. One may also use or increase the content of superplasticizer admixtures, which will allow for reducing batch water, while maintaining the assumed mixture consistency, and as a result thereof lowering the w/c value without the need to increase the cement content. Another solution proposed by some authors is to change the type of coarse aggregate into the aggregate of higher quality.

It is undisputed that the type of coarse aggregate has a substantial effect on the properties of concrete, including strength ones. Neville (Neville, 2000) indicates that not only the strength can be conditioned by the type of aggregate, since low quality aggregate cannot make strong concrete, but also the properties of aggregate have a significantly effect on duration and behavior of concrete in the structure. The studies on concrete made from basalt, granite, gravel and used more and often carbonate aggregate, conducted so far show that changing the type of coarse aggregate results in a difference in compression strength class even by two classes (Piasta W. and others, 2011). The latter type of aggregate deserves special attention. An increase in the number of projects implemented in the recent years in construction engineering has led to a certain deficiency in the market dealing with aggregate. Periodic shortages of aggregates among those traditionally used, were supplemented with carbonate aggregates, although they are not credited with much of the reliance in building practice. Most likely this is so for fear of adverse effects of alkali-carbonate reactions that may occur, and the fact that these aggregates are characterized by high porosity and weak strength parameters. It should be noted, however that in some scientific studies conducted abroad (Baalbaki and others, 1991; Mehta, 1986; Roy, Jiong, 1992; Wu and others, 2001; Zimbelmann, 1985), as well as in the country (Bukowski, Kuczyński, 1972; Mierzwa, 2000; Piasta J., Piasta W., 1994; Piasta J., Piasta W., 1992; Piasta J., Piasta W., 2002) extensive usefulness of carbonate aggregates of adequate quality is justified for high-strength concrete of compression strength f_{cm} amounting to 120 MPa (Fig. 1).

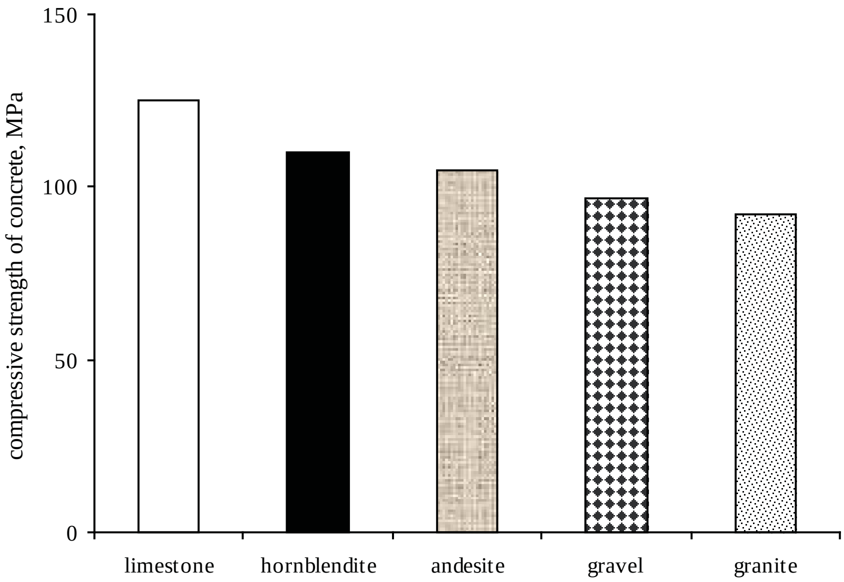

Fig. 1. Compression strength of high performance concretes with different aggregates (Roy, Jiong, 1992)

Although they are undervalued, carbonate aggregates distinguish themselves among crushed aggregates from compacted rocks (usually a mixture of calcite and dolomite at different proportions) characterized by low porosity which less than 3%. Due to their mineral composition they are able to react with cement paste, which brings favorable changes in the contact layer (e.g. formation of monocarboaluminate, portlandite crystals disorientation, reducing porosity and pore size, increasing layer strength). An external effect is, in most cases clearly visible on the basis of higher values of strength and elasticity modulus of concrete. The longer the time of curing the better improvement of the properties of concrete from carbonate aggregates.

Variability of properties of concrete made with different aggregates results from both different physical and chemical properties of the rock, from which the aggregate was made, as well as from diverse structure of the transition layer paste-aggregate, recognized by the vast majority of researchers for the weakest “link” in the structure of concrete. Aggregate plays a vital role in forming the structure of the transition layer, and therefore it has a significant impact on many properties of concrete determining its suitability in terms of construction adequacy and durability of the material.

Tests results and discusion

The following types of aggregate were taken for compression and tensile strength tests: aggregate made from igneous rocks - basalt and granite grit from inland beds having been used for many years, for the use in structural concrete of top classes and aggregates made from sedimentary rocks – dolomite grit, and also gravel, the most commonly used for concrete of different classes of strength.

Concrete classified in 3 groups was subjected to test: ordinary concrete of w/c = 0,70 and w/c = 0,58, and also high strength concrete of w/c = 0,28. In each group concrete was made using four different types of coarse aggregate of 2÷16mm fraction. Four different types of coarse crushed aggregates were applied in concrete: basalt from Gracze mine (B), granite from Graniczna near Strzegom (G), dolomite from Laskowa (D) and natural gravel from KSM Suwałki (O). Natural washed sand of 0÷2 mm fraction from KSM Suwałki was used as fine aggregate. Portland cement CEM I 42,5R was used in all types of concrete. In each group of concrete, the same volume of coarse aggregate was considered.

Aggregate composition of particular types of aggregate was formed from selected aggregate fractions 2÷4, 4÷8, 8÷16 mm 2 to 4, 4 to 8, 8 to 16 mm. In order the volume contents of each aggregate fraction was the same in the compared aggregates (within each group), different bulk density of aggregates was considered. Sand content of aggregate composition, expressed by volume, amounted to 37±1% in each case. In order to maintain a similar consistency of concrete mixtures, in HPC concrete one used the concrete admixture (superplasticizer) in the form of modified polycarboxylate. The consistency ratio of concrete mixtures was 10±3 cm, which corresponds to consistency classes of S2¸S3 according to PN-EN 206-1:2003. Air content in concrete mixtures, determined by means of a pressure method was 1,8±0,1%. Composition of concrete mixtures was given in table 1,2 and 3.

From each type of concrete, 10 cylindrical specimens were made, with a diameter of 150 mm and a height of 300mm (5 were allocated to compression strength testing and 5 to tensile strength at splitting). Specimens were tested after 28 days of curing in laboratory conditions. Upper surfaces of the specimens designed for tensile strength tests were polished to make them be parallel to the basis.

Tab. 1. Composition of ordinary concrete mixtures of w/c = 0,70

concrete components w/c = 0,70		Concrete marking (type of coarse aggregate)			
		B070-B (basalt)	B070-G (granite)	B070-D (dolomite)	B070-O (natural gravel)
Cement	kg/m^3	260	260	260	260
Sand	kg/m^3	697	697	697	697
Coarse aggregate	kg/m^3	1334	1221	1303	1221
Water	dm^3/m^3	182	182	182	182

Tab. 2. Composition of ordinary concrete mixtures of w/c = 0,58

concrete components w/c = 0,58		Concrete marking (type of coarse aggregate)			
		B058-B (basalt)	B058-G (granite)	B058-D (dolomite)	B058-O (natural gravel)
Cement	kg/m^3	325	325	325	325
Sand	kg/m^3	676	676	676	676
Coarse aggregate	kg/m^3	1274	1166	1245	1166
Water	dm^3/m^3	189	189	189	189

Tab. 3. Composition of high strength concrete mixtures of w/c = 0,28

concrete components $(w + w_{Sp})/c = 0,28$		Concrete marking (type of coarse aggregate)			
		B028-B (basalt)	B028-G (granite)	B028-D (dolomite)	B028-O (natural gravel)
Cement	kg/m^3	479	479	479	479
Sand	kg/m^3	699	699	699	699
Coarse aggregate	kg/m^3	1258	1151	1229	1151
Water	dm^3/m^3	128	128	128	128
Superplasticizer	kg/m^3	10,5	10,5	10,5	10,5

In order to obtain a clear answer whether the type of coarse aggregate has a significant impact on strength properties of the tested types of concrete, the test results were subjected to one-factor analysis of variance test [ANOVA] at a significance level of $\alpha = 0,05$ (Sheskin, 1997). One test was performed for each group of concrete with the same w/c ratio. In all analyzes, the level of significance of $\alpha = 0,05$ was considered.

It should be noted that in all groups of concrete (of the same w/c) there is statistically significant effect of the type of coarse aggregate on the strength properties of concrete which was proved by means of the analysis of variance.

Additionally, in order to provide a detailed explanation of the significance of differences between the strength of concretes made from different aggregates, the least significant difference tests – "LSD" were carried out. The p-values indicating the existence of significant differences between the strength results of concretes being compared, were marked with bold letters in tables 4 to 9.

The results of the compression strength tests were presented in tables 4, 5 and 6, separately for each group of concrete. Average strength, variation ratios and LSD test results were given therein. Tables provide information about classes of the tested types of concrete based on compliance criteria according to PN-EN 206-1:2003.

Tab. 4. Average compression strength, variation ratio, class and LSD test results for concrete of w/c = 0,70

		Concrete marking			
		B070-B	B070-G	B070-D	B070-O
Compression strength	$f_{cm,cyl}$ [MPa]	34,5	28,7	36,1	32,0
	ν [%]	1,4	1,6	6,1	2,2
Class of concrete compression strength		C30/37	C20/25	C30/37	C25/30
p results of LSD test of compression strength of B070 concrete					
B070-B		—	**0,000373**	0,143909	**0,035194**
B070-G		**0,000373**	—	**0,000070**	**0,010215**
B070-D		0,143909	**0,000070**	—	**0,003204**
B070-O		**0,035194**	**0,010215**	**0,003204**	—

Tab. 5. Average compression strength, variation ratio, class and LSD test results for concrete of w/c = 0,58

		Concrete marking			
		B058-B	B058-G	B058-D	B058-O
Compression strength	$f_{cm,cyl}$ [MPa]	47,5	36,9	44,9	41,8
	ν [%]	3,6	3,2	1,0	2,5
Class of concrete compression strength		C40/50	C30/37	C40/50	C35/45
p results of LSD test of compression strength of B058 concrete					
B058-B		—	**0,000004**	**0,028384**	**0,000364**
B058-G		**0,000004**	—	**0,000032**	**0,000895**
B058-D		**0,028384**	**0,000032**	—	**0,012162**
B058-O		**0,000364**	**0,000895**	**0,012162**	—

Tab. 6. Average compression strength, variation coefficient, class and LSD test results for concrete of w/c = 0,28

		Concrete marking			
		B028-B	B028-G	B028-D	B028-O
Compression strength	$f_{cm,cyl}$ [MPa]	93,2	78,3	89,0	82,6
	ν [%]	2,9	4,7	1,6	4,1
Class of concrete compression strength		C80/95	C70/85	C80/95	C70/85
p results of LSD test of compression strength of B028 concrete					
B028-B		—	**0,000236**	0,115601	**0,002128**
B028-G		**0,000236**	—	**0,001940**	0,103868
B028-D		0,115601	**0,001940**	—	**0,027531**
B028-O		**0,002128**	0,103868	0,027531	—

In the case of ordinary concrete, the highest compression strength values were found with respect to concretes with grit basalt and dolomite, with some minor differences ranging from 4 to 6%. Compression strength of ordinary concrete with natural gravel and granite aggregate are statistically significantly lower than the strength of concrete with basalt and dolomite aggregate of corresponding relationships of w/c. The differences in the strength of concrete with natural gravel and granite aggregate in relation to the highest strength of the concrete in a particular group of w/c, were 11,4% and 20,5% respectively at w/c = 0,70 and similarly 12,0% and 22,3% at w/c = 0,58.

The above mentioned relationships, resulting from statistical interference, are exactly represented in assigning ordinary concrete to specific classes of strength. Concrete with basalt and dolomite aggregate belongs to the same class, C30/37 at w/c = 0,70 and C40/50 at w/c = 0,58, while concrete with natural gravel was classified to be one class below (C25/30 and C35/45 respectively), and concrete with granite aggregate two classes below (C20/25 and C30/37 respectively).

In the case of high performance concrete (HPC), the highest values of compression strength are also those of concrete with basalt and dolomite grit, at a statistically insignificant difference of 4,5% in favor of basalt. Considerably lower values, at differences statistically significant, were obtained in relation to concrete with natural gravel and granite aggregate, by 11,4% and 16,0% respectively, with regard to HPC concrete with basalt aggregate. However, the differences in concrete strength HPC concrete with natural gravel and granite aggregate are statistically insignificant (table 6).

Similarly as in the case of ordinary concrete, the relationships arising from statistical inference found in HPC concrete are confirmed by its assignment to particular class of strength. HPC concrete with basalt and dolomite aggregate belongs to the class of C80/95, while concrete with natural gravel and granite aggregate is classified one class below that is C70/85.

Results of tensile strength tests, separately for each group of concrete, were shown in tables 7, 8 and 9, in which one can find average tensile strength at splitting, variation ratios and axial tensile strength values calculated as 0,9 $f_{ctm,sp}$, (at dimensioning of concrete structures and reinforced concrete structures in accordance with PN-EN 1992-1-1:2008, it is advisable to use concrete strength in a state of uniaxial tension, and that is why the values of $f_{ctm,ax}$ corresponding to these test results were additionally included in the tables).

Tab. 7. Average tensile strength, variation ratios and LSD test results of concrete of w/c = 0,70

		Concrete marking			
		B070-B	B070-G	B070-D	B070-O
Splitting tensile strength\ (based on tests)	$f_{ctm,sp}$ [MPa]	2,76	2,29	2,93	2,71
	ν [%]	4,6	7,1	4,9	3,7
Axial tensile strength	$f_{ctm,ax}$ [MPa]	2,48	2,06	2,64	2,44
Concrete class		C30/37	C20/25	C30/37	C25/30
Standard axial tensile strength depending on the class according to EC2, MPa		2,9	2,2	2,9	2,6
p results of LSD test of tensile strength of B070 concrete					
B070-B		—	**0,000046**	0,053834	0,602767
B070-G		0,000046	—	**0,000001**	**0,000133**
B070-D		0,053834	**0,000001**	—	**0,018869**
B070-O		0,602764	**0,000133**	**0,018869**	—

Tab. 8. Average tensile strength, variation coefficients and LSD test results of concrete of w/c = 0,58

		Concrete marking			
		B058-B	B058-G	B058-D	B058-O
Splitting tensile strength (based on tests)	$f_{ctm,sp}$ [MPa]	3,25	2,75	3,36	2,87
	ν [%]	6,3	6,5	3,2	3,4

Axial tensile strength	$f_{ctm,ax}$ [MPa]	2,93	2,48	3,02	2,58
Concrete class		C40/50	C30/37	C40/50	C35/45
Standard axial tensile strength depending on the class according to EC2, MPa		3,5	2,9	3,5	3,2
p results of LSD test of tensile strength of B058 concrete					
B058-B		—	**0,000113**	0,295810	**0,001319**
B058-G		**0,000113**	—	**0,000014**	0,251135
B058-D		0,295810	**0,000014**	—	**0,000141**
B058-O		**0,001319**	0,251135	**0,000141**	—

Tab. 9. Average tensile strength, variation ratio and LSD test results of concrete of w/c = 0,28

		Concrete marking			
		B028-B	B028-G	B028-D	B028-O
Splitting tensile strength (based on tests)	$f_{ctm,sp}$ [MPa]	5,54	5,16	6,06	5,07
	ν [%]	2,8	3,1	4,6	2,3
Axial tensile strength	$f_{ctm,ax}$ [MPa]	4,99	4,64	5,45	4,56
Concrete class		C80/95	C70/85	C80/95	C70/85
Standard axial tensile strength depending on the class according to EC2, MPa		4,8	4,6	4,8	4,6
p results of LSD test of tensile strength of B028 concrete					
B028-B		—	**0,005900**	**0,000464**	**0,001090**
B028-G		**0,005900**	—	**0,000001**	0,434937
B028-D		**0,000464**	**0,000001**	—	**0,000000**
B028-O		**0,001090**	0,434937	**0,000000**	—

The highest values of tensile strength were determined with regard to concrete with dolomite and basalt aggregate, both in relation to ordinary and high strength concrete, likewise compression strength values. In each case (at all w/c) the differences between the strength of these types of concrete are maintained at a level of 3-9% in favor of dolomite (at statistically significant difference with respect to HPC concrete). Therefore, concrete with dolomite and basalt aggregate can be regarded as equivalent in terms of tensile strength. Relating to those values, the strength of concrete with granite aggregate and natural gravel is smaller by 18 ÷ 22% and 7 to 15% respectively in groups of ordinary types of concrete, and by 15% and 16% in HPC group, mostly at differences statistically significant. It should be noted that the difference in tensile strength values at a level of approximately 10%, corresponds to the change of one compression strength class in the case of ordinary concrete starting from C25/30 class, and in the case of high-strength concrete the difference is only about 4%. Therefore, it must be concluded that the use of natural gravel or granite aggregate instead of dolomite or basalt aggregate results in substantial reduction of not only compression strength but also tensile strength of concrete.

A general regularity needs to be emphasized that the lowest values of tensile strength were achieved in the case of concrete with granite aggregate, only in the case HPC concrete there is a slight advantage in favor of granite grit compared with natural gravel, however at a difference statistically insignificant. Nevertheless, in ordinary concrete OC of w/c = 0,70 the strength of concrete with granite aggregate is weaker than that with natural gravel by even 15,5%, and in relation to the strength of concrete with basalt aggregate by 17,0%. Similar relationships, although at smaller differences, 4,2% and 15,4% respectively, occur in ordinary concrete OC of w/c = 0,58. The highest tensile strength values were obtained with regard to concrete with dolomite grit.

Comparing test results of strength properties it should be stressed that there is a significant effect of coarse aggregate on the values obtained, as confirmed by a statistical analysis. The differences caused by the type of coarse aggregate, reaching up to about 22%, result in a change in the classification of concrete at the level of the two classes of compression strength (Fig. 2). The similar situation is in the case of tensile strength.

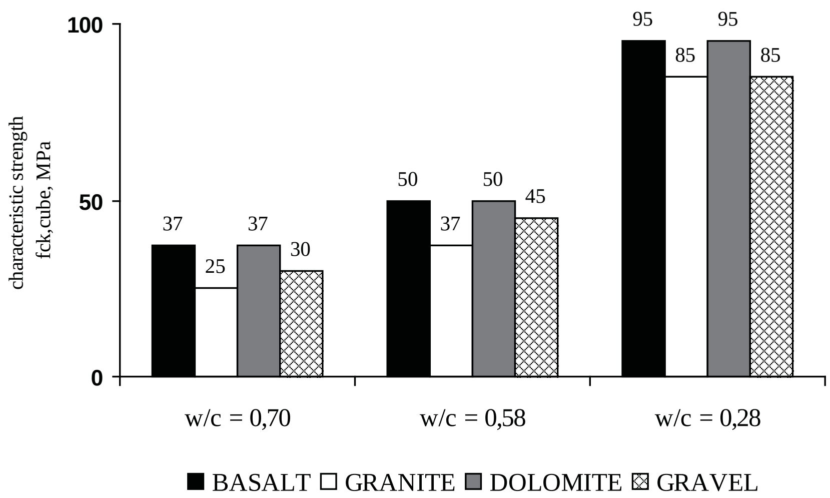

Fig. 2. Compressive strength of concrete with different types of aggregate and at different w/c values. Results obtained in tests

Weak strength test results of concrete with granite aggregate are to be found quite surprising. Granite rock aggregate is generally considered to be at least of good quality, however some of these rocks may be subject to quite considerable weathering, which leads to deterioration of aggregate properties (Jamroży, 2003; Neville, 2000; Piasta., Piasta W., 1994). In warm and humid climate, weathering of granites leads to formation of kaolin, the beds of which were formed in the Miocene period, mainly in strzegom and strzelin massif. Consequently, this may lead to deterioration of aggregate, and thus the properties of concrete. Negative differences obtained in the tests, compared to basalt and dolomite aggregates, may also be associated with different mineral composition and properties of the granite rock (coarse texture) and also aggregate (the breaking rate of granite is 2-4 times higher than that of basalt and dolomite respectively).

Summary

Considering the differences in strength classes of concrete obtained in tests due diversity of concrete composition by the type of coarse aggregate only, it needs to be adopted that this factor should be considered an alternative in the search for better strength properties of concrete, in relation to increasing the cement content. According to what has been said in the introduction, speaking more generally, increasing the proportion of cement in the production of concrete exerts a negative impact on the environment through, among others, an increase of CO_2 emission. This has also got a purely economic aspect for cement and construction industry in general. One can look for "concrete strength" in other sources than those consisting in a unit increase of cement content, through as shown above, an appropriate choice of the type of coarse aggregate. Moreover, given the results of strength tests, it seems to be feasible to use high-quality carbonate aggregates with properties comparable with basalt aggregates.

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