Low Shrinkage Cement Concrete Intended for Airfield Pavements

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Abstract. The work concerns the issue of hardened concrete parameters improvement intended for airfield pavements. Factors which have direct or indirect influence on rheological deformation size were of particular interest. The aim of lab testing was to select concrete mixture ratio which would make hardened concrete less susceptible to influence of basic operating factors. Analyses included two research groups. External and internal factors were selected. They influence parameters of hardened cement concrete by increasing rheological deformations. Research referred to innovative cement concrete intended for airfield pavements. Due to construction operation, the research considered the influence of weather conditions and forced thermal loads intensifying concrete stress. Fresh concrete mixture parameters were tested and basic parameters of hardened concrete were defined (density, absorbability, compression strength, tensile strength). Influence of the following factors on rheological deformation value was also analysed. Based on obtained test results, it has been discovered that innovative concrete, made on the basis of modifier, which changes internal structure of concrete composite, has definitely lower values of rheological deformation. Observed changes of microstructure, in connection with reduced deformation values allowed to reach the conclusion regarding advantageous characteristic features of the newly designed cement concrete. Applying such concrete for airfield construction may contribute to extension of its operation without malfunction and the increase of its general service life.

1. Introduction

Airfield pavement structure is a multilayer arrangement, designed in order to take and transmit loads generated by aircraft traffic. This arrangement is also intended to provide usable functionality within the anticipated operation time. Therefore, concrete parameters used for pavement surfacing construction are of superior influence on life of the whole structure arrangement. Concrete intended for airfield pavement construction, in accordance with [16] requirements, contains up to 5.5% of air. In case of water loss in this material, rheological deformation occurs, as a result of cement and water reaction and they are associated with shrinkage [1, 3-5]. Shrinkage is a derivative of physical and chemical changes occurring in cement slurry microstructure [13]. In terms of airfield pavement, shrinkage phenomenon is particularly dangerous. In favourable circumstances, particularly in the event of failure to observe construction rules, as a result of this type of deformation, concrete slab cracks of pavement surfacing may occur. Such cracks contribute to structure weakening. Concrete stress occurrence is closely associated with independent deformation and change of concrete structure dimensions [12]. As a result of shrinkage, continuous concrete slabs crack and form single piece of
slabs operating as freely supported, on elastic foundation. Slab cracks, and in particular crumbled pieces of concrete composite may also pose a direct threat to air traffic safety. The method of aircraft propulsion makes it possible for small particles to be drawn in, which may result in aircraft damage or immobilization.

2. Nature of concrete pavement shrinkage

According to [2, 6] occurrence of shrinkage is intensified by the increase of cement granularity and contents of soluble alkali. According to [1, 3, 12], two groups of shrinkage deformation can be distinguished and they are caused by irreversible mixture volume decrease (chemical shrinkage) and those caused by drying, i.e. partially irreversible change in mixture capacity (self-activating, plastic and external shrinkage). Issue of concrete service life, in case of airfield pavement exposed to variable weather conditions, is the main reason for increased concrete degradation. This results in shortening the time of operational usefulness of pavement elements within their design use period. With reference to airfield pavements, the term of life refers to pavement fatigue life expressed by means of number of vehicle passages loads which the pavement can cope with until its load capacity wears out. A factor intensifying degradation process is shrinkage deformation which intensifies the scope of stress. In case of airfield pavement concrete, the amount of water can decrease as a result of evaporation or as a result of drawing in water through dry concrete or soil located below. In such a situation, the amount of plastic shrinkage depends on mixture rigidity, temperature, surrounding humidity and wind rate. Due to this fact, selection of innovative concrete composition, distinguished by the reduced shrinkage, may contribute to extending safe structure operation – increasing its life.

3. Purpose and scope of testing

Analysis included the assessment of influence of environmental conditions and the length of curing period on the value of shrinkage deformation. Testing included two batches of concrete of C40/50 class, intended for airfield pavements. The first batch included concrete the composition which complied with standard requirements [16], marked as CC-1, and results obtained in case of this concrete were considered as referential values. The second batch is up-to-date low-shrinkage concrete of modified composition, part of fine aggregate of which (10.8%) was replaced with modifying agent in the form of dust marked as CC-2[10].

The following initial testing of both concrete batches were conducted, during which volume density, absorbability, compression strength, tensile strength and splitting strength, according to guidelines [17-23]. Essential testing specified shrinkage values of cured concrete for 28 days in variable curing conditions.

4. Testing materials

Due to the fact that selection of concrete mixture components has significant influence on the size of shrinkage deformation, coincident initial assumptions for mixtures CC-1 and CC-2 design were assumed. Aggregate composition is decisive in case of shrinkage size. Reactivity of the applied aggregate in comparison to cement slurry influences occurrence of defects in case of contact layer between the aggregate and cement matrix [8]. In case of analysed mixtures, granite grit was assumed (in accordance with requirements [16]) of fraction 2/8mm, 8/16mm and 16/32mm in total amount of 1400kg/m³. Fine aggregate used in mixtures was in accordance with requirements [14] and dozed in the amount of 415 kg/m³ to CC-1 mixture and 370 kg/m³ to CC-2 mixture. In case of CC-2 mixture, modifier was considered in the amount of 45 kg/m³, the composition of which was presented in figure 1. Mixtures CC-1 and CC-2 contain cement CEM I 42.5R (which complies with standard requirements [24, 25]) in the amount of 377 kg/m³, air-supplying agent - 1.7 kg/m³ and flexibilizing admixture in the amount of 0.7 kg/m³.
Figure 1. Phase composition of modifier applied in case of CC-2 concrete

Maximum value of w/c ratio according to standard requirements [16] is 0.4; w/c ratio of the designed mixtures was assumed for 0.37. The lower coefficient value of w/c can be assumed that lower volume of capillary pores, which resulted in decreasing shrinkage. Additional advantage of low w/c ratio is the decrease of porosity in transition zone around aggregate [7].

5. Testing methods

For research purposes, shrinkage was defined as difference of sample length. Basic measurement was sample dimension measured directly after unforming thereof. This length referred to sample length in the course of its drying. Due to close dependence of shrinkage size on weather conditions, diversified thermal and humidity conditions during concrete curing were assumed. Samples stored in normal conditions (lot determined as A) were cured from the moment they were unformed for 28 days, completely immersed in water of temperature 20°C. Samples of B lot were cured from the moment they were unformed for 28 days in temperature 60°C, storing them in a lab dryer. Samples of C lot were cured from the moment they were unformed for 28 days in low temperature of -20°C, storing them in a climatic chamber. Every time, the analysis included 6 concrete samples, accordingly of lot CC-1 and CC-2 stored in the same environmental conditions. Such assumptions during this research stage enabled to omit influence of variable humidity on the size of shrinkage deformation and at the same time enabled to assess the influence of modifier applied to CC-2 mixture composition on the size of shrinkage deformation. In order to determine single shrinkage of CC-1 and CC-2 concrete lots A, B and C 6 samples were used, in accordance with guidelines requirements [16], in the form of beams of cross section 150x150x600mm. Changes of sample length in the course of their drying were measured by means of measuring instrument of reading capacity of more than 0.005mm. Directly after removing each sample from a mould, locating distance \( l_0 \) was determined. Socket extensometer and benchmarks stuck by means of quick-drying glue to the sample surface were used. Deformation increase was determined within the period from the 1\(^{st}\) till 28\(^{th}\) day of unforming. Assumed frequency of measurement performance included determination every 2 days for the period between the 1\(^{st}\) and the 10\(^{th}\) day, every 4 days for the period between the 7\(^{th}\) and 28\(^{th}\) day and every 10 days for the period between the 28\(^{th}\) day and 88\(^{th}\) day. Assumed research procedure complies with instruction [26]. In case of each analysed sample, after specified time, shrinkage deformation was determined \( \varepsilon_s \), according to (1) formula, in which \( d_o \) initial-basic distance (directly after unforming) between measuring points and \( d_t \) is distance determined after anticipated drying time:

\[
\varepsilon_s = \frac{d_o - d_t}{d_o}
\]

Selected CC-1 and CC-2 concrete samples stored in water for 28 days were intended for microscopic observation on scanning electron microscope. Samples preparation and interpretation of obtained results were in compliance with those described in subject literature [2, 6]. Recent fracture
was prepared from CC-1 and CC-2 concrete which were covered with carbon layer approx. 10nm thick. Preparation surface subject to observations by means of scanning electron microscope was not less than 1.0cm², and the scope of magnifying power was assumed between 200x to 100000x [9, 14].

6. Results and Discussions
Compression strength test results of tested concrete after 28 and 56 days of curing in optimum humidity conditions and temperature 20°C proved that concrete CC-2 is of significantly higher strength - table 1.

| Sample                  | Compressive strength, [MPa] | Sample                  | Compressive strength, [MPa] |
|------------------------|-----------------------------|-------------------------|-----------------------------|
| (A) CC-1 after 28 days | 56.3 57.0 57.6              | (A) CC-2 after 28 days  | 58.8 59.4 59.8              |
| CC-1 after 56 days     | 58.7 59.2 59.9              | CC-2 after 56 days      | 63.4 63.7 63.9              |

Application of additive in CC-2 is significant in terms of concrete resistance to decreased and increased temperatures, in comparison to normal temperature - table 2. Particularly advantageous influence was discovered in case of increased temperature effect on concrete. Reasons for such concrete response should be searched in modifier characteristics and parameters.

| Sample / temperature | Tensile strength, [MPa] | Sample / temperature | Tensile strength, [MPa] |
|----------------------|-------------------------|----------------------|-------------------------|
| (B) CC-1 / +60°C     | 4.6 4.9 5.0             | (C) CC-1 / -20°C     | 4.5 4.8 4.9             |
| (B) CC-2 / +60°C     | 5.6 5.7 5.9             | (C) CC-2 / -20°C     | 5.4 5.5 5.7             |

Concrete CC-2 is distinguished by lower volumetric density, absorbability and abrasibility, in comparison to concrete CC-1. These features are significant and they influence cement concrete life of airfield pavement.

Performed deformation testing proved that CC-1 concrete, cured in water of 20°C temperature is distinguished by deformation after 28 days of 0.042‰, while in case of CC-2 concrete this value does not exceed 0.015‰ (Figure 2a). Phenomenon of deformation increasing is influenced by change of curing conditions (Figure 2b and Figure 2c). Concrete samples CC-1 and CC-2 stored in reduced and raised temperature were distinguished by deformation increase. In case of concrete of CC2 type, cured in temperature of -20°C deformations after 28 days of curing reach 0.028‰ (maximum value was determined at 0.033‰). While, the deformation of concrete of CC-1 type, in case of the analysed period are twice as much and amount to 0.047‰ (with maximum value of 0.077‰). During the process of concrete curing in the increased temperature, in case of CC-1 concrete, deformations of 0.032‰ were determined and twice less in case of CC-2 concrete (0.014‰). It should be emphasised that CC-2 concrete deformations in the event of each discussed case, obtained significantly lower values than in case of CC-1 concrete.
Figure 2. Deformation of concrete CC-1 and CC-2 samples cured in variable environmental conditions: a) temperature 20°C, b) temperature -20°C, c) temperature 60°C.

The development of deformations in case of concrete CC-1 and CC-2 (table 3, figure 3) proved significant diversity. With respect to the modified concrete, in all three research cases, deformations reached much lower values.

Table 3. Increasing shrinkage deformations of CC-1 and CC-2 concrete in various conditions (where: T indicates temperature, t indicates days, εp indicates initial deformation, and εk indicates final deformation)

| T [°C] | t [days] | Concrete CC-1 | Concrete CC-2 |
|-------|---------|---------------|---------------|
|       |         | εp ± εk [‰]  | εk - εp [‰]  | εk - εp [‰]  | εk - εp [‰]  |
| -20   | 0÷28    | 0.0338 ± 0.0465 | 0.0127 | 4.54 x 10^-4 | 0.0183 ± 0.0278 | 0.0095 | 3.39 x 10^-4 |
| 20    | 0÷28    | 0.0012 ± 0.0417 | 0.0405 | 1.47 x 10^-3 | 0.0004 ± 0.0150 | 0.0146 | 5.21 x 10^-4 |
| 60    | 0÷28    | 0.0113 ± 0.0315 | 0.0202 | 7.21 x 10^-4 | 0.0048 ± 0.0139 | 0.0091 | 3.25 x 10^-4 |

Figure 3. Shrinkage deformation of CC-1 and CC-2 concrete cured variable environmental conditions: a) temperature -20°C, b) temperature 20°C, c) temperature 60°C.

Based on scanning electron microscope observation CC-1 concrete (distinguished by definitely larger deformations), is subject to micro cracks relatively easily, especially within the area of aggregate-cement matrix. At aggregate interface, there are plate-like portlandite crystals and fine-grained crystals of C-S-H phase, Figure 4a.
Table 4. Porosity characteristics of CC-1 and CC-2 concrete

| Porosity characteristics                                      | Cement concrete CC-1 | Cement concrete CC-2 |
|---------------------------------------------------------------|-----------------------|-----------------------|
|                                                              | $\bar{x}$  | $s_d$  | $A_d$  | $\bar{x}$  | $s_d$  | $A_d$  |
| total air contents in hardened concrete [%]                   | 2,38  | 0,44  | -0,12  | 3,69  | 0,27  | 0,33  |
| contents of micro pores of diameter lower than 300μm [%]      | 0,68  | 0,23  | 0,76  | 1,42  | 0,06  | 0,41  |
| specific surface of air pores system [mm$^{-1}$]              | 21,58 | 2,40  | -0,37  | 24,88 | 1,10  | -0,30 |
| pores distribution indicator [mm]                             | 0,32  | 0,02  | 0,42  | 0,19  | 0,02  | -0,21 |

Concrete CC-2 preparations do not show micro cracks within the area of aggregate-cement matrix interface. Interface layer of these concrete is composed mainly of fine-fibrous C-S-H, up to 100 nm long. In case of cement matrix of these concrete, we can observe less ettringite crystals, Figure 4b.

Figure 4. Microstructure diversification a) concrete CC-1, b) concrete CC-2 [10]

Figure 5. Influence of total air contents in hardened concrete
Air pores characteristics in CC-1 and CC-2 concrete samples for
Porosity system generated in internal structure of hardened concrete has significant impact on size of shrinkage deformation. In case of concrete CC-2, based on observation carried out by means of Scanning Electron Microscope and evaluation of hardened concrete porosity, it has been discovered that distribution and diameters of occurred air-pores create more advantageous structure. Porosity characteristics, according to PN-EN 480-11:2008 – part.11, in case of CC-1 concrete proved the occurrence of pores of larger diameters, located at larger distances, in terms of CC-2 concrete (table 4, figure 5). This correlated directly with the size of observed shrinkage deformations because large air pores contributed to the increase of observed deformations in case of CC-1 concrete. - Figure 6 ÷ 9.

Figure 6. The impact of total air contents in hardened concrete on the size of rheological deformations of concrete CC-1 and concrete CC-2

Figure 7. The impact of characteristic contents of micro pores of diameter below 300μm on the size of rheological deformations of concrete CC-1 and concrete CC-2

Figure 8. The impact of specific surface of air pores system on the size of rheological deformations of concrete CC-1 and concrete CC-2

Figure 9. The impact of pores distribution indicator on the size of rheological deformations of concrete CC-1 and concrete CC-2
Statistical analysis of the obtained test results proved highly significant (p < 0.000001) correlation between the analysed properties. Pearson correlation coefficients in all cases of concrete CC-1 and CC-2 were higher than 0.9. In case of coefficients of determination, each time their values were higher than 0.8 for concrete CC-2 and higher than 0.9 for concrete CC-1. In case of CC-1 concrete, variability of characteristic "shrinkage deformations" in 81% is explained by the variability of characteristic "pores distribution indicator", in 91% is explained by the variability of characteristic "total air contents in hardened concrete" and "contents of micro pores of diameter below 300μm", in 93% is explained by the variability of characteristic "specific surface of air pores system". In case of CC-2 concrete, variability of characteristic "shrinkage deformations" in 82% is explained by the variability of characteristic "pores distribution indicator", in 85% is explained by the variability of characteristic "contents of micro pores of diameter below 300μm", in 86% is explained by the variability of characteristic "specific surface of air pores system", in 87% is explained by the variability of characteristic "total air contents in hardened concrete".

7. Conclusions

According to conducted testing, less favourable internal CC-1 concrete structure (numerous micro cracks in cement matrix and interface areas, expanded ettringite crystallization) and unfavourable air pores characteristics (large pores located at significant distant from one another) prove lowering of mechanical and physical parameters of this concrete and at the same time increasing susceptibility thereof to shrinkage deformation. Different internal structure of CC-2 concrete is distinguished by small air pores located at average distant of 18-19nm, total porosity contents is at 3.7% level and contents of pores of diameter smaller than 300μm of 1.4%. Internal structure of this concrete is continuous, without visible cracks of cement matrix and within the interface area between matrix and aggregate grains and modifier grains. Developed ettringite crystallization has been observed (length of single crystals does not exceed 100μm) and different structure of C-S-H phase, clearly fine-grained. Microstructure formed, due to modification by means of suggested dust, ensures obtaining concrete of low deformation. In case of concrete cured at temperature of 20°C, CC-2 concrete deformations are almost three-times lower than in case of CC-1 concrete. In case of variable environmental conditions that have an influence on concrete, favourable modifier impact of high temperature variation resistance has been proved. In case of CC-2 concrete curing in lower temperature, deformations are more than 1.5 times lower in comparison to deformations observed in case of CC-1 concrete. CC-2 concrete is distinguished by significantly lower deformation in case of curing in raised temperature with regard to CC-1 concrete. Introducing the modifier to the composition of CC-2 concrete mix will guarantee reducing the shrinkage deformation of concrete cured in temperature 60°C with respect to deformations of CC-1 concrete by 0.0176‰.

Reducing shrinkage deformation of concrete exposed to diversified temperature conditions with the improvement of mechanical and physical parameters of hardened concrete CC-2 proves the opportunity to obtain airfield type concrete of significantly higher durability.

To sum up, obtained lab tests results have shown that applying the suggested modifier to the mixture will contribute to the following:

- favourable changes in hardened concrete microstructure,
- improvement of mechanical, physical and performance parameters of hardened concrete,
- reduction of shrinkage deformation size in variable operation conditions,
- extending lifetime of structures containing the suggested additive.

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