

# Pozzolanic reaction of glass powder and its role in controlling alkali–silica reaction



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## ABSTRACT

It is well recognized that finely ground soda-lime glass exhibits high pozzolanic reactivity. Fine glass grains will not undergo an Alkali-silica reaction (ASR) in the presence of alkali, and can even mitigate the ASR between alkali and reactive aggregates. Influences of the pozzolanic reaction of glass powder on solid phases, pore solution in cement paste, and the ASR mitigating effect are investigated in the study. The pozzolanic reaction of glass not only consumes portlandite to form in-situ C-S-H, which appears as reaction rim around glass grains, and precipitated C-S-H, but also reduces monosulfate level. The impacts of the pozzolanic reaction on species in pore solution are characterized by increased aluminum, sulfate, sodium, and silicon concentrations and decreased calcium concentration. The increase in aluminum and sulfate concentrations results from the decrease in solid monosulfate. Glass powder controls ASR by increasing aluminum concentration in pore solution to reduce the dissolution of amorphous silica from reactive aggregates.

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## 1. Introduction

Being amorphous and containing large quantity of silicate, soda-lime glass can be used as a pozzolanic material when finely ground, and its pozzolanic reactivity has been well identified [1–3]. It is well known that concrete with partial aggregates replacement by waste glass cracks extensively because of the deleterious ASR between glass grains and alkali in pore solution. However, glass grains will not cause cracking when the grain size is reduced to 300  $\mu\text{m}$  or finer [4,5]. There are different explanations for this “size-effect”. It is commonly considered that finely ground glass favors a relatively rapid pozzolanic reaction over the slower ASR [6,7]. Based on the relationship between expansion and the ratio of CaO to ( $\text{Na}_2\text{O} + \text{SiO}_2$ ), Shi [8] explained that the formed N-C-S-H gel will not have much expansive property because the “local alkali to calcium ratio” will be lower if the glass particles are very small. A mathematical model proposed by Bazant and Steffens [9] suggests that the swelling pressure of the ASR gel strongly depends on the size of reactive aggregates and is maximum at some intermediate particle size (about 1–2 mm). Rajabipour [10] suggested another explanation that ASR occurs only within cracks that exist in the interior of glass grains, and cracks will not exist in small glass

particles.

Furthermore, several studies confirmed that fine glass powder can even be used as a suppressor, as well as supplementary cementitious materials (SCMs), to mitigate ASR [11–13]. The role of SCMs in mitigating ASR is related to the reduction of alkalinity of pore solution [14], increased alkali fixation of C-S-H [15]. However, this explanation doesn't apply to glass powder, because large amount of alkali will be released from reacted glass, instead, the pozzolanic reaction of glass powder increases the alkali concentration of pore solution. Idir et al. [12] found that the use of glass powder with a mean diameter of 8  $\mu\text{m}$  as replacement of non-reactive sand in mortar leads to a significant increase of the total alkali content in the pore solution; from 9 mmol/g of mortar (without glass powder) to 38 mmol/g (with 40% glass powder). Some unverified hypotheses have been proposed [12] to explain the reason why glass powder mitigates ASR: activated reaction of glass particles, which soften the particles to relieve the expansive pressure; high Na/Si ratios favoring the decrease of the gel viscosity and so the swelling pressure; the dissolved silica will not be able to polymerize at very high alkali content.

Though the precise mechanism by which glass powder mitigates ASR is still unclear, it is definite that this behavior is related to pozzolanic reaction, and consequently influences of glass powder on pore solution and hydration products. For a better understanding of the role of glass powder in mitigating ASR, it is essential to

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know these aspects mentioned above. The aim of this study is to characterize the reaction of glass powder and its influences, then to relate these to the ASR mitigating effect.

## 2. Materials and methods

### 2.1. Materials

Laboratory prepared mixed-color glass powders were used. Amber, green and clear glass bottles for beverages were collected, ultrasonic cleaned, washed, dried, crushed, and ground (with a disc mill) separately. Ground glass powders were sieved, thereafter fine glass powder (<50  $\mu\text{m}$ ) and coarse glass powder (125–200  $\mu\text{m}$ ) were obtained. Fine and coarse mixed-color glass powders were obtained by mixing single-color powders in a powder mixer (Turbula shaker-mixer) on the color-based proportion of 40% green, 30% amber and 30% clear. Quartz (<63  $\mu\text{m}$ ) was used as inert fillers to have the same dilution effect.

Cement used in the study was a laboratory prepared cement with commercial clinker and gypsum. Particle size distribution, compositions of used materials are given in Fig. 1 and Table 1, respectively.

A North American reactive rive aggregate (Wright) and a highly reactive North American river aggregate (Jobe) were used as reactive aggregates. Particles retained on the 4.75 mm sieve were removed. Jobe contained mixed quartz, chert and feldspar, Wright contained mixed quartz and chert. The typical expansion of accelerated mortar-bar test at 14 days (ASTM C1260 conditions) is 0.64% for Jobe and 0.29% for Wright [16].

### 2.2. Methods

In the study, 30% of cement was replaced by mixed-color fine glass powder (GPF) and coarse glass powder (GPC), respectively. Blend with 30% quartz was used as a reference. The particle size distribution of the powders was measured by laser diffractometer using a Malvern Mastersizer S equipped with a small volume sample dispersion unit. Isopropanol was used as dispersion medium. Three blends were homogenized in a powder mixer (Turbula shaker-mixer) for 5 h.

Pastes with a water to solid ratio (by mass) of 0.4 were cast for SEM-EDX, XRD, while pastes with a water to solid ratio of 0.5 were cast for pore solution squeeze. All pastes were cured in sealed vitals

**Table 1**  
Composition of used materials (by XRF).

[%w]	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	SO <sub>3</sub>	K <sub>2</sub> O	CaO	Fe <sub>2</sub> O <sub>3</sub>
Mixed Glass	10.8	1.9	1.8	73.3	—	0.6	10.7	0.3
Cement <sup>a</sup>	0.3	1.5	5.3	19.9	4.8	1.4	62.1	3.4
	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF				
	59.8	12.7	7.0	11.1				

<sup>a</sup> Minerals are obtained by Rietveld calculation.

at 20 °C for the first 7 days. Thereafter, were cured at 38 °C to speed up the pozzolanic reaction.

The paste samples were cut at 7 d, 14 d, 28 d, 60 d 90 d and 180 d respectively, immersed in isopropanol to remove water and stop the hydration. They were then dried and impregnated with an epoxy resin. The samples were polished down to 1  $\mu\text{m}$ . Solids phases compositions in pastes were measured by EDX micro analysis (Bruker AXS XFlash Detector 4030 133 eV) in a scanning electron microscope. The XRD patterns of powdered stopped pastes were collected using a PANalytical X'Pert Pro MPD diffractometer in a  $\theta$ – $\theta$  configuration employing CuK $\alpha$  radiation ( $\lambda = 1.54 \text{ \AA}$ ) with a fixed divergence slit size 0.5° and a rotating sample stage. The samples were scanned between 7 and 65° with an X'Celerator detector, step size and time per step were set to 0.017 (°2 $\theta$ ) and 40 s respectively. For QXRD analysis, pastes were interground with 20% Rutile (by mass) as an inter-standard. Phase identification and Rietveld quantitative phase analysis were carried out using the X'Pert High Score Plus v3.0e software package by PANalytical. The accepted error was 2% for portlandite and 1% for hydrated silicate aluminates.

Pastes for pore solution squeeze were pressed with a pore solution extract device at 28 days, 60 days and 120 days respectively. The solutions obtained were analyzed by inductive coupled plasma (ICP).

Heat evolution up to 28 d of three blends was measured by isothermal calorimetry (TAM Air 8-Channel Standard Volume Calorimeter), 10 g (nearest to 0.001) paste with a water to solid ratio of 0.4 was used for each blend.

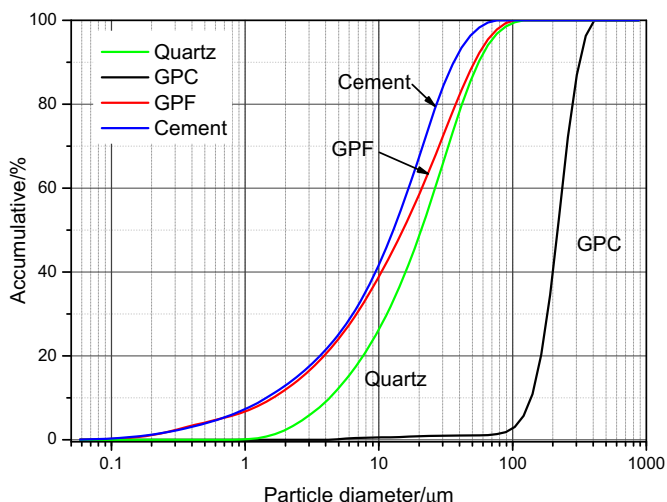
Mortar bars of size 40 × 40 × 160 mm (with metallic measurement studs at each ends) containing different blends were prepared for ASR expansion measurement. The aggregate to blend ratio was 3; the water to solid ratio was 0.4. For each blend, 3 mortar bars were cast and cured for 7 days at 20 °C, 95% RH. Then, mortar bars were cured at 38 °C (in containers with water).

After curing for 28 days, the mortar bars were stored (in containers with water) at 20 °C for 24 h, the initial length of mortar bars was measured. After the initial measurement, mortar bars were stored in sealed plastic containers with alkaline solution containing 0.6 M NaOH (3 bars in 1.5 L soak solution) at 38 °C. Changes in length of mortar bars were measured at different exposure time. Before length measurement, containers and contents were stored at 20 °C for 24 h, and returned to the 38 °C storage after the measurement. Length measurements were done according to Section 7.2.6, ASTM C227.

## 3. Results

### 3.1. Accelerated ASR

ASR expansions of accelerated mortar bars with quartz, coarse and fine glass powder indicate a great mitigating effect of fine glass powder (Fig. 2). In the case of highly reactive aggregate (Jobe), the expansion value for specimens containing GPF is less than 0.1% at 180 days, while the expansion value for the control mortar specimens with quartz is 0.6% at the same age. It is indicated that coarse



**Fig. 1.** PSD of experiment materials.

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