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Effect of siliceous sand volume fraction on the properties of alkali-activated slag mortars

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Effect of siliceous sand volume fraction on the properties of alkali-activated slag mortars

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Abstract. One of the critical factors affecting the performance of alkali-activated slag (AAS) is the nature and dose of alkali activator. The activator type can play a significant role during the transition from pastes to mortars or concretes. Therefore, three basic sodium activators (water glass, carbonate, and hydroxide) of the same molarity of 4M Na^+ were used to prepare AAS-based mortars with different volume fractions of siliceous sand. These were compared by means of workability, mechanical strength, and long-term shrinkage under autogenous conditions. The results were compared to those obtained on pastes with similar workability. Increasing the content of the sand tended rather to decrease the mechanical properties, while greatly decreased autogenous shrinkage. Nevertheless, the most remarkable differences for different activators were observed when comparing the mortars with pastes. The transition from pastes to mortars resulted in the highest reduction in both compressive and flexural strength for sodium hydroxide. The flexural strength of the mortars with sodium water glass and sodium carbonate even increased considerably in presence of sand.

1. Introduction

The most widely used building material is currently ordinary Portland cement (OPC), although its production is not ideal from an ecological point of view. This is due to the high production of CO_2 (around 8 % worldwide), the energy intensity of the production process [1], and due to the consumption of natural resources. Alkali-activated slag (AAS) can be considered as a possible alternative in specific areas of industry. It is advantageous by means of the resistance to aggressive environments [2, 3], resistance to higher temperatures [2] or appropriate immobilization of some heavy metals [4]. In addition, AAS potentially have low ecological and economic impact, since the used granulated blast furnace slag is a secondary raw material and also alkaline activators based on the secondary raw materials can be used [5].

The main hydration products of AAS are similar to the hydration products of OPC, where a C-S-H gel is formed, whereas the AAS is a C-A-S-H gel. In the C-A-S-H gel, the Si^{4+} ions are partially replaced by the Al^{3+} ions [6-8]. However, the structure of AAS hydration products is strongly influenced by the effect of the alkaline activator used. The most commonly used alkaline activators are alkali-metal hydroxides, alkali metal salts or silicates [7, 9].

However, AAS exhibits properties that have hindered their application in industry so far and which are being further investigated in the laboratory. These include, in particular, the shrinkage of AAS, which is several times higher compared to OPC [10-12].

In addition to the activator composition, both fresh and hardened properties of final products like mortars or concretes are influenced by the aggregate content. This raises the potential issue of an interfacial transition zone (ITZ), which strongly affects the mechanical and transport properties. It arises from a deficit of the reactive slag particles in a proximity to sand particles. San Nicolas and Provis [13] found that this zone is larger with coarse sand than with finer sand, because finer aggregate offers more nucleation sites. It was also associated with higher compressive strength. With respect to the different nature of the reaction products for different activators, differences in ITZ and consequent effect on mechanical properties can be expected.

Based on the above, this work pioneers the transition of AAS pastes to mortars with different activators (sodium waterglass – SWG, sodium carbonate – SC, and sodium hydroxide – SH) by means of mechanical properties and shrinkage. The mix proportioning followed our approach very recently published in [14] and was based on the same molarity of all activators and various paste volume fractions in the resulting mortars. The results were compared to those obtained on pastes, which were already published in our previous study, but in a limited timescale [12].

2. Experimental

2.1. Materials

The granulated blast furnace slag with a BET specific surface area of 1.85 m^2/g, density of 2.88 g/cm^3, and 70% contents of amorphous phase was used. The slag was activated using sodium water glass with a silicate modulus of 1.5 (SWG1.5), sodium hydroxide (SH), and sodium carbonate (SC) solutions with the same molarity of 4 mol Na^+/dm^3. More details on the composition of the raw materials can be found in previous work [12]. In the case of mortars, CEN siliceous sand with a maximum grain size of 2 mm (ČSN EN 196-1) was used.

2.2. Specimen preparation

In this study, the mortars were considered as the diluted paste with different amounts of sand. It means that the slag volume fraction in the paste (V_S/V_P) was kept constant at 0.40, while the volume fractions of the paste in the final mortar (V_P/V_M) of 0.35, 0.45, and 0.60 were used. The weight proportions of the raw materials needed to prepare one liter of a mortars are given in Table 1. The mortars were prepared according to ČSN EN 196-1. The laboratory mixer was used. The total mixing time was four minutes, and preprogrammed cycles with different mixing intensities were chosen. Specimens of 40 × 40 × 160 mm were manufactured and used to determine the mechanical properties and autogenous shrinkage. The demolded specimens were sealed with polyethylene foil and cured at ambient temperature under autogenous conditions. The results obtained for the manufactured mortars will be compared to the selected results obtained for the pastes prepared earlier [12] (slag volume fractions in the range of 0.44 to 0.54).

Table 1. Composition of individual mortars (per litre of mixture).

V_S/V_P	0.40	0.40	0.40
V_P/V_M	0.35	0.45	0.60
Slag (g)	403	519	691
Sand (g)	1 689	1 431	1 041
Sodium hydroxide solution (g)	242	311	414
Sodium water glass solution (g)	266	342	456
Sodium carbonate solution (g)	249	321	428

2.3. Methods
The effect of increasing the content of the sand on consistency by means of the flow table test (ČSN EN 1015-3) was investigated. The spread diameter after lifting the cone and the diameter of the paste after 15 jolts of the table were measured. Compressive and flexural strength were determined after 28 days. Autogenous shrinkage was evaluated using a dilatometer in accordance with ASTM C490.

3. Results and discussion

3.1. Workability
The influence of the volume fraction of sand in the mortar and the type of activator on the workability can be seen in Figure 1. As mentioned in Section 2.2, the different mortars were considered as paste with slag volume fraction of 0.40 diluted with different amounts of sand (by volume). Therefore, the lower the paste content in the resulting mortar (V_P/V_M), the higher the sand content, and the lower the workability. With respect to the wide range of sand addition, very different workability was achieved, ranging from the almost unchanged spread diameter even after 15 jolts for all three activators to very high mortar diameters exceeding the original diameter of the flow table (300 mm). In the case of activation with SC or SH, similar effects on workability in spread diameter values can be observed, for which the increase in V_P/V_M from 0.35 to 0.45 resulted in a relatively low workability improvement, contrasting to a great effect of SWG. The highest spread diameter was achieved in SWG mortars, which is in accordance with other works [15, 16]. These results are related to a plasticizing effect of silicates by means of reducing the yield stress [17].

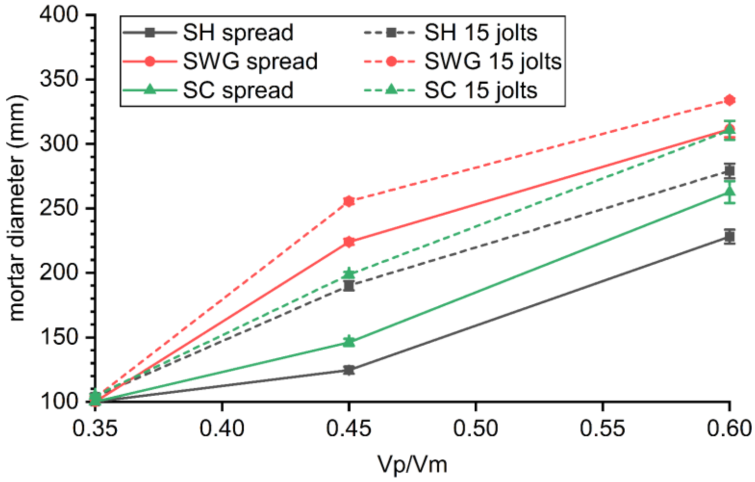

Figure 1. The influence of paste volume fraction on workability.

3.2. Mechanical properties
The influence of the volume fraction of the paste on the flexural strength after 28 days of curing can be seen in Figure 2. These results were compared to those obtained on AAS pastes with a slag volume fraction of 0.52 (green columns), which achieved similar workability after 15 jolts [12]. Distinctively different behavior was observed for different activator type. For the activation with SH the flexural strength decreases with a gradually decreasing slag (paste) content. This is related to the localization of the limited space-filling ability of the reaction products for this kind of activator [6, 18] and therefore poor ITZ. In contrast, when activated with SC and SWG, considerably higher flexural strength was achieved for mortars than for paste. With these activators, a highly refined microstructure is typically achieved [6, 9, 18-20]. Simultaneously, pastes with these activators exhibited severe autogenous shrinkage (see Section 3.3), from which internal stresses and defects originate. The presence of sand reduced shrinkage and likely dissipated the microcracking, and therefore increased flexural strength were achieved. This correlates with a similar effect of replacing the slag with fly ash which reduces the shrinkage, and thus higher flexural strengths can be achieved [10, 21].

Unlike the flexural strength, the compressive strength of the mortars were always lower compared to those of the pastes (Figure 3). However, different degrees of their reductions were observed for different activators. The highest decrease (approximately 66 %) was observed for SH, while compressive strength of SWG and SC decreased only by 15 to 25 % and 27 to 35 %, respectively. These differences are related to the different binding ability of the reaction products, as already mentioned. The lowest compressive strength of pastes and mortars are shown by SH, which is also confirmed by other works [6, 17, 22, 23].

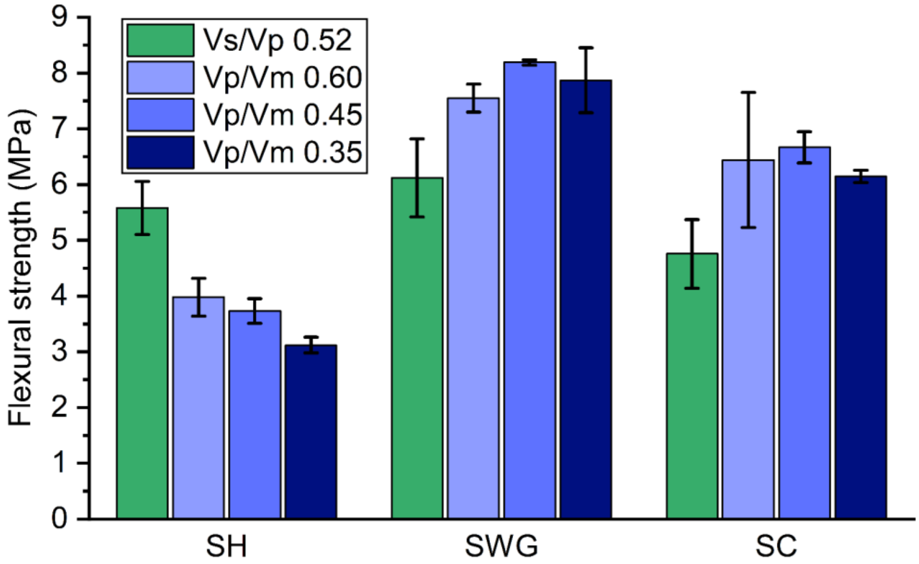

Figure 2. The effect of paste volume fraction on flexural strength after 28 days.

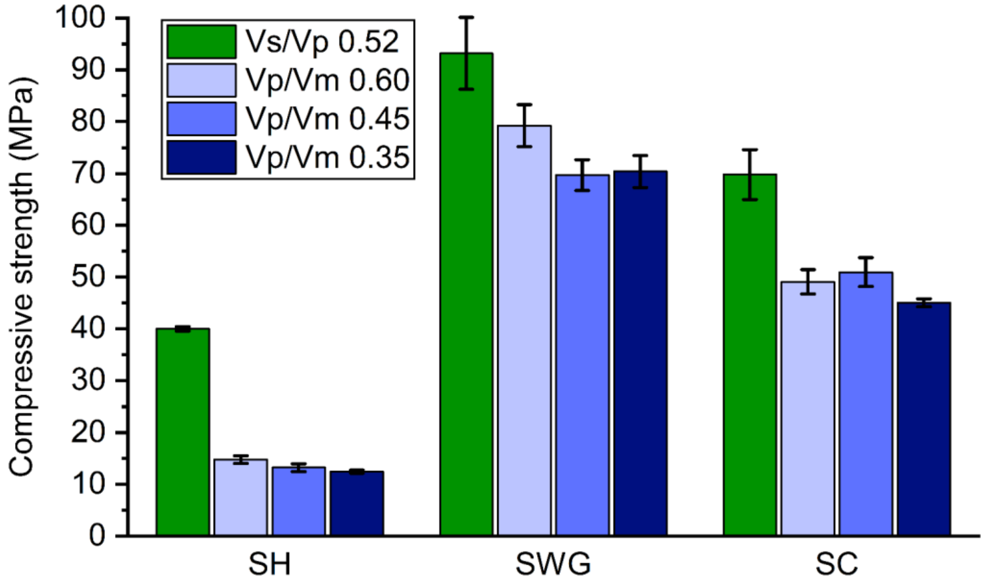

Figure 3. The effect of paste volume fraction on compressive strength after 28 days.

3.3. Autogenous shrinkage

The long-term development of the autogenous shrinkage for SH, SWG, SC pastes and mortars is shown in Figure 4, Figure 5 and Figure 6, respectively. The initial stages (first 28 days) of autogenous shrinkage of the pastes were already discussed in our previous paper [12]. Striking differences in the effect of slag volume fraction in the pastes for different activators were even magnified from the perspective of 180 days as follows. For SH and SC, an increase in the slag volume fraction resulted in an increase in autogenous shrinkage, while opposite trend was observed for SWG.

The autogenous shrinkage of mortars was always lower than that of pastes, but the extent of its reduction depended on the activator type again. For SH, the maximum shrinkage of 0.045 % was reached after 180 days, while for pastes it ranged from 0.20 to 0.43 % for a slag volume fraction of 0.46 and 0.54, respectively. SH pastes and mortars had the lowest autogenous shrinkage compared to their counterparts prepared with the other two activators, which corresponds to the literature [24]. However, extensive autogenous shrinkage of SC and particularly of SWG observed for pastes can only be partially mitigated by the restraining effect of sand. Regardless of the activator type, the shrinkage of 0.40/0.45 and especially 0.40/0.60 could be potentially reduced by the reduced activator content at the expense of reduced workability.

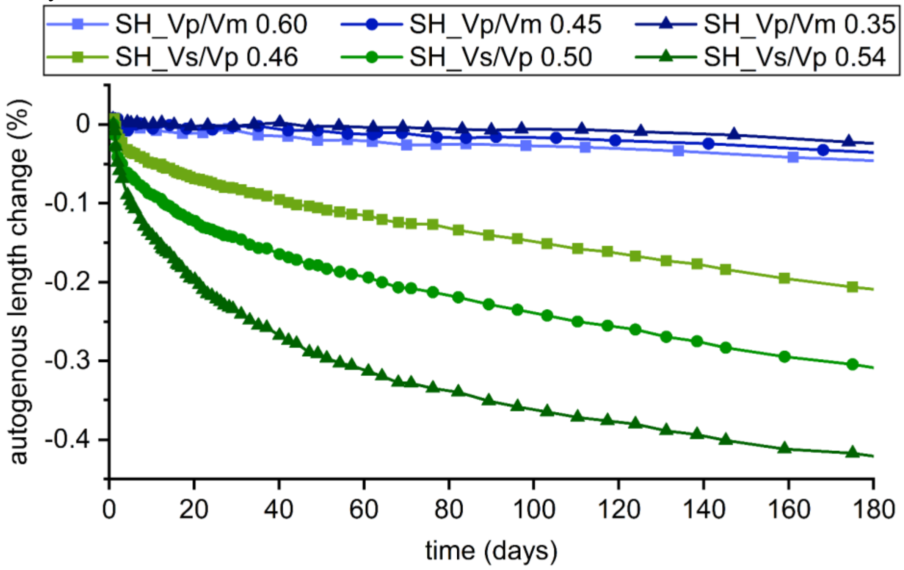

Figure 4. Autogenous shrinkage for SH pastes and mortars.

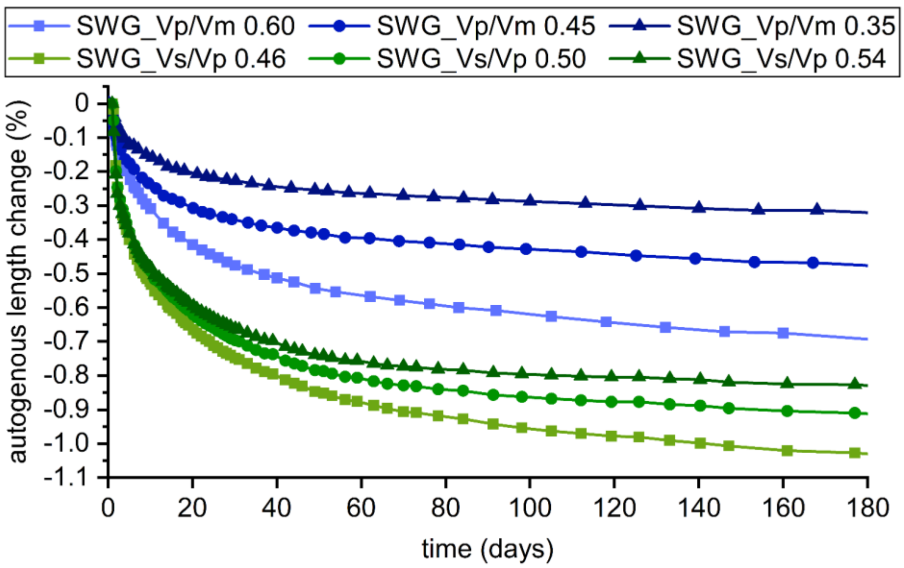

Figure 5. Autogenous shrinkage for SWG pastes and mortars.

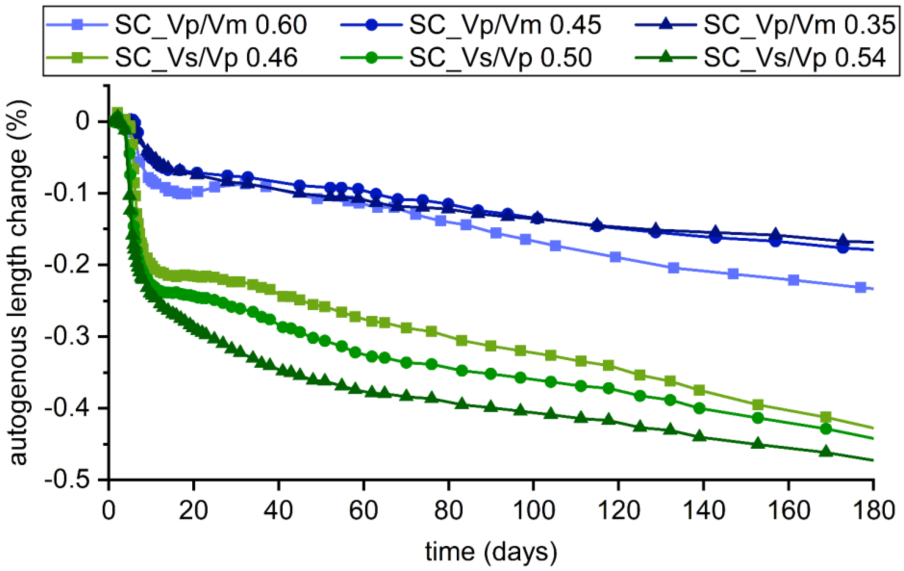

Figure 6. Autogenous shrinkage for SC pastes and mortars.

4. Conclusion

The objective of this paper was to investigate the effect of the siliceous sand volume fraction on the workability, mechanical properties, and long-term autogenous shrinkage of AAS mortars. Their properties were compared with those of AAS pastes with similar workability. Based on the data obtained, the following conclusions can be drawn.

- The addition of siliceous sand greatly influenced the properties of AAS mortars, whereas the degree of influence depended on the type of alkaline activator.
- The workability of mortars gradually increased with an increasing volume fraction of the paste in the final mortal due to a lower total solid content. For the same V_P/V_M ratio, SWG always had the highest workability, while SH always had the lowest.
- For SH, the addition of siliceous sand decreased the flexural strength by about 35% (5,5 MPa to 3,7 MPa), while for SWG there was an increase in flexural strength by 25% and for SC by even 35% (4,7 MPa to 6,7 MPa), compared to pure pastes.
- Compressive strength was always reduced by the sand incorporation for all the activators investigated. The greatest reduction in strength occurred for SH, by approximately 66% (40 MPa to 13 MPa). The lowest strength loss of about 20% (93 MPa to 75 MPa) was observed for SWG.
- Distinctively different trends of autogenous shrinkage with increasing content of solid was observed for different activators and mixture types. Increasing slag volume fraction in the paste with SWG decreased autogenous shrinkage, while the opposite trend was observed for SH and SC. For all activators, autogenous shrinkage was reduced by the presence of sand. This effect was the most pronounced for SH, while the lowest pronounced for SWG.

5. Acknowledgement

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