Utilization of continuous hydrostatic weighing for monitoring of volume changes

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Abstract. This paper deals with the problematics of utilization of continuous hydrostatic weighing to monitor the volume changes in research of new building materials. The aim of this paper is to describe the abilities of continuous hydrostatic weighing and to present the capabilities and results of measurements made using this method. The volume changes in this paper were measured using the laboratory scales connected to computer. The volume changes were studied on the cement-based composites containing up to 40 wt.% of cement substitution by secondary raw material. The high temperature fly ash, packing glass, foundry sand and slag were used as the cement substitution. This research shows that the continuous hydrostatic weighing produces results comparable to other methods for volume change measuring. Therefore, this method can be used for volume change monitoring without using any economically demanding laboratory equipment.

1. Introduction
The volume changes of cementitious composites, mortars, screeds and concrete are very known throughout the years. The cracking of cementitious mortars and concretes in the early stages of hydration are something, that concerns scientists as well as the public audience, because these sorts of failures are often visible by naked eye. Not at first of course, but the microcracks which are developed in the early stages of curing can become a bigger problem, because these cracks open and expose the structure of the matrix of building material. [1, 2] And therefore, they contribute to the reducing of the resistance of the material against exposure conditions. These microcracks which can occur in the very early stages of hydration can lead to structural problems and theoretically even to the collapse of construction. [3] The knowledge of the size of shrinkage or expansion of used building material is crucial for some applications. The volume changes can be reduced or increased by many additives and admixtures. The current aim of development is mainly to reduce the ecological and economical demands of the production of building materials. This can be achieved using secondary raw materials to substitute cement. Substitution of cement is effectively used in blended cements, which consists of clinker and other components. In last few years, many studies try to find use for waste materials and utilize them in building materials. Many products from power plants are being used for such purpose. This paper studies the effect of addition of some other types of secondary raw materials on the volume changes of cementitious mortar, for example furnace slag from power plant, foundry sand with soluble glass or finely ground waste glass. [4, 5]
2. Materials and Methods
In this experiment, the early volume changes of cementitious mortar were studied using the continuous hydrostatic weighing. Laboratory scales connected to the computer with application to log the data from scales were used.

Raw materials
For this study, the following raw materials were used: Portland cement 42.5 R from Českomoravský cement, a.s. - Závod Radotín and various siliceous filler (sand) with the size distribution of 0.00–4.00 mm and ground limestone. The mix contained polypropylene fibers and admixtures (PCE plasticizer). As secondary raw materials the following materials were used. Furnace slag from non-functioning coal thermal power plant Oslavany (SSL), foundry sand containing soluble glass from ArcelorMittal Ostrava (SCSG), waste glass from Vetropack Moravia Glass (Glass) and high-temperature fly ash from coal power plant Tušimice (HFA).

The high-temperature fly ash and finely ground waste glass were used as a substitution of cement in rate of 20, 40 and 60 wt.%. The furnace slag and foundry sand were used as a substitution of filler in rate 100 wt.%. 

Pre-treatment of secondary raw materials
The secondary raw materials had to be pre-treated by crushing, milling and/or sieving. The furnace slag (SSL) was pre-treated by crushing and sieving to a fraction of 0.5–4.0 mm to substitute completely coarse aggregate in reference mixture. The foundry sand (SCSG) which was delivered in large hardened stones with diameter up to 30 cm had to be crushed and then sieved to separate the sand from iron. The SCSG was used to substitute the fine aggregate with fraction of 0.0–0.5 mm. The used waste glass was be pre-treated by milling to substitute primary binder, cement, which had specific surface of around 400 m²·kg⁻¹ (± 50 m²·kg⁻¹). HFA was also pre-treated by milling to achieve the corresponding specific surface of cement. For the pre-treatment of secondary raw materials, the jaw-crusher and laboratory ball grinder were used to achieve the corresponding fractions of aggregate and specific surfaces. In the table 1, the fraction distribution of secondary raw materials used for the substitution of cement (HFA and Glass) are shown.

|                | <0.01 mm | 0.01-0.063 mm | >0.063 mm |
|----------------|----------|---------------|-----------|
| HFA            | 28.84    | 63.35         | 7.87      |
| Glass          | 30.71    | 53.12         | 16.18     |

Mixing
Every mix-design containing cement in combination with SSL, SCSG, Glass, HFA, sand, limestone, PP fibres and dry PCE plasticizer was pre-mixed in laboratory four-speed mixer for 1 minute. Then the mixing water was added, and the mixture was then mixed for additional 3 minutes. At the end of each mixing period, the testing samples were cast, and two 1 kg fresh mortar samples were also poured into specialized PP bags which could be heat-sealed. These samples were then used for the measurement of autonomous volume changes by continuous hydrostatic weighing. The water/binder ratio was changed for each mixture correspondingly to achieve the same plasticity of fresh mortar (tested on flow table in accordance with CSN EN 1015-3). In the table 2, the mixing ratios are shown. [6, 7]
As shown in the table 2, the Glass and HFA were used to substitute the binder, in this case cement by 40 wt.%. The SCSG and SSL were pre-treated to fully substitute either coarse or fine aggregate in the reference mixture. For the purposes of study, several combinations of binder and filler substitutions were tested.

**Volume changes test procedure**

The volume changes of test samples were assessed by the continuous hydrostatic weighing. The principle is shown in the figure 1 [9].

![Illustration of hydrostatic weighing of test samples.](image)

For the volume changes measurements, the RADWAG laboratory scales were used. These scales have automatic calibration in every two hours, which had to be disabled by the manufacturer to enable continuous measurement for days. Under these scales, large tank with water was prepared. Before the measurement, each test sample was weighed dry and the weight was registered. Each test sample was then attached to the bottom of the laboratory scales by a thin string and submerged in water to begin the measurement.

Each test sample was created by the usage of specialized kitchen type of bags for storing food, while vacuuming the excess air and heat-sealing the bag. After mixing of mortar, around 1 kg of fresh mixture was poured into the bag, vacuumed and heat sealed on two, to three places to ensure proper seal. Immediately after this procedure the bag was dry weighed and then hanged below the scales and submerged in water. Every test sample was then tested for 32 hours. The measurement data were transferred from scales into computer program and then evaluated and processed to show the corresponding volume changes.
Thanks to the vacuuming of the air bubbles trapped inside and around the mixture, ideally all the volume changes that occur in the material, are the volume changes caused by chemical reactions and hydration. And, since the bag is sealed, the samples cannot dry out.

3. Results and discussion
The shrinkage of cementitious composites during the early stages of hydration is caused by the chemical processes which are the cause of hardening of concrete/mortar etc. In this study, eight series of measurements were performed to demonstrate how the proposed technique using the laboratory scales connected to a computer can be used in assessing the value of volume change in the early stages of hydration. This method can be used even for longer measurements of the autogenous shrinkage, since the test sample is trapped inside a closed PP bag, which does not let any moisture in or out and therefore the test sample does not change its weight, only its volume.

In the figure 2 the raw measurement data of volume changes of the test samples are shown.

![Figure 2](image.png)

The volume changes were measured by the hydrostatic weighing and compared with volume changes measured by other methods to assess its usability in research. For every mix-design, 3 samples were used. The reference test samples were tested using the above method of continuous hydrostatic weighing and compared to test results using the shrinkage cone method according to the ASTM C827/C827M-16, with the exception, that the mixture in the cone was covered by plastic sheet to prevent drying of the test sample.

The volume changes measured by the hydrostatic weighing are represented as shrinkage percent. The value of shrinkage, for example, of the HFA test sample in the figure 2 was -0.34% after the 32 hours of curing. Since the percentage can be also written as the length change, this value can be also expressed as -3.4 mm/m. The volume changes of all test samples were recorded for 32 hours since mixing.

All recorded volume changes are summarized in the table 3, presented as the mm/m values to correspond with the results from other researches.
Table 3. Volume changes of tested samples [mm/m].

|                | Volume change [mm/m] |
|----------------|----------------------|
| Reference      | -3.6                 |
| Glass          | -3.9                 |
| HFA            | -3.4                 |
| SCSG           | -3.6                 |
| SSL            | -4.0                 |
| SCSG, SSL, HFA| -4.5                 |
| SCSG, HFA      | -3.6                 |
| SCSG, Glass    | -4.0                 |

As shown in the table 3, the test results show, that the addition of any secondary raw material, both as the substitution of binder or filler lead to increase in shrinkage in the first 32 hours of curing, except for the HFA test sample containing 40 wt.% substitution of cement by high temperature fly ash. This corresponds with the results of Guangcheng et. al. (2006). In their research the effect of substitution of cement by silica fume, pulverized fly ash and furnace slag was tested. The results show, the substitution of cement by pulverized ash lead to a small increase in shrinkage, almost comparable to the reference, but the substitution by furnace slag lead to greater shrinkage. [5]

In the figure 3 the relation between the w/b ratio and the shrinkage of the tested samples.

![Figure 3](image-url)

In the figure 3, it is shown the w/b ratio affects the value of autogenous shrinkage of the tested samples. However, the relation is not linear for every type of tested secondary raw material and waste. The relation is not so direct when the HFA and SCSG was used.

4. Conclusion

Results presented in this paper show, that the proposed technique of measuring of volume changes by the continuous hydrostatic weighing is suitable for cementitious materials and is fully capable of measuring of the autogenous volume changes when the mixture is vacuumed and heat-sealed in PP bags. The presented technique does not require any highly sophisticated measuring devices and the measurements can be done by using only the standard laboratory equipment. The laboratory scales with resolution of at least two decimal places (0.00 gram) and ability to connect and transfer the measurement data to computer.

In this paper, the effect of substitution of binder and/or filler in cementitious mortar by the secondary raw materials and wastes on the volume changes in the early phases of curing was tested. The results show that any substitution of binder or filler in the mixture by the tested secondary
raw materials and wastes lead to the increase of shrinkage in the early stages of curing. Only the substitution by the high temperature fly ash can lead to lower shrinkage in the early stages of curing. The results also show that there is some relation between the w/b ratio and the amount of shrinkage. The relation is linear when using the SSL and Glass, but nonlinear when using the SCSG or HFA.

The above problematics will be investigated in further research.

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