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Influence of type and maximum aggregate size on some properties of high-strength concrete made of pozzolana cement in respect of binder and carbon dioxide intensity indexes

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HIGHLIGHTS

- Influence of type and size of aggregate and pozzolana cement on HSC was determined.
- 0/8 mm aggregate with cement at 700 instead of 600 kg/m^3 improved strength by 8.5%.
- In case of 0/16 mm aggregate there was no need to increase cement amount to 700 kg/m^3.
- Basalt or granite of 0/16 mm size and 600 kg/m^3 of cement curbed HSC carbon footprint.

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ABSTRACT

In compliance with up-to-date concrete technology requirements combining technological and ecological aspects, the paper describes the effect of the type and maximum aggregate size and cement content on some properties of high strength concrete. The following kinds of coarse aggregate were used to produce concrete: natural mineral (gravel) and crushed (granite and basalt) aggregates and pozzolana cement – ingredient classified as ecological binder. The concretes contained a highly effective superplasticiser and microsilica. Air content in concrete mixes, water absorption and concrete compressive strength after various periods of hardening were examined. Certain calculations (based on compressive strength results) on values of intensity indexes of cement used and carbon dioxide, treating them as a key for evaluation of eco-efficiency of concrete, were performed. Using pozzolana cement with simultaneous use of a highly effective superplasticiser and microsilica made it possible to obtain high strength concrete, made of mineral natural and crushed aggregates. More encouraging strength tests results were achieved for concrete of crushed aggregates, particularly granite. It was discovered that using aggregate with a maximum particle size less than 8 mm instead of aggregate with particles measuring up to 16 mm with a simultaneous increase in the cement content led to a greater rise in concrete strength. The smallest indexes of binder and carbon dioxide intensity were obtained as a result of use of granite and basalt aggregate, with a maximum particle size up to 16 mm.

1. Introduction

A growing intensity of extreme weather conditions brought about by climate changes has become a serious social and economic problem of XXI century. Natural changes of the climate are particularly connected with solar activity, occurrence of *Milankovitch cycles* (variations in eccentricity, axial tilt, and precession), volcanic activity and ENSO (*El Niño–Southern Oscillation*) phenomenon. However, the increasingly higher and higher ratio of carbon dioxide concentration in the atmosphere, which has been observed for last 150 years, undoubtedly, is becoming increasingly significant. In 2013, for the first time, the CO_2 content in the atmosphere exceeded 400 ppm (http://climate.nasa.gov/news/916/) [1].

C.D. Keeling has been conducting researches on carbon dioxide content in the atmosphere since the fifties of last century. Although they do not constitute a direct evidence for anthropogenic reasons for the intensity of climate changes, today, in light of the other evidence, it is difficult to find more rational interpretation. According to measurements conducted by R.F. Keeling (C.D. Keeling's son) in

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9 observatories in the world [2,3], rise in CO_2 content is associated with a simultaneous lowering of oxygen to nitrogen proportion which is presented in the upper part of Fig. 1. The only plausible explanation of this phenomenon is the use up of oxygen in the processes of combustion of fossil fuels. It is more difficult to agree with one of most recognised alternative hypothesis, according to which the increase in CO_2 content in the atmosphere is a result of rise in the temperature of the oceans and seas, brought about by increased solar activity. Had this hypothesis been true, the proportion of oxygen to nitrogen would not have changed. It is only the carbon dioxide content in the atmosphere that would have changed. In fact, there is an observed, on the one hand, correction between the drop in the proportion of oxygen to nitrogen [2,3] with a commonly known C.D. Keeling curve (lower part of Fig. 1) illustrating the increase in the carbon dioxide concentration in the atmosphere and, on the other hand, the lower activity of the sun in the last 11-year cycles (http://solarscience.msfc.nasa.gov/predict.shtml) [4].

Concrete technology is one of the areas of human activity involved in increase in CO_2 emission, in particular cement production, key constituent of concrete. In addition, high demand for energy, demand for water, erection of buildings and its demolition are the reasons why concrete is not considered to be particularly environmentally friendly or compatible with the demands of sustainable development [5]. Hence, in the opinion of not only the environmentalists' expectations but also the average users' of the environment, concrete construction sector is obliged to undertake immediate action aimed at reducing its environmental impacts, including reduction of CO_2.

The regard for the environment has led to appearance of such notions as: green building, green concrete, green cement, biocement, eco-cement [5–8], which define industrial materials and processes that are environmentally friendly, but at the same time are economically viable and thus meet the expectations of concrete technology. Aïtcin's [9] opinion, according to which "the concrete of tomorrow will be green, green, and green", seems to be the best summary of the significance of this aspect.

The principles of sustainable development regarding construction and concrete industry have also begun to be a concern of not only environmentalists, but also governments on local, state, and national levels. Slowly by slowly, owners and developers have consequently begun to implement "going green" principles, for political reasons as a source of impalpable benefits and promotion. Still, they also find it as a way to improve the quality of the environment, where they live. They have realised that such aspects as reduced energy consumption and reduced life-cycle costs [5] are truly worth it.

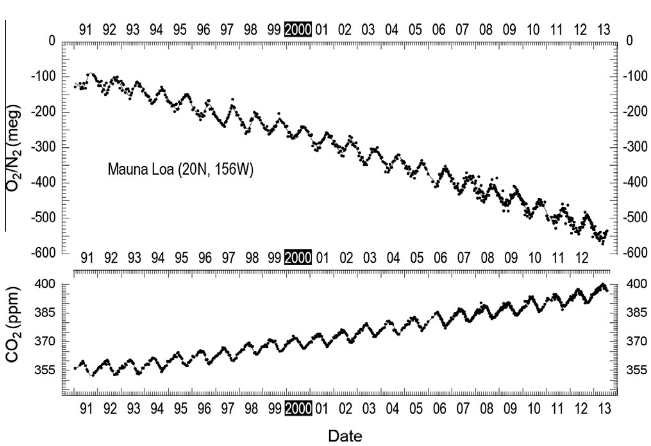

Fig. 1. Correlation between carbon dioxide quantity and oxygen to nitrogen ratio in the atmosphere based on Mauna Loa observations [3].

The aim of the present day technologists' is to produce increasingly sophisticated concrete, in terms of technical parameters, that is absolutely environmentally friendly. The potential tools and strategies needed to meet the environmental challenges in the construction and concrete industry could be achieved in different ways. They are as follows:

- replacement, as much as possible, of Portland cement by supplementary cementitious materials, especially by-products of industrial processes, such as fly ash, ground granulated blast furnace slag and silica fume [5,10–13],
- using eco-cements [7,14,15],
- using recycled materials, including recycled concrete aggregate, in place of natural resources [5,16–20],
- improvement of durability and service life of structures and as a result reducing the amount of materials needed for their replacement [12,16,21,22],
- improvement of concrete mechanical and other properties, which can also reduce the amount of materials needed [5,23],
- reusing wash water [5].

One of the criteria that can be a measure of sustainable development in the cement and concrete industry are Damineli's et al. [24] propositions on binder intensity index and carbon dioxide intensity index (b_i and c_i, respectively). The first one describes the cement mass per 1 m^3 of concrete necessary to achieve 1 MPa strength. The second presents the mass of carbon dioxide emitted in the production process of such a volume of cement that make it possible to attain the concrete strength of 1 MPa. Hence, the b_i index makes it possible to estimate the efficiency of a given cement binder in the process of obtaining the durable concrete. The c_i index means a unitary contribution of the binder into the CO_2 emission. If a complementary assessment of the eco-efficiency of cement is to be achieved, it is essential to use both indexes simultaneously.

As in all processes of concrete production, most of the carbon dioxide emission comes from the production of cement, the data can be treated as nearly estimating this emission for the needs of concrete production with specified parameters. Obviously, estimations should be carried out individually, since emissivity of CO_2 varies from cement plant to cement plant and different raw materials needed to produce clinker are used, and since selected concrete components vary in terms of quality and quantity.

More precise estimations could be achieved by including the volume of CO_2 emitted in the cause of transport of raw materials and cement as a final product, and emitted from technological operations connected with execution of concrete structure (production, transport and compaction of concrete).

In the light of concept of indexes [24], use of cements with mineral additives results in lower value of the c_i index compared to the value of c_i for Portland cements without mineral additives. On the basis of local and international data, Damineli et al. [24] estimated that CO_2 emission index in the production of purely clinker cements is approximately 4.3 kg/MPa and 1.5 kg/MPa in the production of cements with mineral additives [24]. The c_i index is related to the binder intensity index b_i, that for concretes with compressive strength exceeding 50 MPa is approximately equal to 5 kg/m^3/MPa, and for concretes with strength of 20 MPa is even 13 kg/m^3/MPa. Hence there are two ways of reducing CO_2 emission, i.e. selecting cements with mineral additives and producing concretes of high strength, more durable by nature, which can bring a meaningful effect when low proportion of Portland clinker cements are used for the production of high-strength concretes (HSC).

Reports on high-strength concretes in a "green" option refer to replacing a part of cement binder in the concrete with mineral additives [25]. There are few data on achieving this goal using eco-cements [7,14,15], but, according to the literature review made by authors of this paper, no researches have been done on the use of pozzolana cement CEM IV/B-V 32.5R in the high-strength concrete technology. Since the binder is still not widely recognised in this application area, the authors accepted this as a sort of a research challenge. Attempts were taken to determine the extent in terms of HSC needs does this type of cement works with simultaneous addition of natural and crushed aggregates to this concrete, concerning the effect of their maximum particles size. Likewise, there are relatively little data in the available literature covering this area.

Properties of high-strength concrete, to a larger extent, are determined by the type of aggregate, both on a qualitative selection as well as graining. Both gravel aggregates and crushed aggregates of various rocks are used. However, the use of harder rock aggregates does not always result in higher concretes strength [16]. Jamroży [26] stresses the need for selection of aggregates according to their cement paste demanding. He has shown in one of his studies that crushed basalt aggregate has lower cement paste demanding than granite. The rationality of using fractionated aggregate, both fine and coarse, has been emphasised [16]. The issue of influence of maximum size of coarse aggregate particles on concrete strength has been raised *i.a.* by Aïtcin [16], Venkateswara et al. [27], Kurdowski [28] and Neville [29], who agree on the sense behind the use of smaller aggregate particles size if higher concrete strength is sought. Aïtcin [16] indicates that the increase of maximum size of aggregate may evoke some problems with the quality of interfacial transition zone which can be larger and more heterogenous. Futhermore, as smaller aggregate particles are more durable than larger ones, use of the last ones involves risk of occurrence of uncontrolled microcracks, which could lead to weakening of concrete structure. However, Aïtcin [16] claims that it is possible to obtain both a good workability of concrete mixes and strength of concretes made of aggregates of a maximum particles size of 25 mm, provided they originate from sufficiently strong and homogenous rocks. In practise particles of a smaller size are generally used mainly in order to eliminate the above mentioned effect in the face of lack of suitable procedures of optimisation of aggregate testing. According to Chen and Liu [30] aggregate size significantly influences the fracture behaviour of high performance concrete. Fracture energy of concrete increases with the increase of the maximum aggregate size. The larger the size of the aggregate, the more significant the deflection of propagating crack and the greater the fracture process zone can form [29,30]. It is in agreement with Zhang and Sun's studies [31] who claim that autogenous shrinkage of HPC decreases with the increase of maximum coarse aggregate size.

However, generally there are not enough studies in this field, and opinions are not unambiguous. For instance, there is lack of data on the simultaneous impact of maximum size of aggregate particles and cement content on the concrete strength, which is significantly essential in the carbon dioxide emission.

The undertaken researches are associated with this point and are largely connected with an ecological aspect and traditional technologies, focused on the role of aggregate in the HSC technology. This ecological aspect increasingly raised in the concrete technology, i.e., in this case, high strength concrete.

2. Materials and methods

2.1. Cement

The pozzolana cement CEM IV/B-V 32.5 R, used for the needs of this thesis, was created in a laboratory way by mixing of Portland cement CEM II/B-V 42.5N (commercially produced) with fly ash from a CHP (combined heat and power) plant complying with requirements and compatibility criteria according to the standard EN 450-1:2010 (*Fly ash for concrete. Definition, specifications and conformity criteria*) in mass percentages: 86.5% and 13.5% respectively. Properties of the binder prepared in the laboratory are presented in Table 1.

2.2. Aggregate

The following types of aggregate were used to produce concretes: pit sand (0/2 mm), gravel aggregate divided into two fractions: 2/8 mm and 8/16 mm, granite and basalt crushed aggregate (2/8 mm and 8/16 mm). All the aggregates complied with requirements of the EN 12620:2002 standard (*Aggregates for concrete*).

2.3. Superplasticiser

The authors used a highly effective new generation superplasticiser based on polycarboxylate ether. The physical and chemical parameters are given in Table 2.

2.4. Microsilica

Amorphous microsilica was used. The characteristics are listed in Table 3.

2.5. Concrete mix recipes

Concrete recipes were determined for the following variants: cement in the amount of 600 kg/m^3 along with aggregate mix of dense pile up to 8 mm and up to 16 mm and 700 kg/m^3 with aggregate mix of dense pile up to 8 mm and up to

Table 1
Chemical composition, physical and mechanical properties of cement.

Characteristic	Result
Chemical compounds (%)	
SO_3	2.65
SiO_2	30.45
Al_2O_3	12.08
Fe_2O_3	4.92
CaO	40.95
MgO	1.74
K_2O	1.49
Na_2O	0.47
Insoluble residue (%)	30.34
Ignition loss (%)	4.43
Blaine' specific surface (m^2/kg)	418
Density (kg/m^3)	2740
Compressive strength (MPa)	
2 days	17.4
28 days	36.4

Table 2
Physical and chemical properties of superplasticiser.

Property	Result
Chemical base	Policarboxylate ether
Physical state	Water solution
Colour	From beige to brown
Density at 20 °C (kg/m^3)	1063
pH at 20 °C	5.5
Chloride content (%)	0.1
Na_2O_{eq} (%)	0.6
Boiling point (°C)	100
Absolute viscosity (MPa s)	30

Table 3
Physical and chemical properties of microsilica.

Parametr	Result
Physical state	Powder
Colour	Grey
Odour	Odourless
Bulk density (kg/m^3)	150–170
pH at 20 °C	5.0–7.0
Chloride content (%)	$\leqslant$0.15
Melting point (°C)	1.550–1.570

Table 4
Recipes of concretes.

Constituent (kg/m^3)	Recipe designation			
	Rec-1 (600-0/8)	Rec-2 (600-0/16)	Rec-3 (700-0/8)	Rec-4 (700-0/16)
CEM IV/B-V 32.5 R	600	600	700	700
Sand 0/2 mm	615	525	574	490
Coarse aggregate 2/8 mm	1020	555	952	518
Coarse aggregate 8/16 mm	0	555	0	518
Water	140	140	140	140
Microsilica	60	60	70	70
Superplasticiser	6	6	7.7	7.7
w/c	0.23	0.23	0.20	0.20

16 mm (Table 4). The class of consistency of concrete mixes was beyond S1–S4 corresponded to recommendation of the EN 206-1:2000 standard (*Concrete–Part 1: Specification, performance, production and conformity*).

2.6. Testing procedure

Firstly, ingredients of the concrete mix as follows: coarse aggregate of the 8/16 mm fraction, coarse aggregate of the 2/8 mm fraction, sand 0/2 mm and microsilica were placed in a laboratory concrete mixer and mixed for 1 min. The next step was addition of 75% of total amount of water, cement CEM II B-V 42.5N (86.5%), fly ash (13.5%). The whole was mixed for 3 min. The last stage was gradually addition of 25% of water along with the superplasticiser (the remaining 25% of water was added with an appropriate amount of superplasticiser), with switching the laboratory concrete mixer on for the next 3 min.

Placing of concrete mix in forms of plastic cubic moulds of side 150 mm was laid in 2 layers. After 24 h, the samples were demoulded and placed in a climatic chamber for a period of 28 days, where temperature was kept at 18 ± 2 °C and relative humidity at 95% providing standard curing conditions.

Consistency of concrete mixes was marked by slump cone method according to the requirements of the EN-12350-2:2009 standard (*Testing fresh concrete. Slump-flow*). Measurements of density of concrete mixes were conducted in compliance with the EN 12350-6:2009 standard (*Testing fresh concrete. Density*). Air contents were measured (immediately after making the mix and after 45 min of its preparation) in accordance with the EN 12350-7:2009 standard (*Testing fresh concrete. Air content. Pressure methods*). Determination of concrete absorption was performed on samples after 28 days of hardening, according to the procedure specified in the Polish standard PN-88/B-06250 (*Ordinary concrete*). The mentioned standard is no longer compulsory, but is still used in engineering practise. Tests on compressive strength, in compliance with requirements of the EN 12390-3:2009 standard (*Testing hardened concrete. Compressive strength of test specimens*), were performed after:

- 1, 7, 28 days (on 5 samples for each series of concrete),
- 56, 90 and 180 days (on a single sample for given series).

Tests results of 1-, 7- and 28-day concrete compressive strength were subjected to a statistical analysis using the method of analysis of variance (ANOVA) complemented with contrast analysis. The analysis was supplemented with *post hoc* tests including the most sensitive testing method which is the least significant difference (LSD) test. Discussing the results, attention was focused on statistically essential differences between compared groups for results obtained after 28 days of hardening. For the remaining cases (f_{c1} and f_{c7}) only the registered trends were discussed. Comparisons by the LSD method were performed by considering the following variants:

- a maximum size of aggregate particles – a type of aggregate – cement content,
- a maximum size of aggregate particles – a type of aggregate, without distinguishing the cement content,
- a maximum aggregate size – cement content, without distinguishing the type of aggregate.

For the mean results of the compressive strength obtained after 28 days b_i and c_i (binder and carbon dioxide intensity) indexes were calculated. For the results obtained in later periods (after 56, 90 and 180 days of hardening) extreme values were noted (minimum and maximum). In order to calculate a unitary emission for the CEM IV/B-V 32.5 R cement, 2011 data from one of Polish cement plants were used, assuming the cement content in the amount of 86.5%. The rest was accepted as an "emission-free" ash. The calculations included the following cement value, i.e. 448 kg CO_2 per 1 ton of cement. The emission from combustion of biomass, 5% of remaining additives according to the EN 197-2: 2000 standard (*Cement – Part 2: Conformity evaluation*) and the participation of the setting regulator were not taken into account.

3. Results and discussion

Test results of the air content in concrete mixes (immediately after making the concrete mix, and after 45 min of its implementation), the density of concrete mixes and water absorption of concrete after 28 days are summarised in Table 5.

3.1. Air content and density

Low air contents in concrete mixes, ranging from 0.7% to 2.8%, both immediately after making of the concrete mix as well as 45 min later seems to be particularly noticeable. For a given amount of cement: 600 and 700 kg/m^3 respectively, mixes of aggregates of maximum particles size up to 16 mm were characterised by lower air contents. The concrete mixes obtained during researches, exhibited self-compacting properties, spontaneously flowing and de-aerating. There are no obligatory requirements concerning air content for high strength concretes or self-compacting concretes. Literature sources [32,33] indicate the value of 2% but some of them indicate a higher value, even by 6% [32]. The results should therefore be considered satisfactory, and concrete mixes properties should be considered as improved, especially in a variant of the ready-mix concrete, where in practise application of concrete mixes of the consistency close to S4 class is required. The density of concrete mixes ranged from 2300 kg/m^3 to 2390 kg/m^3. This is obviously related to the density of aggregates, the smallest for gravel aggregate and the largest for crushed basalt aggregate.

3.2. Water absorption

Values of 28-day water absorption of concrete samples did not exceed 3%. There was no significant variation of water absorption of concrete on the type of aggregate used. The range of changes depending on the amount of cement (600 and 700 kg/m^3) was also insignificant, amounting to approximately 0.2%. As regards ordinary concretes subjected to the influence of natural atmospheric factors, water absorption rate should not exceed 5% and 9% in case of concretes protected from impact of absorption (according to PN-88/B-06250). The concretes, made in for this study, belong to the self-compacting and high-strength concretes. Hence, they are special in two ways. Such cement matrix composites should be expected to have better parameters in comparison with ordinary concretes parameters. The results obtained here prove that pozzolana cement has got very good characteristics in various

Table 5
Air content and density of concrete mixes and water absorption of concretes.

Aggregate typecement contentgraining of aggregate*	Air content (%)		Density (kg/m^3)	Water absorption (%)
	0′	45′		
Gravel-700-0/8	2.8	2.1	2300	2.79
Gravel-700-0/16	0.8	0.8	2290	2.39
Gravel-600-0/8	2.6	2.6	2330	2.96
Gravel-600-0/16	1.1	1.1	2330	2.80
Granite-700-0/8	2.6	2.4	2300	2.66
Granite-700-0/16	1.2	1.2	2280	2.93
Granite-600-0/8	1.1	1.1	2340	2.54
Granite-600-0/16	1.0	1.0	2310	2.83
Basalt-700-0/8	1.7	1.4	2350	2.65
Basalt-700-0/16	0.7	0.7	2320	2.68
Basalt-600-0/8	1.2	1.2	2390	2.64
Basalt-600-0/16	0.8	0.8	2390	2.48

* *Note*: cement content and graining of aggregate are given in kg/m^3 and mm, respectively.

configurations with aggregate, regarding aggregate type and maximum particles size. Water absorption is a property relatively easy to study and, at the same time, a factor determining durability index of concrete in some way. Research results appear to portend positively in terms of concrete strength made of pozzolana cement. The small values of water absorption obviously have a relation with participation of microsilica in concretes. It is microsilica that, interacting with the binder, contributes to the compaction of the concrete structure due to formation of greater amounts of hydrated calcium silica phases. Obtaining concretes with low water absorption suggests that the pozzolana cement is compatible in cooperation with microsilica, which of course would require a deeper research in this area.

3.3. Compressive strength

A tested key property of concrete was compressive strength. It was assumed that application of pozzolana cement would lead to obtaining concretes of high strength parameters, provided that appropriate qualitative and quantitative selection of aggregates and assistance by a highly effective superplasticiser and microsilica has been carried out.

With a minimum value of 60 MPa, taken as a criterion of high strength concrete, all concretes of 28 days and older (56, 90, 180 days) fulfilled this condition (Table 6). Moreover, 7-day strengths exceeded value of 60 MPa, except for one type of concrete, i.e. made of gravel aggregate with a maximum particles size up to 8 mm, combined with cement content of 600 kg/m^3. A maximum 28-day compressive strength was reached by concrete made of cement CEM IV/B-V 32.5N, used in the amount of 700 kg/m^3, applying granite aggregate with a maximum particles size of 8 mm (Fig. 2), which was also confirmed by a statistical analysis. This also covered the period of: 7 and 56 days (Table 6). After 90 and 180 days, in terms of concrete strength, basalt aggregate concrete with a maximum particles size up to 16 mm, proved to be slightly better than crushed granite aggregate concrete. However, particular care should be exercised when interpreting this trend, keeping in mind that the 180-day strength was for a single concrete sample for a given series. Concrete compressive strength increased after longer periods of hardening (90- and 180-day period), which should be attributed to the characteristic properties of pozzolana cement. Undoubtedly, explanation of attaining high values of strength must be sought in the precise selection of dense pile of aggregate, good quality of aggregate, relatively large amount of cement (600 kg/m^3 and 700 kg/m^3), effectiveness of superplasticiser and microsilica, compatible with pozzolana cement. With such a large number of factors influencing the high value of

Table 6
Compressive strength of concretes.

Aggregate type-cement content-graining of aggregate*	f_{c1} (MPa)	f_{c7} (MPa)	f_{c28} (MPa)	f_{c56} (MPa)	f_{c90} (MPa)	f_{c180} (MPa)
Gravel-700-0/8	51.03	68.80	86.10	89.50	93.70	95.00
Gravel-700-0/16	38.57	64.33	82.57	84.30	91.40	92.90
Gravel-600-0/8	38.67	58.77	76.57	78.90	88.30	91.50
Gravel-600-0/16	40.20	61.20	78.30	82.40	85.20	88.90
Granite-700-0/8	49.23	75.60	94.97	97.20	100.10	101.90
Granite-700-0/16	42.93	69.97	88.07	91.60	95.40	96.50
Granite-600-0/8	37.93	63.93	80.27	89.70	97.00	98.90
Granite-600-0/16	35.57	66.67	87.13	93.90	96.50	98.00
Basalt-700-0/8	48.03	75.60	82.27	86.60	91.20	93.10
Basalt-700-0/16	42.13	71.60	85.77	91.50	93.50	101.80
Basalt-600-0/8	42.23	67.20	73.73	74.80	89.10	94.60
Basalt-600-0/16	41.20	72.67	86.40	90.20	102.10	106.50

* *Note*: cement content and graining of aggregate are given in kg/m^3 and mm, respectively.

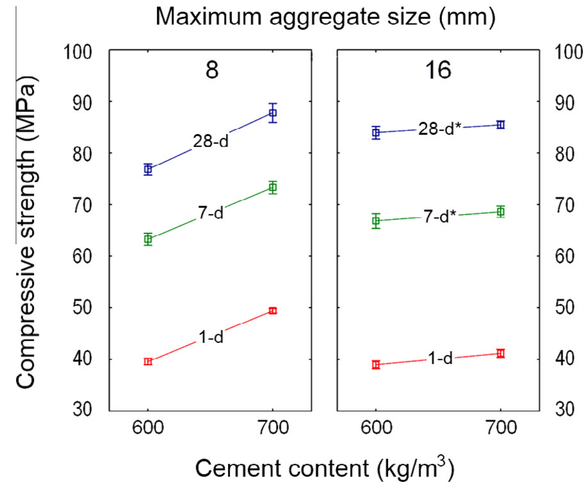

Fig. 2. Influence of maximum aggregate size and cement content on 1-, 7- and 28-day compressive strength of concrete (marked as 1-d, 7-d and 28-d, respectively) depending on aggregate type (*Note*: the upper and bottom bars represent the confidence intervals stated at 95% confidence level; if asterisk is added there is lack of statistical difference between compared groups).

strength, and therefore a possibility of a synergistic effect, it is hard to precisely pinpoint which of them had a dominant influence. Although, according to the statistical analysis presented below, the maximum particles size of aggregate seems to have a relevant meaning in case of a greater cement content, provided that aggregate of 8 mm is used.

Fig. 3 presents the effect of maximum particles size of aggregate on the increase of concrete strength as a function of the cement content, without taking into account the type of aggregate. The graphs show that it is easier to obtain an additional increase in strength by increasing the cement content by 100 kg/m^3 for concrete of aggregate to 8 mm than for concrete of aggregate 0/16 mm. Analysing Fig. 4, it can be concluded that without taking into consideration the impact of diverse cement content (600 and 700 kg/m^3), and taking into account only aggregate type and maximum particles size, for the three aggregates used in the test, only in case of the strongest rock, i.e. basalt, did the maximum particles size decide on the increase in the concrete strength after 28 days of hardening. When 0/16 mm aggregates were used instead of 0/8 mm aggregates an increase of strength by 10% was registered. This can be a confirmation for Aïtcin's hypothesis [16] that using a greater maximum particles size could lead to a risk of appearance of cracks in larger, originally weaker, grains of aggregate. As it can be noted, in case of good quality rock, from which aggregate is obtained, no such effect is registered. For other types of aggregate, lack of differences was not detected even in the *post hoc* LSD test, a method considered to be the most liberal of the method of testing, i.e. allowing for detecting of even the smallest of differences between the mean values of tested characteristics. However, taking into account the maximum particles size up to 8 mm, use of granite aggregate made it possible to attain better concrete strength than in case of 0/8 mm basalt aggregate, although basalt rock is considered to be more durable than granite. This could result from the impact of the type of bonding between basalt aggregate and cement paste, which is different when high amount of fly ash in cement is used. In case of smaller maximum aggregate size (0/8 mm) it can be expected that interfacial transition zone (ITZ) occupies more volume because of larger specific surface area of aggregate. More detailed results on factors affecting concrete compressive strength are specified in the analysis in Fig. 2. In case of increasing cement content by 100 kg/m^3, the largest increase resulting from use of aggregate with the maximum particles size

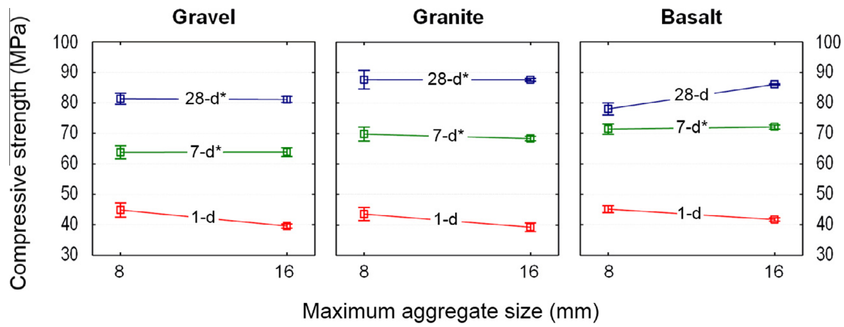

Fig. 3. Influence of cement content on 1-, 7- and 28-day compressive strength of concrete (marked as 1-d, 7-d and 28-d, respectively) depending on maximum aggregate size, without differentiating type of aggregates (*Note*: the upper and bottom bars represent the confidence intervals stated at 95% confidence level; if asterisk is added there is lack of statistical difference between compared groups).

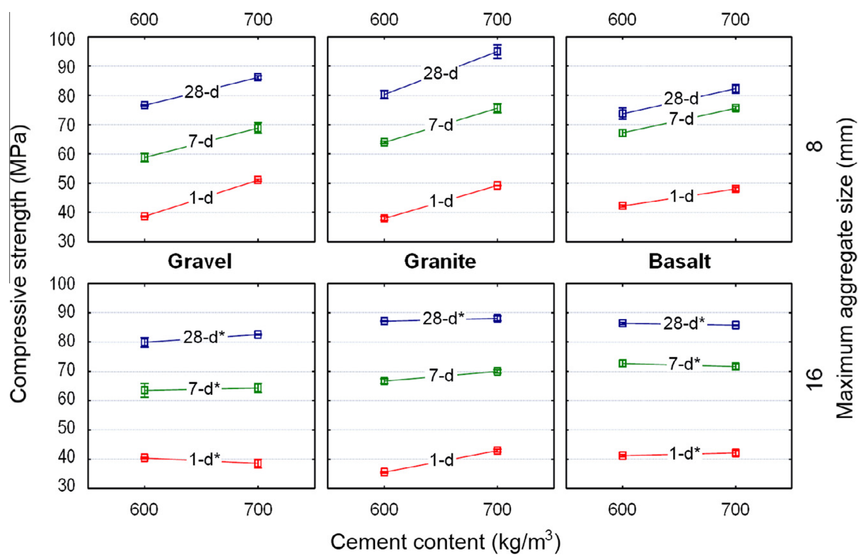

Fig. 4. Influence of maximum aggregate size on 1-, 7- and 28-day compressive strength of concrete (marked as 1-d, 7-d and 28-d, respectively) depending on aggregate type, without differentiating amount of cement used (*Note*: the upper and bottom bars represent the confidence intervals stated at 95% confidence level; if asterisk is added there is lack of statistical difference between compared groups).

of 8 mm was obtained for granite aggregate concrete and the lowest for basalt concrete. In case of aggregate with maximum particles size up to 16 mm, only after one day, did a greater amount of cement decide on a minimum increase of concrete strength (f_{c1}), but it was only true for granite aggregate. A similar effect, statistically significant, though less meaningful, was found for 7-day strength (f_{c7}), also for concrete from the same aggregate. For all types of aggregate with 0/16 mm graining, concerning their effect on 28-day strength, no difference in results was registered, even statistically. Cement content comes into play in case of a lower maximum aggregate size (0/8 mm). Without taking into consideration the aggregate type, better results were obtained for 700 kg/m^3. However, when aggregate up to 8 mm is used, granite seems to be advisable for both cement amounts. The reason for the relatively low increase in 28-day strength, compared to 7-day strength, for concretes made with the use of basalt aggregate with 0/8 mm graining is also worth asking. With a lower maximum particles size, a larger area of contact between the aggregate and cement paste (ITZ) can be expected. It is conceivable that in this case an unfavourable tendency to weaken a transition zone between basalt aggregate and cement paste in the presence of a large amount of fly ash in the binder appeared. A similar effect, although to a lesser extent, was noted in case of the same aggregate but with 0/16 mm graining. Moreover, it was true only for basalt aggregate and 700 kg/m^3 cement content that 28-day compressive strength was better for 0/16 mm graining than for 0/8 mm.

Generally, without taking into consideration aggregate type, when smaller maximum aggregate size is used (0/8 mm) greater cement content (700 kg/m^3) allows for gaining better strength, which makes no difference in case of aggregate up to 16 mm.

3.4. Binder and carbon dioxide indexes

Interesting observations were provided by an analysis on the results of calculations concerning binder intensity and carbon dioxide intensity indexes, which reduction is key to environmental friendliness.

Based on the data shown in Fig. 5 it can be concluded that the best indexes were obtained for HSC concretes made with the use of 600 kg/m^3 cement with the maximum particles size of 16 mm. The most beneficial was the use of granite aggregate (b_i = 6.9 kg/m^3/MPa, c_i = 3.09 kg/MPa) and basalt (b_i = 7.0 kg/m^3/MPa, c_i = 3.11 kg/MPa). Slightly less favourable was the use of gravel (b_i = 7.7 kg/m^3/MPa, c_i = 3.44 kg/MPa) aggregate. The least satisfactory results were obtained with a larger amount of cement (700 kg/m^3), in case of the use of gravel and granite aggregate with 0/16 mm graining; for basalt the graining was 0/8 mm. It seems that in order to achieve a relatively good quality HSC concrete

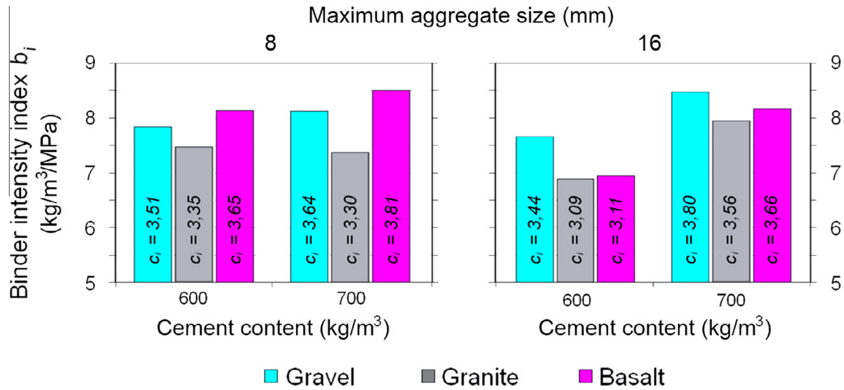

Fig. 5. Binder intensity (b_i) and carbon dioxide intensity (c_i) indexes estimated for 28-day compressive strength of concrete and carbon dioxide emission from cement production at the level of 448 kg CO_2/t_{CEM} (*Note*: c_i is given in kg/MPa).

Table 7
Values of binder intensity (b_i) and carbon intensity (c_i) indexes depending on maximum aggregate size and cement content obtained on the base of 56-, 90- and 180-day compressive strength test results.

Maximum aggregate size (mm)		8		16		Best in group	
Cement content (kg/m^3)		600	700	600	700	600	700
56-day	Gravel	7.6 (3.4)	7.8 (3.5)	7.3 (3.3)	8.3 (3.7)	16 mm	8 mm
	Granite	6.7 (3.0)	7.2 (3.2)	**6.4 (2.9)**	7.6 (3.4)	16 mm	8 mm
	Basalt	8.0 (3.6)	8.1 (3.6)	6.7 (3.0)	7.7 (3.4)	16 mm	16 mm
90-day	Gravel	6.8 (3.0)	7.5 (3.3)	7.0 (3.2)	7.7 (3.4)	8 mm	8 mm
	Granite	6.2 (2.8)	7.0 (3.1)	6.2 (2.8)	7.3 (3.3)	Similar	8 mm
	Basalt	6.7 (3.0)	7.7 (3.4)	**5.9 (2.6)**	7.5 (3.4)	16 mm	16 mm
180-day	Gravel	6.6 (2.9)	6.1 (2.8)	6.7 (3.0)	7.5 (3.4)	8 mm	16 mm
	Granite	6.1 (2.7)	6.9 (3.1)	6.1 (2.7)	7.3 (3.2)	Similar	8 mm
	Basalt	6.3 (2.8)	7.5 (3.4)	**5.6 (2.5)**	6.9 (3.1)	16 mm	16 mm
	Best in group	Granite	Gravel	Basalt	Basalt		

Note: carbon intensity (c_i, given in kg/MPa) value is presented in parenthesis, after binder intensity (b_i, given in kg/m^3/MPa) value; the lowest b_i and c_i value for each compressive strength time (56, 90 and 180 days, respectively) are bolded.

there is no need to increase proposed proportion of the pozzolana cement CEM IV above 600 kg/m^3, provided there are no precise requirements to attain high class concrete. In general, both b_i and c_i indexes obtained for concretes produced with the use of the CEM IV cement have their values within the range indicated by Damineli et al. [24]. The c_i index is closer to its upper limit range, but its worst result is more than 1 kg/m^3/MPa lower than the 4.3 kg/m^3/MPa value specified for CEM I. Analysis of indexes of binder intensity, specified for the results of strength tests (Table 7), showed a gradual reduction in their value with time and amount of cement used, with preference of using it in smaller amounts. The analysis on indexes of the binder CO_2 emission in the context of concrete compressive strength achieved (Table 7) confirmed the reduction of the c_i value with time and the amount of the cement used, with a preference for using it in a smaller amount, especially in case of aggregate up to 16 mm, which was also emphasised in 3.3.

4. Conclusions

Based on research carried out, the following conclusions were reached:

- Pozzolana cement CEM IV/B-V 32.5R with a simultaneous use of highly effective superplasticiser and microsilica made it possible to obtain high strength concretes, made both of mineral natural (gravel) aggregates as well as from crushed (granite and basalt). In areas of research conducted, resultant concretes showed self-compacting properties, which places them in a group of "green" composites, fulfilling the principle of sustainable development.
- Increase of the cement content from 600 to 700 kg/m^3 resulted in the growth of concrete strength (at least by 8.5%) only when 0/8 mm aggregates were used. For 0/16 mm aggregates, practically no statistically significant difference was noted, for both levels of amount of cement used.
- Taking strength as the only criterion for HSC concrete quality assessment for our studies the use of 700 kg/m^3 cement proved to be more favourable in case of 0/8 mm aggregates. However, when basalt aggregate was used to produce concrete, 0/16 mm aggregates appeared more effective for this cement content.
- Taking into account both concrete compressive strength as well binder and carbon dioxide intensity indexes (b_i and c_i), with a lower cement content (600 kg/m^3) more rational was the use of aggregate with 0/16 mm graining, regardless of the type of aggregate.
- If the CO_2 emission during crushing of aggregates is not factored in, the best solution is to use basalt and granite aggregate. As far as 180-day compressive strength was concerned, granite aggregate of 0/8 mm and basalt aggregate of 0/16 mm were advisable.

A selection of a maximum particles size of the aggregate between 8 and 16 mm with a simultaneous use of pozzolana cement CEM IV/B-V 32.5R, although relevant, is not unequivocal.

Each time it requires individual consideration of the following factors: type and local availability of aggregate, concrete strength requirements and CO_2 emission connected with extraction and production of concrete constituents, especially cement. However, the points mentioned above concerning the influence of type and maximum size of aggregate on the some HSC properties seem to mark out a new direction of investigations when CO_2 emission is taken into consideration. In order to support the conclusions different types and origin of gravel aggregate as well as other rock sources of crushed aggregate should be tested. Similarly, there is a need to check a wider range of maximum aggregate size. Moreover, all the above mentioned factors require each time individual consideration of a type and availability of aggregate, strength parameters of the rock and, finally, real and individual carbon dioxide emission connected with extraction or production of concrete ingredients.

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