Drying Shrinkage Deformation Comparison Between Foam Concrete, Geopolymer Concrete, Disintegrated, and Non-disintegrated Cement Mortar

R Gailitis\textsuperscript{1}, A Sprince\textsuperscript{1}, L Pakrastins\textsuperscript{1}, G Sahmenko\textsuperscript{1} and T Kozlovskis\textsuperscript{1}

\textsuperscript{1} Faculty of Civil Engineering, Riga Technical University, 1 Kalku Street, LV-1658, Riga, Latvia.

E-mail: rihrads.gailitis@edu.rtu.lv

Abstract. Foamed concrete has been known as a building material for nearly 100 years. In the beginning, it was used as an insulation material with very low density. Since then there have been attempts to make this material more load-bearing and structural. In present-day foamed concrete is being used in soil reinforcement, building blocks and in other sorts of building applications [1]. Another innovative material - the geopolymer concrete has been around only for 40 years. It is being used in buildings and infrastructures such as railroads, reservoirs, and houses and others. The main benefit of the geopolymer is that it is green material that is partially made by utilizing waste products. The geopolymer manufacturing carbon footprint is 2 times less than the Portland cement carbon footprint. Another way to reduce Portland cement carbon footprint is to reuse old cement. In the past few decades, there has been a considerable amount of researches regarding the partial replacement of cement using disintegrated cement in cement mortar or concrete. As it is known to obtain powder mineral filler material planetary ball milling is applied, but it is ineffective. It has been discovered that grinding by collision is a more effective method for refining brittle material. One of the ways to refine is to disintegrate with disintegrator. This raises the question of whether old cement disintegration together with sand can improve its long-term properties and what differences do these different cement and alkaline activated compounds have. The aim of this article is to determine the difference of shrinkage deformation for foamed concrete and disintegrated cement mortar which is Portland cement based cement composites and geopolymer concrete which represents alkali-activated cement composites. The size of all shrinkage specimens was 46mm in the diameter and 190mm in height. The shrinkage deformations of the specimen were determined by consistently measuring specimen deformation displacement. Shrinkage deformation values for foamed concrete in the 81st day did reach 11.85mm *10\textsuperscript{-2}, disintegrated old cement mortar 4.88mm *10\textsuperscript{-2}, non-disintegrated new cement mortar 5.02mm *10\textsuperscript{-2}, non-disintegrated old cement mortar 4.33mm *10\textsuperscript{-2}, but for geopolymer concrete, on the 81st day, it was 3.73mm *10\textsuperscript{-2}.

1. Introduction

One of the dominant technologies in mining industries for the production of minerals and in material treatment is grinding by the ball mills. However, grinding by collision is a more effective method for refining brittle material and one of the few machines that do collision grinding is disintegrator. The grindability of different hardness mineral materials using milling by collision in disintegrator does not differ in particle size after multiple milling stages while the materials with higher hardness have shown a decrease in the mean particle size after one step milling about 20\% [2].
Foamed concrete is a cellular cementitious material obtained by introducing foam in the cement matrix. This process gains development of air voids within the specimen microstructure, and thus contributes to obtaining properties such as low self-weight, thermal insulating characteristics, acoustic absorption, increased fire resistance and better workability. It also reduces the strength of the material [3,4]. Conventionally foamed concrete has a density of 280-1800 kg/m³. The density of the cellular (foamed) concrete can be controlled by adding a calculated amount of proper foam into the slurry of water and cement, with and without the addition of aggregate. Foam stability is one of the most important factors for foamed concrete. Unstable foam can cause segregation and uneven density through the material. However, it is relatively difficult to control foam stability because it is affected by many aspects such as foam agent, foam achieving technology, water/cement ratio, and others [4–8]. However, foamed concrete also shows disadvantages, such as low strength, high drying shrinkage, and water absorption. It has been determined that there is a close relationship between the pore structure of foamed concrete and the properties of foamed concrete such as strength, water absorption and drying shrinkage [9].

Another novel material is geopolymer. Geopolymer belongs to a group of novel three-dimensional inorganic materials. This novel material got multiple beneficial properties such as low density, low cost, environmentally friendly nature, and high mechanical performance [10]. As a composite material geopolymer concrete is two or more constituent material arrangement. A continuously called matrix and the dispersed phase or phases, either fibers or particulates, in order to develop another material with the desired combination of properties [11].

Geopolymer is comparable in performance to ordinary Portland cement [12]. Geopolymer concrete main advantage is its contribution to the environment. It is estimated that carbon footprint made by geopolymer concrete manufacturing is 26 to 46% less than Portland cement concrete if in concrete mix Portland cement is replaced completely [11,12]. It is reckoned that production of 1 ton of caolin geopolymer contributes to 0.180 tons of CO₂, that is 6 times less than the manufacturing of Portland cement concrete [13].

According to statistics the restrained tensile stress rather than imposed load is the main factor in introducing cracking in concrete structures, especially throughout the construction period. The volume of concrete continues to decrease after hardening without external load; this phenomenon is called shrinkage. The shrinkage stresses are caused by restrained effect produced by reinforcement in order to maintain compatibility of concrete and reinforcement strains along with the self-balanced equilibrium conditions. According to capillary tension theory, the main driving force of concrete shrinkage is the capillary pressure in the concrete pore walls when water is absorbed in the pores. The capillary pressure will vary as the pore structure changes, which results in different shrinkage characteristics of the concrete [14,15].

In contrast to Portland cement concrete, that shrinks primarily due to negative capillary pressure that leads to a volume contraction of the cement paste during water loss, the shrinkage of geopolymer occurs not only due to water loss over time during reaction and evaporation but also because the pore structure depends on several critical factors, such as alkaline activator, water content, binder materials, and curing condition. The pores in geopolymer are generated during reaction, mainly from small disordered zeolites, which makes it fundamental to understand the correlation between mix design parameters and pore structure as part of the mechanism of geopolymer shrinkage behavior [16]. However, there are also drawbacks in the metakaolin-based geopolymers. The high specific surface area of the platy metakaolin particles leads to excessive mixing water demand and high yield stress. Moreover, the high water/binder ratio will have an apparent deleterious effect on the pore structure, durability, and efflorescence of the geopolymer products. On the other hand, fly ash is made from spherical particles that could work as a “ball bearing” and reduce the viscosity of the paste, therefore improving particle packing to refine pore structure of the binder [17].

In terms of sustainable raw material management, it is crucial to recycle industrial waste as much as possible and also to develop new technologies that not only reduce industrial waste landfills but also produce materials with new added value [18].
This study shows how does shrinkage affect materials due to their microstructure that is achieved with different binders and different fillers.

2. Material and methods
Foam concrete mix was produced in Warmhouse Ltd. industrial turbulence mixer with the effect of cavitation. The foamed concrete mix was prepared according to the composition shown in Table 1.

Table 1. Foamed concrete mix.

| Ingredients                        | Units    | Mass proportion |
|------------------------------------|----------|-----------------|
| Cement CEM I 42.5N                | kg/m³    | 1.0000          |
| Quartz sand 0/0.5mm                | kg/m³    | 1.2500          |
| Foam agent (Tukums) mixed together with 0.35l H₂O | kg/m³    | 0.0044          |
| PP fibers                          | kg/m³    | 0.0013          |
| Micro silica Elkem 971 U           | kg/m³    | 0.0333          |
| Water                              | kg/m³    | 0.3333          |
| Plastificator Stachema             | kg/m³    | 0.0129          |
| W/C                                | -        | 0.3333          |

Cement mortar mixes were produced in laboratory planetary mixer Hobart, using fine-graded mineral aggregate (quartz sand) and specially prepared white (Aalborg) cement. Mortars with disintegrated and non-disintegrated cement were prepared according to the composition shown in Table 2.

Table 2. Disintegrated and non-disintegrated cement mortar mix.

| Ingredients                        | Units    | Mass proportion |
|------------------------------------|----------|-----------------|
| Cement CEM I 42.5N                | kg/m³    | 1.0000          |
| Quartz sand 0.4/1mm                | kg/m³    | 1.7500          |
| Quartz sand 0/0.5mm                | kg/m³    | 1.2000          |
| Water                              | kg/m³    | 0.5000          |
| Plastificator Stachema             | kg/m³    | 0.0040          |
| W/C                                | -        | 0.5000          |

Cement amount in the composition is the same for mortars with old (stored in a laboratory for 10 years) and fresh Aalborg cement. In figure 1 is shown how different is the fresh and old cement.

Figure 1. Fresh and old cement.

Dry cement and sand mixes are prepared using disintegrator DESI-16C in order to recover cement binding properties. Sand and old cement were disintegrated together in disintegrator for 5 minutes as it is shown in figure 2 and figure 3.
Figure 2. Disintegration process.

Figure 3. Disintegrated and non-disintegrated old cement with sand.

Geopolymer cylindrical specimen matrix was based on fly ash sourced from the local power plant in Skawina city (Poland). This kind of fly ash is suitable for geopolymers because of its physical properties and chemical composition. The fly ash contains spherical aluminosilicate particles as well as it is rich with oxides such as SiO$_2$ (47.81%), Al$_2$O$_3$ (22.80%). The high value of SiO$_2$ and Al$_2$O$_3$ gives advantages for geopolymerization.

Geopolymer specimens were prepared using sodium promoter, fly ash, sand (ratio sand and fly ash – 1:1). The process of activation has been made by 12M NaOH solution combined with the sodium silicate solution (at a ratio of 1:2.5). In order to make the composite the technical NaOH in flakes was used and water solution of sodium silicate R–145. Tap water was used instead of the distilled one. The alkaline solution was prepared by means of pouring the aqueous solution of sodium silicate and water over solid sodium hydroxide. The solution was mixed and left thru the night until its temperature is stabilized and the concentrations equalized. The fly ash, sand, and alkaline solution were mixed for about 15 minutes by using a low-speed mixing machine (to receive the homogenous paste). Next, the mix was poured into the plastic molds. The specimens were hand-formed and then the air bubbles were removed with vibrations. Molds were heated in the laboratory dryer for 24h at 75 °C. Then, the specimens were unmolded [19,20].

All prepared specimens had the following dimensions: Ø 46 x 190 mm.

For shrinkage deformation tests, 6 aluminum plates (10 x 15 mm) were glued to each specimen in pairs. Afterward, strain gauges were attached to those plates.

Shrinkage deformations were monitored for the first two weeks every day, afterward every two days.

Figure 4. Prepared shrinkage test specimens.
3. Results and discussion

Figure 5. Test sample shrinkage deformations.

From figure 5 it appears that foamed concrete is the most exposed compound to shrinkage deformations. In contrast, the disintegrated and non-disintegrated compounds show relatively significant deformations in the first two weeks, but afterward, the deformation change is relatively small. Geopolymer concrete, in contrast, shows a constant increase throughout the testing time.

Because of the different relative humidity levels thru the specimen testing graphs in figure 6 show the shrinkage deformations in context with the factor that causes them – the change of the relative humidity (delta value that represents the change of the relative humidity throughout the test).

Figure 6. Disintegrated non-disintegrated cement mortar, geopolymer and foamed concrete test sample shrinkage deformations with relative humidity.
From figure 6 it can be deduced that all the tested compounds have got similar shrinkage deformation reaction time to the change of relative humidity level. The average response in shrinkage deformations from drop or increase to changes in relative humidity level is 1.5 days.

Due to the previous statement regarding the link between relative humidity and shrinkage, it is necessary to get a factor that would represent material willingness to shrink. So, by dividing shrinkage deformation with relative humidity variation in time (delta) the shrinkage deformation factor is achieved.

**Figure 7.** Disintegrated non-disintegrated cement mortar, geopolymer, and foamed concrete test sample shrinkage deformation factor.

From figure 7, it appears that the most affected compound is the foamed concrete that is followed by the disintegrated and non-disintegrated compounds and the most resistant is geopolymer.

**Figure 8.** Disintegrated non-disintegrated cement mortar, geopolymer and foamed concrete test sample shrinkage deformations with relative humidity.
Relative humidity delta value that is shown in figure 6 and figure 8 is the relative humidity value that throughout the test differs from the relative humidity value that was at the beginning of the test. The relative humidity level at the beginning of the tests for disintegrated and non-disintegrated cement mortars was 17.9%, for geopolymer 29.0% and for foamed concrete it was 46.0%. Using these values the relative humidity delta value is calculated using equation (1):

\[ RH_{\Delta} = RH_{t=0} - RH_{t=n} \] (1)

where:
- \( RH_{\Delta} \) – relative humidity delta value;
- \( RH_{t=0} \) – relative humidity at the beginning of the test;
- \( RH_{t=n} \) – relative humidity value \( n \) days after the test began.

To determine the effect of the humidity level change on to shrinkage factor change figure 8 was made.

The shrinkage deformation factor is calculated by dividing shrinkage deformation with relative humidity delta value. Every single shrinkage deformation reading is divided with relevant humidity delta value.

From the deformation factor graphs, it appears that geopolymer is the most resistant to the moisture level variations from all the tested compounds. The most affected seem to be foamed concrete and the disintegrated and non-disintegrated cement compounds.

4. Conclusions

Regarding shrinkage, the most sensitive from the tested compounds was foamed concrete. Much more resistant to shrinkage is regular cement mortar and disintegrated cement mortar. The lowest shrinkage shows geopolymer concrete. The shrinkage deformations for disintegrated old cement mortar is 23%, non-disintegrated new cement mortar 25%, non-disintegrated old cement mortar 15% and foamed concrete 68% greater than geopolymer concrete.

From figure 8 it is also determined that geopolymer concrete is less likely to gain or lose shrinkage deformations due to rapid increases or decreases of relative humidity in the environment. In this case, foamed concrete shows the higher possibility to gain or lose deformation due to change in humidity gains or lose in the environment.

This means that if all the tested compounds are used as a structural material then there is a bigger possibility for foamed concrete to develop cracks in structure due to variations in relative humidity levels in an environment that could lead to loss of its structural properties. These conclusions also mean that due to higher sensitivity to humidity changes, especially, rapid ones, it is recommended to somehow shield foamed concrete structures from direct moisture interactions that could lead to high structure saturation with water.

Acknowledgments

This work has been supported by the Latvian Council of Science within the scope of the project ‘Long term properties of innovative cement composites in various stress-strain conditions’ No. lzp-2018/2-0249.

References

[1] Mugahed Amran Y H, Farzadnia N and Abang Ali A A 2015 Properties and applications of foamed concrete; a review. Construction and Building Materials 101, pp 990-1005
[2] Goljandin D, Kulu P, Käerdi H, Bruwier A. Disintegrator as device for milling of mineral ores. Material Science 11, pp 398-402
[3] Falliano D, De Domenico D, Ricciardi G, Gugliandolo E 2019 Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. Construction and building materials 198, pp 479-493
[4] Suleyman Gokce H, Hatungimana D and Ramyar K 2019 Effect of fly ash and silica fume on hardened properties of foam concrete. *Construction and building materials* 194, pp 1-11

[5] Nguyen TT, Bui HH, Ngo TD, Nguyen GD, Kreher MU, Darve F 2019 A micromechanical investigation for the effects of pore size and its distribution on geopolymer foam concrete under uniaxial compression. *Engineering Fracture Mechanics* 209, pp 228-244

[6] Ghorbani S, Ghorbani S, Tao Z, de Brito J, Tavakkolizadeh M. 2019 Effect of magnetized water on foam stability and compressive strength of foam concrete. *Constr Build Mater* 197, pp 280-290

[7] Li T, Wang Z, Zhou T, He Y, Huang F 2019 Preparation and properties of magnesium phosphate cement foam concrete with H2O2 as foaming agent. *Constr Build Mater* 205, pp 566-573

[8] Vatin NI, Barabanshchikov YG, Komarinskii M V., Smirnov SI. 2015 Modification of the cast concrete mixture by air-entraining agents. *Magazine of Civil Engineering* 56, pp 1-10

[9] Sun C, Zhu Y, Guo J, Zhang Y, Sun G 2018 Effects of foaming agent type on the workability, drying shrinkage, frost resistance and pore distribution of foamed concrete. *Constr Build Mater* 186, pp 833-839

[10] Yan S, He P, Jia D, Wang J, Duan X, Yang Z, et al. 2017 Effects of high-temperature heat treatment on the microstructure and mechanical performance of hybrid Cr-SiC-(AL2O3) reinforced geopolymer composites. *Composites Part B* 114, pp 289-298

[11] Lokuge W, Wilson A, Gunasekara C, Law DW, Setunge S 2018 Design of fly ash geopolymer concrete mix proportions using multivariate adaptive regression spline model. *Constr Build Mater* 166, 472-481

[12] Luna-Galiano Y, Leiva C, Villegas R, Arroyo F, Vilches L and Fernández-Pereira 2018 Carbon fiber waste incorporation in blast furnace slag geopolymer composites. *Materials Letters* 233, pp 1-3

[13] Nguyen KT, Le TA and Lee K 2018 Evaluation of the mechanical properties of sand-based geopolymer concrete and the corrosion of embedded steel bar. *Constr Build Mater* 169, pp 462-472

[14] Huang L, Hua J, Kang M, Zhou F and Luo Q 2019 Capillary tension theory for predicting shrinkage of concrete restrained by reinforcement bar in early age. *Constr Build Mater* 210, pp 63-70

[15] Baleviu R, Augonis M, Bistrickait R and Diliūnas S 2018 Shrinkage effect on Cracking Resistance of Flexural Reinforced Concrete Members. *Mechanica* 24, pp 11-18

[16] Ling Y, Wang K and Fu C 2019 Shrinkage behavior of fly ash based geopolymer paste with and without shrinkage reducing admixture. *Cement and Concrete Composites* 98, pp 74-82.

[17] Yang T, Zhu H and Zhang Z 2017 Influence of fly ash on the pore structure and shrinkage characteristics of metakaolin-based geopolymer pastes and mortars. *Constr Build Mater* 153, pp 284-293.

[18] Mucsi G, Szenczi Á and Nagy S 2018 Fiber reinforced geopolymer from synergetic utilization of fly ash and waste tire. *Journal of Cleaner Production* 178, pp 429-440

[19] Korniejenko K 2018 Geopolymers for increasing durability for marine infrastructure. American Concrete Institute, ACI Special Publication, Vol. 2018-June, Issue SP 326, pp 20.1-20-10

[20] Łach M, Mikula J and Hebda M 2016 Thermal analysis of the by-products of waste combustion. *Journal of Thermal Analysis and Calorimetry* 125, pp 1035-1045