Abstract
In Polish climatic conditions frost resistance of concrete is one of its most important durability properties. There are many material and technological factors influencing on that property of concrete, however, it can be assumed that modification of structure of cement matrix porosity by introducing air-entraining admixtures into concrete mix is the most effective used solution.
In the paper innovative way in that manner, based on the production of air-entraining cement (AEC) was presented. Portland-fly ash cement CEM II/B-V according to European Standard for common cements EN 197-1 is included in the research. Cement containing siliceous fly ash with addition of air-entraining admixtures (AEA) was obtained by semi-industrial test. Scope of analysis covered ability of cements to aerate mortar and concrete as well as their physical and mechanical properties. Based on the performed investigations authors indicated possibility of obtaining cements with air-entraining admixture which meet the requirements for common cements and are able to aerate effectively mortar and concrete mix according to design assumptions.

Originality
Originality of the research relays on the development of production technology of innovative composite cements which contain optimal quantity of selected air-entraining agents (AEA). Optimal AEA addition to cement provides concrete porosity characteristics in line with requirements of accurate standards, and the same freeze and thaw resistance of concrete. Comparing to American Standard ASTM C595 for blended cements the research also includes cements produced by inter-grinding of the constituents.
The research was based on scientific and application approaches. Eventually all the tests and works have been performed to develop guideline for production technology of innovative cements as well as application conditions of these cements in the technology of concrete resistant to freeze and thaw.

Keywords: concrete, mortar, air entraining cement, frost resistance, AEA
1. Introduction
In Polish climatic conditions frost resistance of concrete is one of its most important durability properties. The wide literature and extensive research prove that concrete made with composite cements containing high amounts of mineral additives (blastfurnace slag and/or siliceous fly ash) despite a better tightness, may not be frost resistant [3-9]. According to the recommendations of the American Concrete Institute [10] there is a possibility to provide the frost resistance of such concrete, however, proper aeration of the concrete mix is necessary. This issue is considered in the European Standard EN 206-1:2003 “Concrete – Part 1: Specification, performance, production and conformity” which recommends aeration of the concrete mix for an exposure class XF, i.e. aggression caused by freezing/thawing. Proper aeration of concrete made of cement containing high content of mineral additives is difficult to obtain and requires proper amount of air-entraining agent (AEA) what depends on the kind and quantity of mineral additive in composite cement [1÷3, 5, 10]. The US standards ASTM C150 for Portland cement [11] and ASTM C595 for composite cements [12] cover the applicability of AEA blended with cements in aerated concrete technology. The problem of frost resistance of concrete made with cement containing mineral additives is included in the research project realized within Polish National Research and Development Centre “Innovative air-entraining cements in concrete.” The general aim of the project is to develop an innovative production of air-entraining cements (AEC) which can properly aerate concrete; that is ordinary Portland cements and composite cements containing high amount of mineral additives. Technological assumptions of AEC were based on proper selection of type and quantity of air-entraining agent, resulting in required air entraining and full frost resistance of concrete. Objectives of the project include two basic issues: technological guidelines and application conditions of AEC in air entraining concrete technology with required pore characteristics.
In the paper selected results of AEC properties and ?? of aerated concrete are analyzed. The results of cement with AEA addition, providing 4-6 % aeration of concrete, were specified. Selected concrete characteristics made of AEC, including pore characteristics and frost resistance were also presented.

2. Methods and Samples
Air-entraining Portland-fly ash cements CEM II/B-V (AEC) were the subject of investigation. Research program covered two issues. Properties of AEC according to European Standard EN 197-1 were one of them. The other one concerned the properties of concrete made of AEC. Analysis included the following determinations:
- water demand, setting time and soundness according to EN 196-3+A1:2009;
- consistency according to EN 1015-3:2000, table test;
- compressive strength according to PN-EN 196-1:2006;
- heat of hydration by semi-adiabatic method according to PN-EN 196-9:2010;
- air content in mortar according to standard EN 1015-7:1999;

The following examinations of concrete made with AEC were performed:
- air content in concrete mix according to EN 12350:2011,
- air void characteristics in hardened concrete according to EN 480-11:2008
- compressive strength according to EN 12390-3:2011
- frost resistance test in accordance with PN-88/B-06250

AEC was produced by constituents mixing method; 67% Portland cement CEM I 52.5R, 33% siliceous fly ash and proper amount of AEA admixture. Reference cement have the same proportion of constituents but without AEA admixture. The quantity of AEA providing 4-6% aeration level of concrete mixes was chosen based on control tests of air content in normative mortars.

3. Results and discussion
3.1 AEC properties
Test results of AEC and characteristics of normative mortars made of CEM II/B-V are given in tables 1 and 2.

Tab. 1 Test results of cement mortars made of reference CEM II/B-V and AEC
### Tab. 2 Test results of cement mortars made with reference CEM II/B-V and AEC

<table>
<thead>
<tr>
<th>Cement</th>
<th>Air content [%]</th>
<th>Water demand [%]</th>
<th>Setting time [min.]</th>
<th>Consistency [cm]</th>
<th>Soundness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II/B-V</td>
<td>Ref 6.5</td>
<td>30.7</td>
<td>182</td>
<td>227</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>AEC 9.4</td>
<td>30.3</td>
<td>209</td>
<td>294</td>
<td>18.0</td>
</tr>
</tbody>
</table>

AEC has lower water demand, which property is required to obtain normative cement paste consistency. It can be stated that AEC provide very good mortar consistency. There were no problems with soundness of all tested cements.

The comparison of compressive strength development of AEC and reference CEM II/B-V, after 2 and 28 days of hardening, is shown in figure 1. Cement with AEA addition achieved lower early and 28 days compressive strength comparing to the reference CEM II/B-V, approximately by 25%.

![Figure 1 The comparison of compressive strength development of AEC and reference CEM II/B-V](image)

According to classification of common cements included in EN 197-1:2012 compressive strength results of AEC are one class lower than that of reference cement.

### 3.2 Concrete properties

Concrete mixes were produced with cements specified in section 2 and 3.1, ie AEC – Portland-fly ash cement CEM II/B-V with AEA addition, Reference cement - CEM II/B-V without AEA addition. The composition of the concrete mix corresponded to standard concrete according to European Standard EN 480-1[13] and EN 934 [14]. The proportions of concrete mixtures constituents have been determined by experimental method, with constant w/c=0.45 and consistency V2. Concrete mix compositions are given in table 3.

### Tab. 3 Composition of concrete mix

<table>
<thead>
<tr>
<th>Constituents</th>
<th>CEM II/B-V reference</th>
<th>CEM II/B-V AEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/2</td>
<td>525 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Granite aggregate 2/8</td>
<td>390 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Granite aggregate 8/18</td>
<td>373 kg/m³</td>
<td></td>
</tr>
</tbody>
</table>
Cube concrete samples of 150 mm side were made in accordance with EN 480-1. The scope of the concrete investigations covered determination of compressive strength after 7 and 28 days of hardening. Frost resistance was determined by strength decrease and weight loss after 75 cycles of freezing and thawing. Results of compressive strength and frost resistance measurements are given in table 4. Air void microstructure characteristics test was performed according to EN 480-11 by means of microscopic method with digital image analysis [13,14]. Concrete samples after frost resistance determination were the objects for pore characteristics test. Pore distribution results are given in Table 5. Figure 2 shows polished and contrasted concrete samples with digital image analysis of concrete aeration. Air void size distribution is presented in Figure 3.

Tab. 4 Test results of concrete made of reference CEM II/B-V and AEC

<table>
<thead>
<tr>
<th>Concrete made of cement</th>
<th>Air content [%]</th>
<th>Compressive strength [MPa]</th>
<th>Frost resistance-75cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7 days</td>
<td>28 days</td>
</tr>
<tr>
<td>CEM II/B-V</td>
<td>Ref 2.05</td>
<td>25.0</td>
<td>59.3</td>
</tr>
<tr>
<td></td>
<td>AEC 4.86</td>
<td>18.5</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Tab. 5 Air void microstructure characteristics in hardened concrete according to PN-EN 480-11

<table>
<thead>
<tr>
<th>Concrete made of cement</th>
<th>A [%]</th>
<th>α [1/mm]</th>
<th>L [mm]</th>
<th>A_{300} [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II/B-V</td>
<td>Ref 2.05</td>
<td>51.8</td>
<td>0.134</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>AEC 4.90</td>
<td>44.1</td>
<td>0.115</td>
<td>2.67</td>
</tr>
</tbody>
</table>

L - air voids spacing factor in hardened concrete
A - total air content in hardened concrete
A_{300} - the content of air voids smaller then 0.3 mm in hardened concrete
α - specific surface of air voids
Figure 2 Digital image analysis of concrete aeration. Concrete made of: reference CEM II/B-V on the left, AEC on the right.

Figure 3 Air void size distribution in hardened concrete. Concrete made of: reference CEM II/B-V on the left, AEC on the right.

According to the table 5, total air content 4.86% in air entraining concrete sample met standard requirements for hardened concrete [15]. It can be observed on figure 3, air void distribution in air entraining concrete specimen is significantly better compared to no air entraining concrete sample. Significantly increase of small air bubbles < 300 µm and regular distribution in the AEC matrix can be observed. According to the table 5 amount of macropore $A_{\text{300}}$ 2.67% is significantly higher than standard requirements value i.e. 1.8% for extreme exposition class XF4 [16]. Air void spacing factor $L$ met also standard requirements for 0.2 mm. That parameters are very important for design and perform frost resistant concrete.

Results given in the table 4 provide fact of decreased compressive strength of air entraining concrete. AEC influencing on mechanical strength of air entraining concrete must be taken into account for concrete class designing.

4. Conclusions
Presented and discussed in the paper properties of air-entraining cements allow to conclude that they meet the requirements according to EN 197-1 for common cements, showing their special properties in air entraining concrete mix.

Introduction of AEA into cement results in a decrease of compressive strength of normative mortar, one class lower compared to no air entraining cement mortar.

According to the results in the paper, air entraining cement (AEC) allows to get established air entraining degree of concrete mix, simultaneously providing required parameters of air void distribution and pore size, which is the condition of producing frost resistant concrete.

Acknowledgements
Research Project realized within Polish National Research and Development Centre No. PBS1/A2/4/2012, i.e. "Innovative air-entraining cements in concrete."

References
[16] Beton-Teil1: Festlegung, Herstellung, Verwendung und Konformitätsnachweis (Regeln zur Umsetzung der ÖNORM EN 206-1)