Impact of Air Entraining Method on the Resistance of Concrete to Internal Cracking

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Abstract. This paper presents the test results of air entrained concrete mixtures made at a constant W/C ratio of 0.44. Three different air entraining agents were used: polymer microspheres, glass microspheres and a conventional air entraining admixture. The aim of this study was to compare the effectiveness of the air entraining methods. Concrete mixture tests were performed for consistency (slump test), density and, in the case of AEA series, air content by pressure method. Hardened concrete tests were performed for compressive strength, water absorption, resistance to chloride ingress, and freeze-thaw durability – resistance to internal cracking tests were conducted in accordance with PN-88/B-06250 on cube specimens and with the modified ASTM C666 A test method on beam specimens; porosity characteristics (A, A₃₀₀, L) were determined to PN-EN 480–11:1998. No significant mass and length changes were recorded for the concrete air entrained with the conventional methods or with polymer microspheres. The results indicate that polymer microspheres are a very good alternative to traditional air entraining methods for concrete, providing effective air entrainment and protection from freezing and thawing. The glass microsphere-based concretes showed insufficient freeze-thaw resistance. The test results indicate that both the conventional methods (AEA) and the air entrainment by polymer microspheres are effective air entraining methods. It has to be noted that in the case of the use of polymer microspheres, a comparable value of L and a very good freeze-thaw resistance can be achieved at a noticeably lower air and micropore contents and at lower strength loss.

1. Introduction
In building practice, achieving a repeatable and stable pore structure with respect to both the total volume of voids and the size of air bubbles may encounter some problems [1]. Adequate air entrainment is problematic due to at least two reasons. First, the spacing factor is not directly dependent on the amount of air-entraining admixture added and second, the critical value of L may vary with the type of concrete used [2].

It is generally accepted that only some of the air voids present in the concrete have an important influence on its freeze-thaw durability. The key parameter allowing a reasonable distinction between the pores that play a role and those that have no influence on freeze-thaw resistance is A₃₀₀ parameter, i.e., the content of pores with diameters up to 300 μm. Larger pores, having no significant effect on the spacing factor, L, or on freeze-thaw resistance only increase the porosity of concrete.
The test results collected from many existing structures such as flyovers, bridges, road pavement lengths, parking lots, or airfield facilities show a number of pore structure and freeze-thaw resistance related irregularities [3][4]. As for the air void system, these were [3]:

- insufficient or excessive air content in the hardened concrete,
- deficient air-bubble distribution: insufficient content of bubbles with diameters below 300 μm, and too many larger bubbles with diameters up to 4 mm,
- incorrect dispersion of air bubbles, described by high values of the pore spacing factor, $L > 0.20$ mm.
- numerous voids of irregular shape, probably forming an interconnected system.

Tests indicate that achieving the required parameters of the air pore microstructure in pavement concretes is difficult if the concrete is to be freeze-thaw resistant. Incorrect pore structures have been reported despite using air entraining agents in compliance with relevant standards [4].

A mix design that satisfies all the requirements is relatively easy to develop in a laboratory. But attaining the required pore structure parameters in the field is not easy at all. Efficacy of air entrainment may vary as a result of a number of factors including the consistency and temperature of the mixture, the mixing time, the haul time, or placement and compaction methods used [1, 5]. Some of the air present in concrete is lost during transport or vibration, with much more substantial air content reductions occurring in pumping (about 1–1.5%). Instability of air pores [6] is due to: floating of large air bubbles, dissolution of air bubbles smaller than 0.10 mm, or air bubble coalescence.

A repeatable and stable structure of pores is even more difficult to achieve in concrete made with various mineral additives (fly ash, blast furnace slag, silica fume) used in combination with two or three chemical admixtures (e.g., superplasticizers, air entraining agents, retarders).

Air entraining agents are often ineffective in providing adequate pore structure in high fluidity concrete. The use of a superplasticizer will increase air bubble size leading to larger distances between them [7]. Substantial destabilisation of the air void system (represented by a significant increase in the spacing factor) can occur without a visible change in air content [8-10].

The pore structure stability-related problems can be eliminated by using dimensionally stable particles of a given diameters, the so-called microspheres. Uniformly dispersed in concrete, microspheres provide the air pores with adequate and time-independent dimensions. This innovative solution eliminates the basic challenges associated with the coalescence and size variability of air bubbles. Various types of microspheres made of a variety of materials (polymer, fly ash, glass, ceramic) and with different diameters are currently available on the market.

The high effectiveness of the polymer microsphere-based method was confirmed through the study of air entrainment of concrete conducted by the authors of this paper [11]. The test results indicate that the use of polymer microspheres provides freeze-thaw protection at the air content considerably lower than that of concrete air entrained using conventional methods (AEA). In a separate study by the same authors [12], fly ash microspheres with diameters up to 300 μm produced noticeably worse results compared with polymer microspheres of 40 μm or 80 μm. The effect of each microsphere type was directly related to their size.

The purpose of the study discussed in this paper was to compare the effectiveness of air entrainment by conventional air entraining agents, polymer microspheres and by glass microspheres.
2. Materials and Methods
The tests were carried out on three air entrained concretes with W/C=0.44. Three different air entraining agents (AE) were used: polymer microspheres, glass microspheres and a conventional air entraining admixture. The tests aimed at comparing the efficacy of these methods.

The concretes were made up of the following ingredients:

- Portland cement CEM I 42,5 R (C),
- natural sand 0-2 mm (S),
- coarse aggregate – amphibolite 2-8, 8-16 mm (48:52%) (A),
- polymer microspheres D=40µm (MSP) – series C1,
- glass microspheres D=40µm (MSG) – series C2,
- air-entraining agent (AEA) – series C3,
- plasticizer (PL).

Table 1 compiles the compositions and properties of the concretes. Concrete mixture tests were performed for consistency (slump test), density (ρb) and, in the case of series C3, air content by pressure method (AC).

Hardened concrete tests were performed for compressive strength ($f'_cm$), water absorption ($n_w$), resistance to chloride ingress (Q), and freeze-thaw durability – resistance to internal cracking tests were conducted in accordance with PN-88/B-06250 [13] on cube specimens and with the modified ASTM C666 A test method on beam specimens; porosity characteristics ($A$, $A_{300}$, $L$) were determined to PN-EN 480–11:1998 [14].

The specimens were cured in water for seven days and then allowed to air-dry for 21 days. The strength and absorption were tested on 10x10x10 cm concrete cubes. The compressive strength of concrete was determined to PN-EN 12390-3:2011 [15] and water absorption to the Polish standard, PN-88/B-06250. The ASTM 1202-12 Rapid Chloride Permeability Test (RCPT) [16] was used to measure chloride ions ingress into the concrete.

The test for the resistance to internal cracking F150 was performed by direct freezing and thawing of cube specimens, using the normal method in accordance with PN-88/B-06250. The specimens were saturated in water for 7 days and then subjected to cyclic freezing at $-18±2°C$ for 4 hours and thawing at $+18±2°C$ for 4 hours. A total of 150 freeze-thaw cycles were performed. The reference specimens for compressive strength tests were stored in water at a temperature of $+18±2°C$ throughout the freeze-thaw resistance testing. The tests included visual evaluation of the cubes, measurements of their mass and determination of the relative compressive strength loss $∆R$ at the end of the final thawing period. Concrete is regarded as resistant to freezing and thawing if the loss in mass is 5% or less and the loss in compressive strength is 20% or less.

The resistance of concrete specimens to rapidly repeated cycles of freezing and thawing was determined in accordance with the modified ASTM C666 A method on 80x80x340 mm concrete beams. After a 28-day curing period, the specimens were immersed in water for seven days and then stored in water-filled metal containers. The specimens were subjected to 300 freeze-thaw cycles.

Polished sections were prepared as described in PN-EN 480-11:1998. The same standard was used as the basis for determining air void characteristics from the cumulative length of chord intercepts. The
setup (Photograph 1) comprising a stereoscopic microscope, a CCD camera and a measuring table was used for automatic image analysis.

**Table 1.** Composition and properties of concrete mixtures

| Series | W/C | C kg/m³ | S kg/m³ | A kg/m³ | PL % m.c. | AE % m.c. | AC % | ρb kg/m³ |
|--------|-----|---------|---------|---------|-----------|-----------|------|----------|
| C1     | 0.44| 353     | 621     | 1382    | 0.89      | 0.50      | -    | 2512     |
| C2     | 0.44| 366     | 606     | 1348    | 0.79      | 0.63      | -    | 2482     |
| C3     | 0.43| 351     | 594     | 1323    | 0.54      | 0.10      | 7.0  | 2422     |

Figure 1. The setup for air pore structure testing

### 3. Results and discussions

Table 2 summarizes the results obtained for the hardened concrete. The compressive strength range was from 65.4 to 80.2 MPa, with the lowest strength recorded for the concrete with a conventional air entraining admixture added. Water absorption values were within a 3.82÷4.21% range. The test for the resistance to chloride ingress indicated moderate chloride permeability in the concretes containing polymer and glass microspheres and high permeability in concretes produced with a conventional air entraining admixture.

The spacing factor, $L$, ranged from 0.217 to 0.630 mm. The contents of micropores $A_{300}$ were from 0.29 to 1.80 %, and the total air content, A, from 2.69 to 7.20 %. The pore structure tests indicate that the glass microspheres, which in contrast to polymer microspheres are rigid, failed at the concrete mixture preparation stage. As the polymer microspheres provide very small air bubbles, the requirement of $A_{300} > 1.5\%$ does not need to be met.

Figure 1 shows mass changes of cube specimens after 150 cycles of freezing and thawing. No significant mass changes were recorded for the concrete air entrained with the conventional methods or with polymer microspheres. In the concretes made with glass microspheres, the mass gain of 12 g was observed, which confirms internal damage. Compared with the reference specimens, the compressive strength loss in the specimens subjected to freezing was 2.9% (conventional air entrainment - C3) and 0.4% (polymer microspheres - C1). The strength loss of the specimens that were air entrained by glass
microspheres (C2) was 28.2%, that is, the concrete of those specimens was regarded as non-freeze-thaw resistant.

Figures 2 and 3 summarize the variations in mass and length of the beam specimens after 300 cycles of freezing and thawing. No significant mass and length changes were recorded for the concrete air entrained with the conventional methods or with polymer microspheres. For the specimens with glass microspheres, a considerable mass loss was observed, as was a noticeable extension. Due to substantial defects, the tests on those specimens were ended after 287 cycles.

The test results indicate that both the conventional methods (AEA) and the air entrainment by polymer microspheres are effective air entraining methods. It has to be noted that in the case of the use of polymer microspheres, a comparable value of $L$ and a very good freeze-thaw resistance can be achieved at a noticeably lower air and micropore contents and at lower strength loss.

**Table 2. Test results for hardened concretes**

| Series | $f'_{cm}$ (MPa) | $n_w$ (%) | $dm_{150}$ (g) | $\Delta R_{150}$ (%) | $dm_{300}$ (g) | $dL_{300}$ (mm) | $Q$ (Coulomb) | $A$ (%) | $A_{300}$ (%) | $L$ (mm) |
|-------|----------------|-----------|----------------|---------------------|----------------|----------------|----------------|--------|-------------|---------|
| C1    | 73.0           | 3.82      | -1.25          | 0.4                 | -1.5           | 0.035          | 2791           | 2.99   | 0.76        | 0.217   |
| C2    | 80.2           | 3.96      | 12.0           | 28.2                | -137.5*        | 2.045*         | 3216           | 2.69   | 0.29        | 0.630   |
| C3    | 65.4           | 4.21      | 0.25           | 2.9                 | -8.5           | 0.035          | 4807           | 7.20   | 1.80        | 0.250   |

* after 287 cycles

**Figure 2.** Change in mass of the cube specimens after 150 freeze-thaw cycles
4. Conclusions
The analysis of the test results obtained for the concretes air entrained through three different methods leads to the following conclusions:

- Internal resistance tests conducted on beams and cubes show that glass microspheres used for air entraining of concrete provide no freeze-thaw protection;
- The other two methods, i.e., the use of a conventional air entraining admixture and incorporation of polymer microspheres, are effective concrete air entrainment methods;
- The results indicate that polymer microspheres are a very good alternative to the conventional air entraining of concrete. It has to be emphasized that in the case of the polymer microspheres,
a comparable value of $\bar{L}$ and a very good freeze-thaw resistance can be achieved at a noticeably lower air and micropores content and at lower strength loss.

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