Influence of concrete additives on cement paste shrinkage

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Abstract. The paper deals with the analysis of the effect of chosen latent hydraulic additives on concrete drying shrinkage. Variant dosage of latent hydraulic additives in cement paste was examined. Measuring of shrinkage in time was accompanied by testing of compressive strength and tensile strength at the age 28 days and 280 days. Results of investigations are summarized and compared.

1. Introduction
Shrinkage is a property of concrete, which fundamentally affects the long-term behaviour of concrete structures. Shrinkage and creep form a pair of rheological properties of concrete causing volume changes. Shrinkage affects the deflections of structures, the development of cracks and the durability of structures. In large prestressed structures, the shrinkage leads to significant losses in prestressing force. In certain types of structures – as retention tanks, waterproofing concrete basements, so called white tank systems, in which the maximum crack width limit governs the structural design, shrinkage crucially affects proportioning of reinforcement. The growing trend to use concrete additives with latent hydraulic properties has become incentive of the research focused on latent hydraulic additives.

2. Experimental work
The project investigated influence of chosen latent hydraulic additives – silica fume, metakaolin and fly ash on shrinkage. The shrinkage was examined on cement paste specimens 40 x 40 x 160 mm. Three reference specimens are from cement paste. Three sets differ in latent hydraulic additive content. The substitution of cement with the additive was 20 % and 50 %. Additionally to testing of shrinkage, the compressive tests and flexural tests were performed; first measuring of strengths was at the age of 28 days and the closing measuring of strength was performed after termination of shrinkage testing at the age 280 days.

2.1. Composition of mixes
The intention was to base the mixture design on the same water – binder ratio. Calculation of the water – binder ratio used the approach with a $k$-value correction according to relation (1) [1].

$$\omega_0 = \frac{w_a}{c_a + k \cdot a}$$  \hspace{1cm} (1)

where

- $\omega_0$ is water – cement ratio
- $w_a$ is water content [kg/m$^3$]
- $c_a$ is cement content [kg/m$^3$]
\[ a \] is content of additive \([\text{kg/m}^3]\)

Originally, the k-value approach was derived for the design of concrete mixture and it assumes limitation of the additive content \([2], [3]\). In the research project, the replacement of cement was higher than the given additives limit.

The high silica fume content lead to pure workability of the mixture. In the silica fume samples with replacement of 20% of cement, the lower workability did not impair the quality of specimens. But in samples with 50% of silica fume, the low water content made impossible proper compaction and the elaborated specimens (figure 1) could not be used for testing and new specimens had to be prepared. The correction k-value was increased to \(k = 2.4\).

![Figure 1](image_url). Defect sample with high replacement of cement by silica fume and low water – binder ratio.

Mixture compositions of cement pastes and labelling of mixes are summarised in a table 1.

| Component          | REF | ME-20 | ME-50 | P-20 | P-50 | MI-20 | MI-50 |
|--------------------|-----|-------|-------|------|------|-------|-------|
| Cement CEM I 42.5  | 1375| 1118  | 874   | 1164 | 946  | 1030  | 736   |
| Metakaolin         | -   | 223.6 | 437   | -    | -    | -     | -     |
| Fly ash            | -   | -     | -     | 232  | 472  | -     | -     |
| Silica fume        | -   | -     | -     | -    | -    | 206   | 369   |
| Water              | 550 | 537   | 524   | 503  | 454  | 577   | 649   |
| Aggregate type     | -   | -     | -     | -    | -    | -     | -     |
| Superplasticizer   | -   | -     | -     | -    | -    | -     | -     |
| Water/binder ratio | 0.4 | 0.4   | 0.4   | 0.4  | 0.4  | 0.4   | 0.4   |
| k-value            | -   | 1     | 1     | 0.4  | 0.4  | 2     | 2.4   |

2.2. Elaboration of specimens
The manufacturing of cement pastes started with mixing of dry components – cement and additive, after 30 seconds, water was added. Total mixing time was two and half minutes. Compaction of cement pastes was performed on a vibrating table. After filling the moulds, the specimens were covered by stretch foil and stored in laboratory environment until the next day; after 24 hours, the specimens were demoulded.

Shrinkage measurement pins were inserted in the mould (figure 2 and 3). During demoulding of the first specimens the anchorage length of measuring pins appeared short and they were pulled out of the specimens. So that the anchor bolts had to be elongated, sufficient anchorage length was 20 mm.
2.3. Measuring of shrinkage

The investigations focused in decrease of volume due to drying, so that during time when water which was not used for hydrating of cement is evaporated. Autogenous shrinkage, which causes decrease of volume due to chemical processes in first hours after mixing, is not covered by the research.

The first value of length was measured 24 hours after demoulding, the total time of recording the drying shrinkage was 280 days. The specimens were stored at the same place in the laboratory throughout the entire measurement. The samples were exposed to the environment of the laboratory where the temperature ranged between 22 °C and 28 °C. The relative humidity ranged from 33% to 49% and the absolute humidity was about 8-13 g/m³. These values have been regularly monitored and their history is displayed in figures 4 and 5.

![Air temperature of the environment](image4.png)

**Figure 4.** Air temperature of the environment.

![Relative humidity of the laboratory environment](image5.png)

**Figure 5.** Relative humidity of the laboratory environment.
Table 2. Measurement frequency.

| Age of specimens | frequency of measuring |
|------------------|------------------------|
| 1 to 16 days     | every day              |
| 17 to 28 days    | 3 times a week         |
| 29 to 58 days    | 2 times a week         |
| 59 to 118 days   | 2 times in a month     |
| 119 to 280 days  | every month            |

The measuring itself was carried out using a digital indicator. Data were measured to the nearest thousandth of a millimetre. Three prisms were elaborated for each mixture, and three values were recorded for each measurement. Hence, the resulting shrinkage value is an average of nine records. The measurement was divided into several periods, in which the frequency of measuring decreased in relation with deceleration of shrinkage – see table 2.

3. Results of shrinkage measurements
The results of measurements are arranged in graphs depicting time dependence of shrinkage in micrometres per meter run. The graphs (figure 6 to 10) compare:
- samples with same type and different amount of additive,
- samples with different additive type and same % of cement replacement.

**Figure 6.** Drying shrinkage – fly ash.
Figure 7. Drying shrinkage – metakaolin.

Figure 8. Drying shrinkage – silica fume.
Figure 9. Drying shrinkage – 20 % of cement replaced by additives.

Figure 10. Drying shrinkage – 50 % of cement replaced by additives.
3.1. Results of strength testing
Strength testing was performed according to standard recommendations [4], [5]. Results are depicted in a form of column diagrams (figure 11).

3.1.1. Compressive strength

Comparison of compressive strength at 28 days and at 280 days show that shrinkage of cement pastes, i.e. concrete without aggregates, significantly reduces compressive strength.

This research demonstrated favourable effect of 50% replacement by metakaolin and fly ash on long term increase of compressive strength. For both additives the 28 days strength was lower than strength of reference sample. At the age of 280 days, the situation inversed and the samples with additives had strength by 25 % higher. Sample ME-20 (20% replacement by metakaolin) has almost the same strength as reference sample, thus the higher cost of additive does not provide any benefit.

In contrary, replacement of cement by lower dose of silica fume and fly ash had adversely affected terminal compressive strength. In case of pastes with silica fume, the reason of lower strength is obviously higher shrinkage. Extremely low strength of samples MI-50 (50% replacement by silica fume) is caused also by increasing of water/binder ratio, which was proposed to enable satisfactory workability without application of plasticiser.

![Figure 11. Comparison of compressive strength.](image)

![Figure 12. Comparison of flexural strength.](image)
3.1.2. Flexural strength
The prism specimens with dimension 40/40/160 mm were tested in a three-point bending test with arrangement according to set-up given in [6].

Results display anticipated relation of shrinkage and flexural strength (figure 12). Non-standard results obtained for MI-50 sample (50% replacement by silica fume) can be explained by sinking of the steel rollers into the excessively cracked specimen during the test.

4. Comments
Concerning shrinkage, the values measured in the research project are higher than values for common and high-performance concretes. The main reason is absence of the aggregate. Another factor contributing to the increased drying shrinkage is the low humidity of the lab environment, where the average relative humidity was around 42%. However, in our case, it is important that all samples had the same conditions and relations of different cement pastes shrinkage are therefore relevant.

The research approves previous studies about reduction of shrinkage by addition of fly ash. The record of shrinkage rises gently, and the peak is far below other additives. The graphs clearly show that at 90 days the volume changes reached 90% of the ultimate value. In can be concluded that fly ash decreases shrinkage, what positively affects compressive and tensile strength.

Metakaolin manifests the fastest initial increase in shrinkage compared to other additives. Nevertheless, the total shrinkage of samples ME-50 (50 % replacement by metakaolin) is still at an acceptable level.

From the results follow, that curing in the first 7–8 days would prevent the initial increase and thus effectively reduce the total shrinkage.

The graph comparing all additives indicates that replacing cement with 20% metakaolin to decrease shrinkage is not prosperous, as the shrinkage relation of ME-20 is almost identical with reference sample. However, for higher amount of metakaolin, the curve of shrinkage dependence moves towards more favourable values.

For metakaolin and fly ash, it can be concluded that increase of the additive leads to decrease of total drying shrinkage.

In contrast, influence of silica fume on volume changes is negative. The layout of the MI-20 shrinkage was in principle expected. The volume changes of the sample MI-50 was abnormal. The peak value of shrinkage was reached after 48 days, when a breakpoint came and according to measurements, the sample started swelling. It probably relates to high increase of internal stresses during initial 48 days, when progressive cracking led to disintegration of the specimen. Shrinkage measurement of one of the MI-50 was prematurely terminated because of damage of the specimen by the self-weight. The other specimen crumbled before testing of strength. Moreover, the tensile strength 0.69 MPa determined at one of the MI-50 specimens demonstrates high degree of drying.

Substitution of cement by silica fume shall be limited. Pastes with higher silica fume content have lower compressive strength, what is caused by high drying shrinkage.

The compressive strength is related to density; the lower is the density of the material, the lower is the compressive strength.

Low content of metakaolin and fly ash (20% replacement) did not retarded initial compressive strength compared to reference sample. Flexural strengths are generally higher at age 280 days than tensile strength at the age of 28 days with the exception of silica fume.

5. Conclusions
The research deals with shrinkage of concrete with various latent hydraulic admixtures. Three types of admixtures were tested – fly ash, metakaolin and silica fume. In the initial phase of the project shrinkage of pastes was measured to reveal the tendencies and basic principles.
The research confirms findings of previous studies that fly ash reduces shrinkage. With increasing fly ash content, the shrinkage decreases, what at the same positively affected compressive and tensile strength.

Replacing cement with 20% metakaolin to decrease shrinkage is not prosperous. The effect of metakaolin on shrinkage manifested at higher dosage of this admixture.

For replacement of cement by silica fume, it is recommended to limit the substitution by 20%. Higher dosage of silica fume leads to excessive drying shrinkage.

The paper presents result of the initial investigations of drying shrinkage of cement pastes with partial substitution of cement by admixtures with latent hydraulic properties. Future research will focus in shrinkage of concretes with aggregate and numerical analysis of drying shrinkage and verification of models for drying shrinkage (e.g. model B4).

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References

[1] Härdtl R 2010 The K-Value Concept Applied for GGBFS - Principles and Experiences, International RILEM Conference on Material Science 2010, ISBN: 978-2-35158-110-0, e-ISBN: 978-2-35158-111-7, pp 189 – 198.
[2] ČSN EN 206+A1 2017 Concrete - Specification, performance, production and conformity. ÚNMZ, Prague
[3] ČSN EN 197-1 2012 Cement – Part 1: Composition, specifications and conformity criteria for common cements. ed. 2. ÚNMZ, Praha,
[4] ČSN EN 12390-3 2009 Testing hardened concrete – Part 3: Compressive strength of test specimens. ÚNMZ, Praha.,
[5] ČSN EN 12390-5 2009 Testing hardened concrete – Part 5: Flexural strength of test specimens. ÚNMZ, Praha.,
[6] ČSN EN 1015-11+A1. Methods of Test for Mortar for Masonry-Part 11-Determination of Flexural and Compressive Strength of Hardened Mortar.
[7] Bažant Z P and Baweja S 2000 Creep and shrinkage prediction model for analysis ad design of concrete structures: Model B3, ACI Special publication creep and shrinkage of concrete, A. Al-Manaseer, Editor,
[8] Bažant Z P et al. 2015 RILEM draft recommendation: TC-242-MDC multi-decade creep and shrinkage of concrete: material model and structural analysis. Model B4 for creep, drying shrinkage and autogenous shrinkage of normal and high-strength concretes with multi-decade applicability. Materials and structures 48 (2015).