The Influence of Metakaolinite as the Additive on the Extent of Shrinkage Deformations in Case of Cement Concrete Intended for Airfield Pavements

Linek Malgorzata

1 Kielce University of Technology, Tysiąclecia Państwa Polskiego Street 7, 25-314 Kielce, Poland
linekm@tu.kielce.pl

Abstract. The research paper presents the suggestion of using metakaolinite as concrete additive. The assessment of efficiency of using metakaolinite included the influence thereof on the modification of the registered shrinkage deformations. Cement concrete contains cement CEM I 42.5, basalt grit, fine washed aggregate, water and air entraining and plasticizing additive. The influence of the applied metakaolinite on the obtained parameters of concrete mix and hardened concrete was determined. The analyses included concretes curing in standard conditions. Analyses included the assessment of the internal structure of concrete composite in terms of changes of porosity and continuity of contact areas between aggregate grains and cement matrix. Modifications of mechanical and physical parameters and the extent of the registered shrinkage deformations were assessed. Deformation tests were conducted within the period from 1st until 28th day of curing. Reduction of cement quantity and replacement thereof with the suggested metakaolinite allows obtaining the pavement quality concrete of more favourable internal micro structure and distinguished reducing the extent of shrinkage deformations.

1. Introduction

The essence of the sustainable development and the necessity of reducing environmental degradation requires searching for and using construction materials which are eco-friendlier. Attempts were made to use the alternative concrete mix composition materials in form of pozzolan. Metakaolinite was presented as the substitute material of some part of cement volume in the mix intended for airfield pavements. This material, thanks to fragmentation similar to cement granulation, react in water environment with free calcium hydroxide (Ca(OH)₂) producing hydrated calcium silicates (CSH) [1]. The use of metakaolinite in concrete was discussed in the works [2, 3].

Concrete stress occurrence is closely associated with independent deformation and change of concrete structure dimensions [4,5]. Shrinkage is a derivative of physical and chemical changes occurring in cement slurry microstructure [6] 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 [7]. Imposed thermal loads are multiple repeated gas stream impact of high kinetic energy and high temperature onto the pavement [8]. Stream dynamics can cause pavement defects and its intensity is lower together with the distance from the nozzle and within immediate vicinity thereof. During the variable heating and cooling, the range of concrete stress changes. As a result of immediate temperature and humidity changes, shrink deformations can occur, contributing to the occurrence of micro cracks of concrete. [9]

2. Purpose and scope of the research
The main objective of the research was the assessment of the influence of the applied metakaolinite on the change of the registered shrinkage deformations. It was assumed that the shrinkage corresponds to the change of a sample length \((d_0)\) intended for laboratory tests. Figure 1 presents graphic interpretation of the assumed shrinkage symbol.

![Diagram of shrinkage measurement using laboratory sample](image)

**Figure 1.** Diagram of shrinkage measurement using laboratory sample

3. Materials
The scope of laboratory tests with regard to base materials included the analysis of grain size distribution, observation of internal structure and chemical analysis. Cement CEM I 42,5 N-MSR/NA was selected for the research, as the most frequently used material for airfield pavements constructions. As cement substitute (20%) metakaolinite was also used in concrete mix. In case of these materials, analogical scope of laboratory tests was conducted. The remaining components of concrete mix (coarse aggregate, fine aggregate, water and admixtures) were selected in accordance with the requirements of the applicable standard [10] and remained unchanged, regardless of the dozed modifier. The applied metakaolinite of grain-size distribution of 200μm is aluminosilicate containing silicon oxide (IV) and aluminium oxide, as well as trace amounts of iron, magnesium, calcium, sodium, potassium or titanium oxides. Figure 2 presents the detailed screening curve of the applied metakaolinite in comparison to the cement.

![Screening curve of the analysed cement and metakaolinite with the grain size distribution function](image)

**Figure 2.** Screening curve of the analysed cement and metakaolinite with the grain size distribution function
4. Methodology and test results
The experiment assumed to perform two series of concrete. The first series was reference concrete (series R), in accordance with the requirements of [10]. The second series included concrete with partial cement substitute in the form of metakaolinite (series M). The composite included the following basic materials: natural sand fraction 0/2 mm, basalt chippings fraction 2/8 mm and 8/16 mm, admixture reducing the amount of water, aerating admixture, pipeline water which complies with requirements of [11] maintaining water-cement ratio at 0.4 – in accordance with the requirements of [10]. Aggregate grading composition of mix series R and M was selected according to the guidelines of [10] taking into consideration limit curves of good grain size distribution (Figure 3).

![Figure 3. Designed aggregate mixture curve, together with limit curves (lower and upper)](image)

The purpose of the research was the evaluation of influence of the selected modifiers on the change of hardened concrete parameters over time. Prepared concrete mix of series R and M after concrete pouring (cubic forms 150x150x150 mm, samples 150x300mm and 150x150x600mm, in accordance with the standard [12]) was subject to standard curing [13] for the assumed research periods (28 days). Hardened concretes were used in destructive testing, their volumetric density was specified according to [14], their ultimate compressive strength according to [15], tensile splitting strength [16] and blending strength according to [17].

Quantity selection of the components (table 1) was based on experimental methods maintaining the consistency of reference mix at S1 level and taking into consideration the exposure class XF4, with the air amount between 4.5-5.5%. Mineral additives in the form of metakaolinite was used in the amount of 20%, as partial cement substitutes.

| Components       | R [kg/m³] | M [kg/m³] |
|------------------|-----------|-----------|
| Cement           | 370.00    | 296.00    |
| Mineral additives| -         | 74.00     |
| Aggregate 0/2mm  | 597.00    | 597.00    |
| Aggregate 2/8mm  | 861.00    | 861.00    |
| Aggregate 8/16mm | 751.00    | 751.00    |
| Water            | 148.00    | 148.00    |
| Plasticizer      | 2.59      | 2.59      |
| Aerating agent   | 1.66      | 1.66      |
During scientific research, the amount of the required samples was determined using student’s T-distribution assuming the significance level of 0.05. The minimum essential number of samples ranged between 4 and 5, depending on the type of the conducted test. In case of such assumptions, 6 samples were selected, which, each time, were intended for the laboratory tests. It was assumed that defining the influence of the applied metakaolinite on the change of extension of shrinkage deformations will take place in case of two series. Each time, 6 samples of concrete R and M stored in the same environmental conditions were subject to the analysis.

Samples maintained in standard conditions [13] were cured from the moment of disbanding until the 28th day completely immersed in water of 20°C. Defining the shrinkage included deformation measurement every day according to strictly described procedure. Research procedure included weighing and defining the dimension of a sample, and then the shrinkage was determined. Identical storage conditions of samples of R and M series helped to avoid the influence of variable humidity on the extent of shrinkage deformations. At the same time, they enabled the assessment of the influence of metakaolinite used in M mix composition on the extent of shrinkage deformations. Shrinkage of concrete of R and M series was determined using 6 beam samples (of dimensions 150x150x600mm in accordance with [12, 18]).

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. 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 $d_0$ 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 1st till 28th day of unforming. Assumed frequency of measurement performance included determination every 2 days for the period between the 1st and the 10th day, every 4 days for the period between the 7th and 28th day. Assumed research procedure complies with [18]. In case of each analysed sample, after specified time, shrinkage deformation was determined $\varepsilon_s$ according to (1) formula, in which $d_0$ initial-basic distance (directly after unforming) between measuring points and $d_t$ is distance determined after anticipated drying time:

$$\varepsilon_s = \frac{d_0 - d_t}{d_0}$$

4.1. Evaluation of the influence of metakaolinite on concrete mix parameters

In order to evaluate the influence of selected modifiers on the change of concrete mix parameters the tests were conducted including the following: (table 2): mix density using cylinder of 8 dm$^3$ capacity according to [19], consistency using concrete slump method according to [20], air contents using manometer method according to [21].

Pursuant to the obtained laboratory test results, it was proved that the suggested mineral additives are distinguished by finer grading than cement. This feature influenced the increase of density of modified mix by 23kg/m$^3$ with respect to the reference mix. Increased density of mix ensures more tight cement matrix. Consequently, it may contribute to the increased resistance of the hardened cement concrete to aggressive environmental factors. The observed influence of the applied metakaolinite on parameters of concrete mix is also similar in case of the application in basalt aggregate, which was presented in [22].

The concerning phenomenon resulting from the application of modifiers is the reduction of air contents in the fresh mix, which may be reflected in the decreased frost resistance of hardened concrete.
Table 2. Results of the basic concrete mix parameters

| Mix parameters   | R     | M     |
|------------------|-------|-------|
| Density          | kg/m³ | 2260  | 2283  |
| Consistency      | mm    | 30    | 0     |
| Air contents     | %     | 5.5   | 3.0   |

4.2. The evaluation of influence of metakaolinite on the selected physical and mechanical parameters of hardened concrete

Based on the obtained laboratory test results, concrete types containing metakaolinite were of slightly higher volumetric density (Figure 4).

![Figure 4](image)

**Figure 4.** Average hardened concrete density of series R and M during diversified curing periods

Obtained results of average compressive strength, in the event of using metakaolinite additives, prove their positive impact on the examined parameter. It should be noticed that all of the designed concrete types achieved the design class C30/37. Using metakaolinite in the mix composition influences the maintenance of the obtained concrete class. It should be mentioned that it was equivalent to reducing cement contents at the same time.

![Figure 5](image)

**Figure 5.** Average compressive strength of hardened concrete types of series R and M after the assumed curing periods (7 and 28 days)

Series of concrete types R and M were subject to the analysis of the influence of applied metakaolinite on average tensile splitting strength. The test was conducted using samples curing in standard conditions for 7 and 28 days.
Figure 6. Average tensile splitting strength (a) and average bending strength (b) during fracturing of hardened concrete types of R and M series after 14 and 28 days of standard curing.

According to the obtained laboratory test results, it was proved that replacing 20% of cement with metakaolinite influences the maintenance of the analyzed feature at a comparable level.

4.3. The assessment of influence of the applied metakaolinite on the extent of shrinkage deformations

In case of all analyzed cases, clearly lower values of shrinkage deformations for concrete of M series were registered (Figure 7, Figure 8 and Figure 9). In case of reference concrete, deformations ranged between 0.064‰, whereas in case of concrete of M series, they ranged from 0.042‰.

Figure 7. Deformations of concrete R samples cured in variable time

Figure 8. Deformations of concrete M samples cured in variable time

According to the obtained results from the shrinkage deformations analysis it was proved that metakaolinite used in the composition of M concrete has significant impact on the extent of reduced shrinkage (Table 3). Performed deformation testing proved that R-1 concrete is distinguished by deformation after 28 days of 0.030‰, R-2 concrete is distinguished by deformation of 0.024‰, R-3
concrete is distinguished by deformation of 0.064‰, R-4 concrete is distinguished by deformation of 0.049‰, R-5 concrete is distinguished by deformation of 0.052‰ and R-6 concrete is distinguished by deformation of 0.038‰. Average deformations of R concrete after 28 days are 0.0428‰. While in case of M concrete this value does not exceed 0.031‰ (Figure 9). Performed deformation testing proved that M-1 concrete is distinguished by deformation after 28 days of 0.024‰, M-2 concrete is distinguished by deformation of 0.019‰, M-3 concrete is distinguished by deformation of 0.043‰, M-4 concrete is distinguished by deformation of 0.035‰, M-5 concrete is distinguished by deformation of 0.039‰ and M-6 concrete is distinguished by deformation of 0.027‰.

Table 3. Increasing shrinkage deformations of R and M concrete in various series (where: t indicates days, $\varepsilon_p$ indicates initial deformation [%], and $\varepsilon_k$ indicates final deformation [%]).

| sample | t [days] | Concrete R $\frac{\varepsilon_k - \varepsilon_p}{t}$ | Concrete M $\frac{\varepsilon_k - \varepsilon_p}{t}$ |
|--------|---------|--------------------------------|--------------------------------|
| 1      | 28      | 0.001 ÷ 0.030  1.04×10^{-3}  | 0.005 ÷ 0.024  9.28×10^{-4}  |
| 2      | 28      | 0.002 ÷ 0.024  7.86×10^{-4}  | 0.004 ÷ 0.019  7.50×10^{-4}  |
| 3      | 28      | 0.019 ÷ 0.064  1.61×10^{-3}  | 0.012 ÷ 0.042  1.07×10^{-3}  |
| 4      | 28      | 0.012 ÷ 0.049  1.32×10^{-3}  | 0.008 ÷ 0.035  9.64×10^{-4}  |
| 5      | 28      | 0.011 ÷ 0.052  1.46×10^{-3}  | 0.001 ÷ 0.039  1.36×10^{-3}  |
| 6      | 28      | 0.008 ÷ 0.038  1.07×10^{-3}  | 0.004 ÷ 0.027  8.21×10^{-4}  |

![Figure 9. Average deformations of R and M concrete cured in variable time](image)

Changes in the internal structure of cement composite with metakaolinite were determined with respect to the reference concrete. The positive impact of metakaolinite is based on sealing internal structure, and consequently on increasing the resistance to the influence of harmful external factors. However, increasing metakaolinite content in mix composition influences reduction of concrete porosity, which was proved in the presented laboratory tests and may adversely affect concrete durability. For only the distribution of air pores of small diameters located not far from one another provide frost resistant concrete. The metakaolinite changes air pores structure in concrete and concrete mortar which is reflected in significant increase of resistance to water and external factors.

5. Conclusions

According to the analysis of the obtained laboratory test results it was proved that the applied cement substitute in the form of metakaolinite of grain-size distribution of 200μm provides:
- airfield cement concrete distinguished by the physical and mechanical parameters comparable to reference concrete, with cement reduction by 20%,
- airfield cement concrete distinguished by the increased resistance to shrinkage deformations, which is reflected in smaller deformations registered in case of M series concrete. The observed average deformation for this type of concrete is 0.31‰ after 28 days and is lower than in R concrete (0.428‰).

References
[1] D. Małaszkiewicz, "Metakaolinite as puzzolan-type additive to concrete – expertise review", Construction Industry and Environmental Engineering, vol. 6, pp. 81-94, 2015.
[2] J. Konkol, G. Prokopski, Optymalizacja składu betonów z dodatkiem metakaolinitu, Journal of civil engineering, environment and architecture, t. XXXIII, vol. 63 (4/16), 2016, p. 297-304.
[3] J. Konkol, G. Prokopski, The influence of the age of concretes with FBC fly ash or metakaolinite additives on their strength properties, Road and Bridges, vol. 13, 2014, p. 49-67.
[4] M. Bacharz, W. Raczkiewicz: Impact of selected environment conditions on the shrinkage strains in respect to standard recommendations, IOP Materials Science and Engineering, vol. 471, (2018).
[5] A. M. Neville, Properties of concrete (in Polish), Stowarzyszenie Producentów Cementu, Cracow, 2012.
[6] W. Piasta, H. Sikora, Absorption, water permeability, strength and deformation of concrete aerated (in Polish), VII Conference Dni Betonu, Wisła, pp. 939-948, 2012.
[7] M. Linek: Low Shrinkage Cement Concrete Intended for Airfield Pavements, IOP Materials Science and Engineering, vol. 245 (2017) 032032 doi:10.1088/1757-899X/245/3/032032.
[8] P. Nita, Concrete surface airport. Theory and structural dimensioning (in Polish), Publishing Air Force Institute of Technology, 2005.
[9] M. Linek: Low-shrink airfield cement concrete with respect to thermal resistance, MATEC Web of Conferences, vol. 133, 07002 (2017), doi: 10.1051/matecconf/201713307002.
[10] NO 17-A204:2015 Airfield concrete pavements - Requirements and test methods for cement concrete pavements.
[11] PN-EN 1008:2004 Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete.
[12] PN-EN 12390-1:2013 Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds.
[13] PN-EN 12390-2:2011 Testing hardened concrete - Part 2: Making and curing specimens for strength tests.
[14] PN-EN 12390-7:2011 Testing hardened concrete - Part 7: Density of hardened concrete.
[15] PN-EN 12390-3:2011 Testing hardened concrete - Part 3: Compressive strenght of test specimens.
[16] PN-EN 12390-6:2011 Testing hardened concrete - Part 6: Tensile splitting strength of test specimens.
[17] PN-EN 12390-5:2011 Testing hardened concrete - Part 5: Flexural strength of test specimens.
[18] ITB Instruction No 194/98: Study of mechanical properties of concrete on samples taken in the forms (in Polish), Building Research Institute, Warsaw, 1998.
[19] PN-EN 12350-6:2011 Testing fresh concrete. Part 6: Density.
[20] PN-EN 12350-2:2011 Testing fresh concrete. Part 2: Testing the consistency with the cone fall method.
[21] PN-EN 12350-7:2011 Testing fresh concrete. Part 7: Air content - Pressure methods.
[22] M. Linek, P. Nita, P. Wolka, W. Żebrowski: Application of natural mineral additives in construction, IOP Earth and Environmental Science, vol. 95, (2017) 022006 doi:10.1088/1755-1315/95/2/022006.