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Abstract

Ground granulated blast-furnace slag (GGBS) is a popular supplementary cementitious material widely used to improve durability and sustainability of concrete and mortars. However, its filler effect, trigged by GGBS delayed setting, may lead to increased cracking susceptibility. Plastic shrinkage cracking performance is directly related to its excessive drying of exposed surfaces during the first few hours of setting. In an attempt to reduce this negative effect, Superabsorbent polymers (SAP) can be used as internal curing agents. This paper aims to analyse the efficiency of SAPs in reducing plastic shrinkage and hence in mitigating cracks formation in PC-GGBS mortars. Three types of SAPs with different water absorption capacity were used. Mortars specimens were subjected to specially designed severe conditions of restraint and moisture loss during the first 24h after mixing. Cracking patterns were analysed by optical microscopy and image processing software. Evaporation rate (by water loss mass) and setting times (by Vicat apparatus) were also tested. The results showed that SAPs addition reduces up to 90% of plastic shrinkage crack widths (for lower GGBS contents). Only above 50% of GGBS substitution, visible cracks can be observed in SAP mortars.

1. INTRODUCTION

One of the main concerns in concrete durability is cracking formation. In addition to aesthetic factor, cracks lead to development of weak planes for further distresses. They also increase interconnections in concrete microstructure that accelerate the ingress of aggressive agents. In particular, cracks can be formed during fresh stage, which occurs between time of placement and final set. These early-age cracks are the result of plastic shrinkage [1]–[4].

Plastic shrinkage cracks are mainly attributed to four driving forces: (1) rapid evaporation of water, which creates menisci and high tensile stresses in capillary water near surface; (2) differential settlement, since cracks often appear over obstructions (e.g. reinforcing bars and large aggregate particles) or at locations where there is a sudden change in cross-sectional thickness; (3) differential thermal dilation in which a temperature gradient develops inside fresh concrete due to evaporation of water from the surface; and (4) autogenous shrinkage in the plastic phase [2], [5], [6].

In an attempt to increase sustainability of concrete and mortars, supplementary cementitious materials, such as, ground granulated blast-furnace slag (GGBS), are commonly used. These materials result in a filler effect which, in turn, can change concrete performance

[7]–[9]. Addition of fillers with finer particles may increase the risk of plastic shrinkage cracking; they lead to smaller pore size and hence higher capillary pressure in fresh state [4], [10], [11]. Moreover, delayed GGBS hydration leads to retarded evolution of mechanical properties and, consequently, increased susceptibility for plastic shrinkage cracking [4], [12], [13].

Established strategies against early-ages cracking can be normally divided into active and passive methods. Active solutions aim at limiting the early water loss by wetting the surface with water, applying curing compounds that limit evaporation, surface covering with plastic sheets, or shading the elements from sun and/or wind [1], [6], [14], [15]. On the other hand, passive solutions consist of designing concrete by adding specific admixtures, such as, internal curing agents. In this context, Superabsorbent polymers (SAP) have a potential application to lower possibility of plastic shrinkage cracking [16]–[19].

SAP is a cross-linked network of hydrophilic polymers with the ability to absorb and retain large volumes of water [16], [20]. Due to its high capacity to provide water-filled cavities in hardening stages, SAP can control hydration processes and hence their effects on early-age shrinkage. However, SAP performance is very dependent on the type of cement used; pH and ions concentration of pore solution significantly affect absorption capacity and absorption/desorption kinetics [21], [22].

Although there are some studies on SAP application in GGBS matrices [23]–[26], its effects on plastic shrinkage cracking development is still unclear and deficient. Therefore, this paper aims to analyse the efficiency of SAPs in reducing plastic shrinkage and hence in mitigating cracks formation in GGBS-PC mortars. The investigation endeavoured to relate the effects of water evaporation, settlement, and early autogenous shrinkage.

2. METHODOLOGY

Mortars were prepared in proportion of 1:2 (binder : sand) and with water/binder ratio (w/b) of 0.5. Four levels of Portland cement (PC) replacement (CEM I 52.5R) by GGBS [27] were considered: 0%, 25%, 50% and 75% by mass. Table 1 shows chemical and physical characteristics of binder used in the experimental programme. 90% of the binder's particles are below 41.5 ± 0.3 µm and 49.8 ± 0.2 µm, respectively for PC and GGBS.

Table 1: Characterization of PC and GGBS

	Chemical composition (%)									Fineness
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	(m^2/kg)
PC	20.1	4.9	2.7	62.4	2.2	3.2	0.3	0.6	2.8	410
GGBS	34.5	13.1	0.2	38.5	9.7	0.4	0.2	0.6	0.6	390

Three types of modified polyacrylamide SAPs, partially crosslinked with different alkalis contents, were used in the proportion of 0.25% by mass of binder. SAP X, SAP Y and SAP Z had water absorption capacities (WAC) in mixing water of 28 g/g, 24 g/g and 32 g/g, respectively. They were measure by the difference in mortars' consistence, using flow-table method [26], [28]. Figure 1 shows SEM micrographs of SAPs with particles sizes in the range of 63-125 µm.

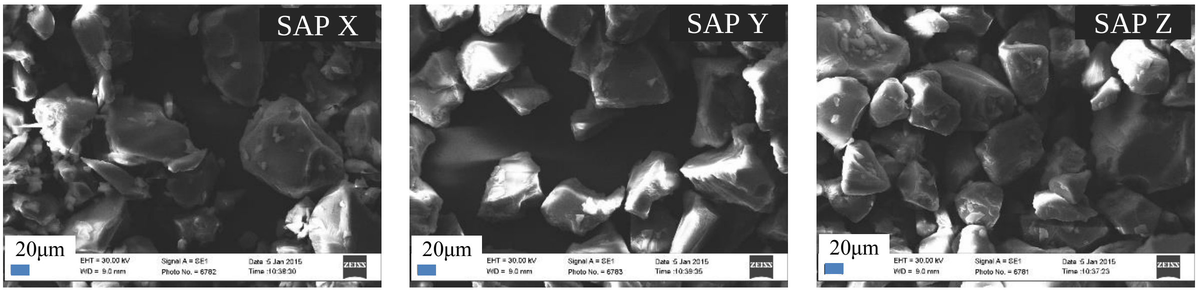

Figure 1: The SEM micrographs of SAPs used in the experimental programme.

Table 2 shows the mix proportion of mortar samples used in this experimental programme. Amount of SAP and water/binder (w/b) ratio were based on theoretical assumptions, including Power and Brownyard's model [29]. The same total w/b ratio was adopted for all samples, considering an effective w/b ratio greater (or equal to) 0.42. Thus, PC hydration would not be interrupted by lack of water in any time, and later GGBS reaction would be continued with the respective additional w/b ratio (from SAP) [26].

Table 2: Mix proportion of mortars

Sample name	Type of SAP	GGBS content	PC (g)	GGBS (g)	SAP (g)	Sand (g)	Water (g)
R0	-	0%	1,433.1	0.0	0.0	2,866.2	716.6
R25		25%	1,074.8	358.3	0.0	2,866.2	716.6
R50		50%	716.6	716.6	0.0	2,866.2	716.6
R75		75%	358.3	1,074.8	0.0	2,866.2	716.6
X0	SAP X	0%	1,433.1	0.0	3.6	2,866.2	716.6
X25		25%	1,074.8	358.3	3.6	2,866.2	716.6
X50		50%	716.6	716.6	3.6	2,866.2	716.6
X75		75%	358.3	1,074.8	3.6	2,866.2	716.6
Y0	SAP Y	0%	1,433.1	0.0	3.6	2,866.2	716.6
Y25		25%	1,074.8	358.3	3.6	2,866.2	716.6
Y50		50%	716.6	716.6	3.6	2,866.2	716.6
Y75		75%	358.3	1,074.8	3.6	2,866.2	716.6
Z0	SAP Z	0%	1,433.1	0.0	3.6	2,866.2	716.6
Z25		25%	1,074.8	358.3	3.6	2,866.2	716.6
Z50		50%	716.6	716.6	3.6	2,866.2	716.6
Z75		75%	358.3	1,074.8	3.6	2,866.2	716.6

Setting times were determined by the Vicat apparatus [30]. Plastic shrinkage cracking performance was evaluated according to ASTM C1579-13 [31]. Freshly mixed samples were subjected to specially designed conditions of restraint and moisture loss, which were severe enough to produce surface cracking.

Figure 2 shows the moulds designed for plastic shrinkage tests. Three prismatic specimens of 50 mm x 50 mm x 240 mm were produced for each mortar composition. For restraint conditions, a 300 mm stainless steel threaded bar (Φ 8 mm) was positioned in the middle of each specimen. Additionally, three 0.4 mm aluminium sheets/plates (30 mm x 30 mm) were placed equally and symmetrically on each steel threaded bar, totalizing nine restraint points for each mortar. All aluminium plates were fixed at both sides with a hex M8 nut in order to guarantee the right position during mortar casting. The free-border between the aluminium plates and the specimen external surface was 10 mm. Figure 3 shows the dimensions and positions of each element.

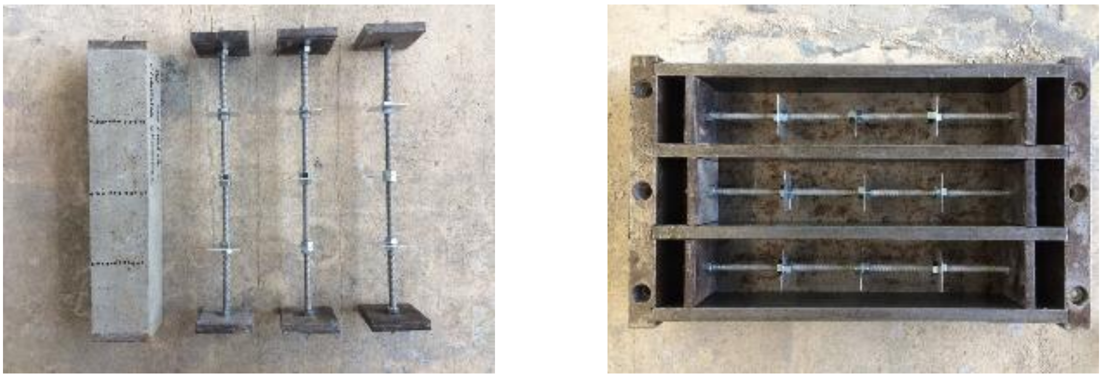

Figure 2: Designed moulds for plastic shrinkage tests.

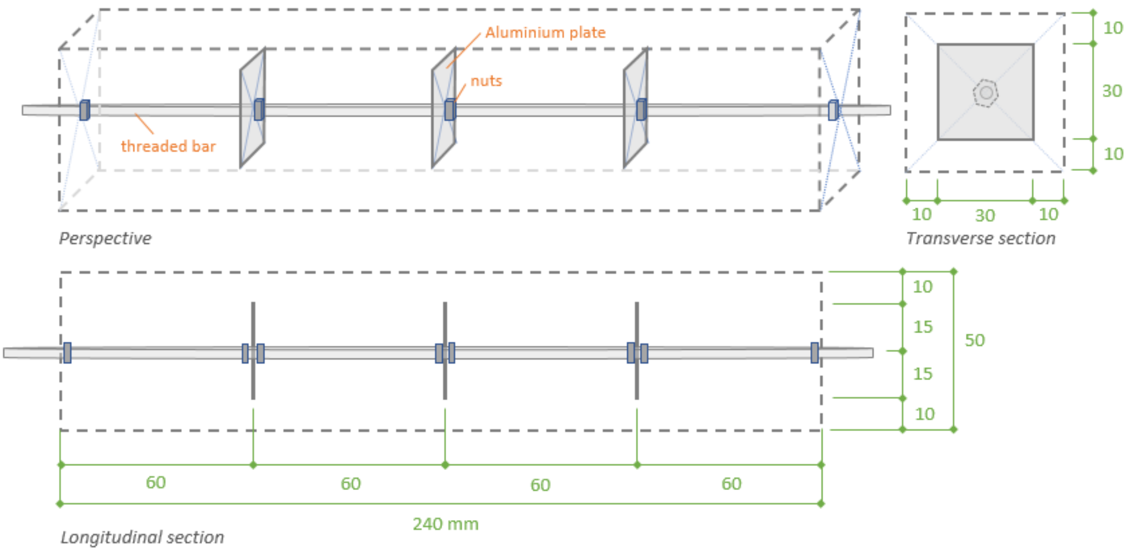

Figure 3: Dimensions of the moulds used for plastic shrinkage tests (in mm, no scale).

Moulds were filled with fresh mortar in two layers, followed by compaction using a vibrating table. After that, they were kept in a ventilation chamber (40 ± 3ºC and 15 ± 10% RH) for 24 hours. The moisture loss was controlled periodically in order to evaluate water evaporation rate of the system [6], [32], [33]. The assembly masses were recorded six times during the first 8 hours, and at 24 hours (when the experiment was finished). After specimens being demoulded, cracks on the free surface were analysed by the Optical Microscope Wild Makroskop M420 1,25x. Crack widths were measured by the ImageJ software.

3. RESULTS AND DISCUSSIONS

Figure 4 shows the final setting times of mortars. Samples with higher levels of cement replacement had their final setting retarded due to its slower hydration process compared to PC. The higher GGBS content, the higher final setting times [34], [35]. This trend is illustrated by the traced arrows on Figure 4.

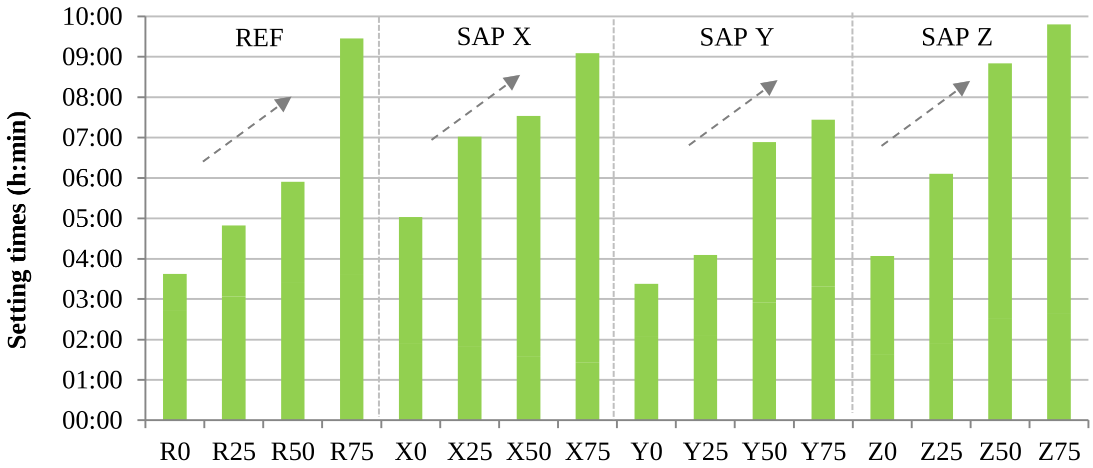

Figure 4: Results of setting time of mortars (traced arrows show overall tendency).

Moreover, it seems that SAP Y generally reduced setting time, while SAPs X and Z increased it. However, there is still no consensus in the literature whether SAPs increase or decrease setting time [20], [36], [37]. Significant scatter in experimental results can be caused by variations in raw materials, type and particle size of SAPs, accuracy of test methods, and also, by the fact that SAPs can leach out some monomers into the fresh mix.

Figure 5 shows PC-GGBS specimens with and without SAPs subjected to plastic shrinkage testing. All reference samples (without SAP) displayed visible cracks to the naked eye, while in all SAPs mortars, similar cracks appeared only for higher GGBS contents. Figure 6 shows the representative micrographs of cracked surfaces of each specimen.

SAPs significantly reduced the widths of average plastic shrinkage cracking for all GGBS contents (Figure 7). Also, the higher GGBS substitution level, the larger cracks recorded.

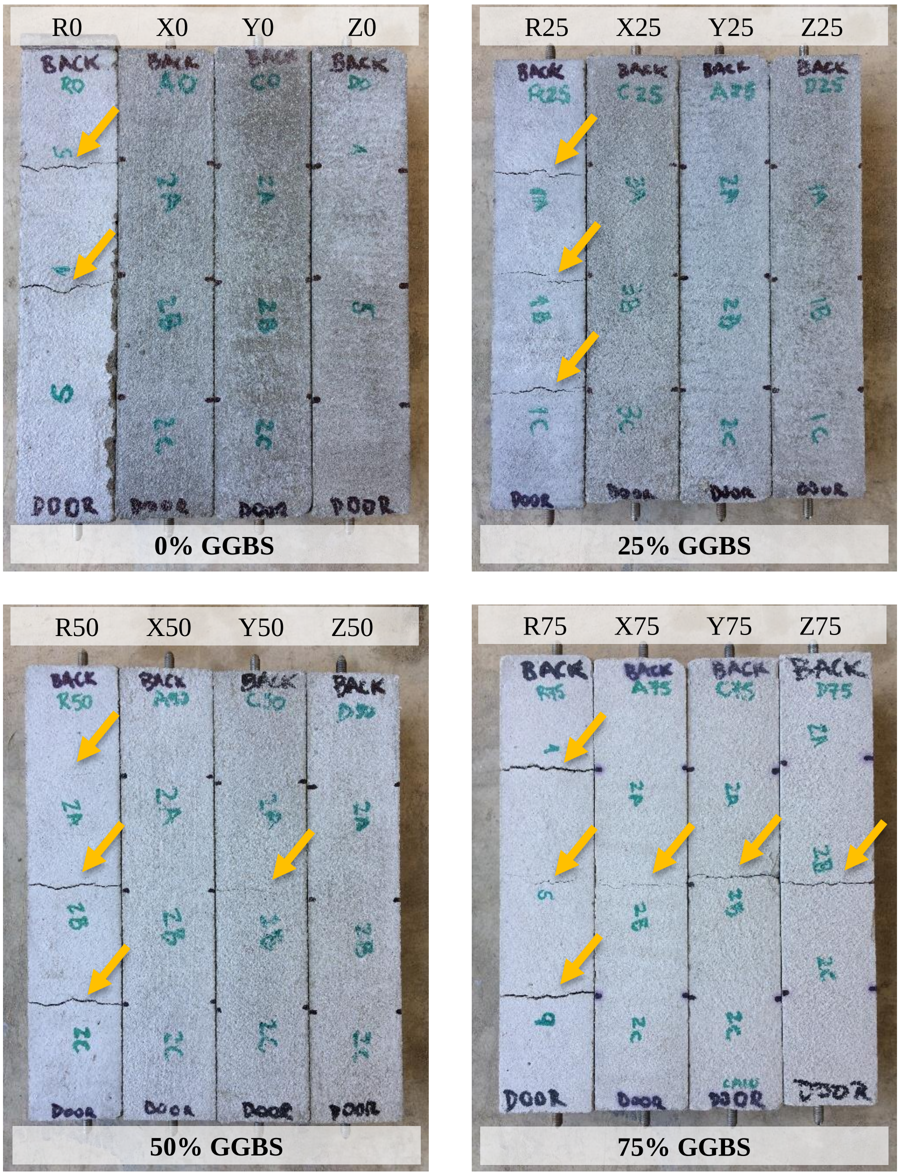

Figure 5: Representative specimens of each mortar compositions after plastic shrinkage test (grouped by GGBS content); arrows indicating cracks seen by naked eye.

The high scatter of results, observed from relatively high values of standard deviation (SD), can be related to different plastic shrinkage cracking. Cracks below 0.05 mm are very fine and the difficulty of their identification entails low precision analysis. Usually, the minimum visible cracks that can be seen to the naked eye is around 0.1 mm width [33], [38]. However, cracks between 0.1-0.05 mm can be identified by an optical microscope. Below this limit, no clear crack pattern can be found, but rather some clusters of large pores in the vicinity of the top of restraint points, which can be considered as “germs” of future cracks [33]. Thus, where very large cracks (above 0.1 mm) and very fine cracks (below 0.05 mm) were considered for determining total average, relatively high SD values were obtained (e.g. for SAP samples with high GGBS contents).

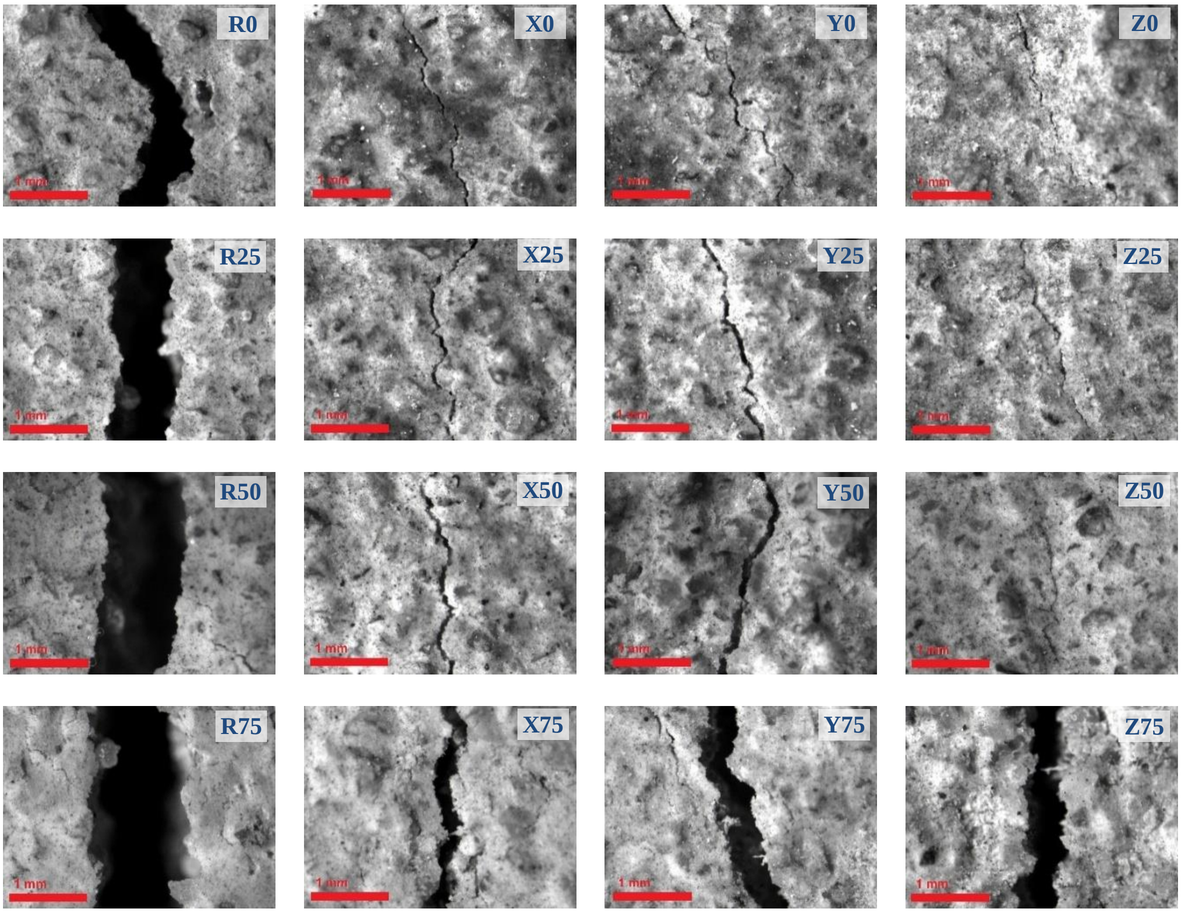

Figure 6: Comparison of cracks formed in each mortar mix (scale indicated in red = 1 mm).

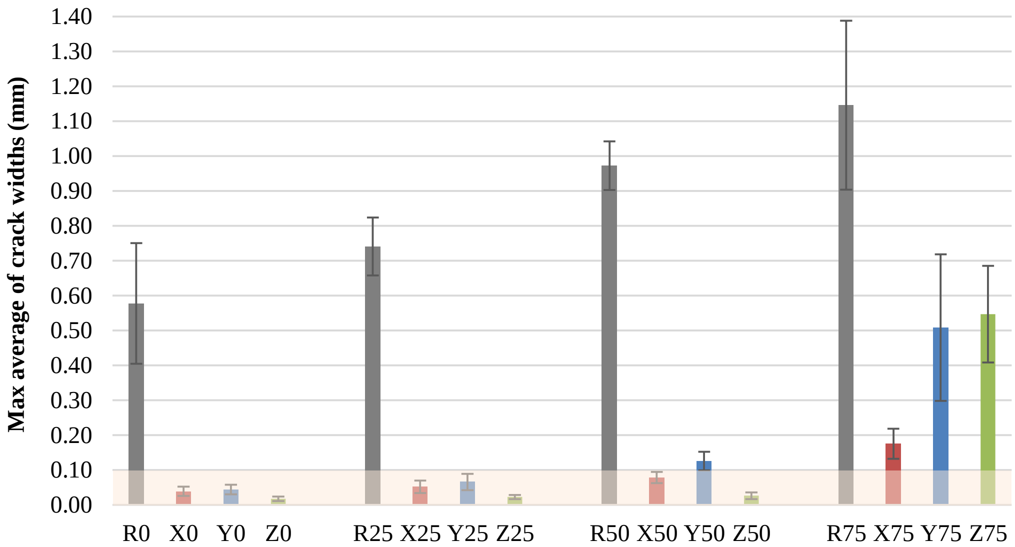

Figure 7: Plastic shrinkage maximum cracks widths. Highlighted zone (below 0.10 mm) indicates cracks that cannot be seen by the naked eye.

Visible cracks (above 0.10 mm) started to appear for 50% GGBS and SAP Y, and for 75% GGBS and SAPs X and Z. This can be associated with the higher amount of free-water available from SAP Y mortars. This polymer had the lowest WAC among all SAP studied. The lower WAC in mortars the lower is efficiency of SAP in reducing autogenous shrinkage in PC-GGBS systems [26], [39].

On the other hand, the driest group of mortars was the one with SAP Z (with the highest WAC) [28], [39], resulting in formation of the finest cracks in mortars with up to 50% of GGBS. Above this level, SAPs Y and Z seemed to have similar performance, while SAP X specimen showed the smallest cracking formation between all mortars with 75% GGBS. This can be attributed to the potential early-age expansion of SAP X [11], [39], [40].

Overall, SAPs can reduce width of plastic shrinkage cracking up to 90% (for mortars with GGBS contents below 50%). Above this GGBS level, reduction in crack widths by SAPs is in the order of 50% (or more) when compared to the reference sample.

Figure 8 shows moisture loss over time. For the clarity of presentation, only results for 0% and 75% of GGBS were presented. Samples with 25% and 50% GGBS had intermediate behaviours, with similar general pattern to the displayed results. The effectiveness of the designed system for plastic shrinkage testing has been confirmed according to ASTM C1579-13 [31]. This is because evaporation rate values were around 5-6% at 24 hours. Additionally, the reference samples (without SAPs) had cracks with widths greater than 0.5 mm.

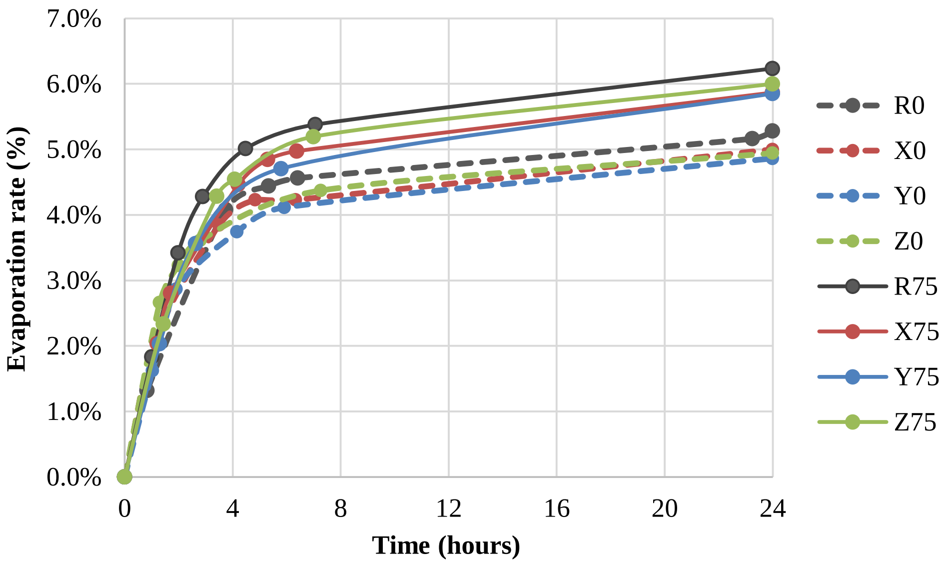

Figure 8: Evaporation rate control during plastic shrinkage tests.

In general, the higher GGBS content the higher water evaporation, and hence the larger cracks formed (as seen in Figure 7). The reference samples (without SAPs) had the highest evaporation rate compared to the SAPs mortars with the same GGBS content. However, it appears that the type of SAP did not have any significant effect on decreasing water mass loss. Thus, reduction of GGBS content seems to be more critical in controlling moisture loss than SAP addition in mortars exposed to severe conditions.

Serpukhov and Mechtcherine [33] also found that SAP does not considerably impact the concrete hardening-strain by changing climatic parameters, especially after final setting time.

Even with differences in temperature, wind speed, and relative humidity, SAP composites had similar behaviour to the reference samples at later stages. This suggests that losses of water during the first few hours are not very dependent on environmental conditions for mixes with and without SAPs.

Evaporation rate can be related to the settlement results, where increased GGBS content delays final setting times. Thus, the mix remains fresh for longer time leading to intensified water loss before final setting. On the other hand, the presence of SAPs does not substantially affect this property (Figure 4).

Cracks propagation is influenced by evaporation rate, settlement, and early autogenous shrinkage [31]. Ghourchian et al. [4] showed that cracking usually occurs during the constant evaporation rate period (any time after initial setting), when capillary pressure develops rapidly due to increasing stiffness.

Increase of GGBS content can negatively affect all these properties and lead to intensified crack formations (especially for over 50% of GGBS). Reduced clinker content results in slower hydration and hence, slower growth of bulk modulus. As a result, larger deformations take place in concrete with blended cements exposed to early-age evaporation [4].

Thus, the main role of SAPs in reducing plastic shrinkage in PC-GGBS mortars is much more influenced by the capacity in reducing autogenous shrinkage than controlling water evaporation and setting time. Serpukhov and Mechtcherine [33] found that addition of SAPs slows down a build-up of capillary pressure, which results in decreased plastic shrinkage and related cracking. Thus, plastic shrinkage reduction by SAPs can be primarily attributed to SAPs' effect on autogenous shrinkage.

This outcome strengthens the statement of ability of SAPs to mitigate autogenous shrinkage and to reduce cracking susceptibility, even in severe environments [11], [16], [20], [41].

6. CONCLUSIONS

From the experimental results, the following can be concluded:

- Plastic shrinkage cracking development is significantly reduced by addition of SAPs for all GGBS contents. This is due to mitigated autogenous shrinkage effect, since water evaporation and setting times are not significantly altered by addition of polymers. SAPs slow down a build-up of capillary pressure, which in turn results in decreased plastic shrinkage and related cracking formation;
- Crack widths are closely related to the level of GGBS substitution; the higher GGBS level, the larger cracks. This is directly attributed to delayed settlement and, consequently, to greater moisture loss. Reduced clinker content leads to slower evolution of hydration and hence, slower formation of the solid skeleton. As a result, larger deformations take place in GGBS mortars exposed to early-age water evaporation;
- SAPs reduce plastic shrinkage crack width up to 90%, especially for mortars with GGBS contents below 50%;
- Visible cracks (above 0.1 mm) can be observed on surfaces of mortars with 50% GGBS and SAP Y, and with 75% GGBS for SAPs X and Z;
- A specially designed method for plastic shrinkage testing has been proved to be effective for mortars evaluation. The specimen restraints and water mass loss system

lead to average crack widths greater than 0.5 mm for the reference samples, and water evaporation rates around 5% at 24 hours of testing.

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