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Performance of ground clay brick in ASR-affected concrete: Effects on expansion, mechanical properties and ASR gel chemistry

Fatih Bektas [a,*], Kejin Wang [b]

[a] National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, Ames, IA 50010, USA
[b] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50010, USA

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ABSTRACT

The effects of ground clay brick (GCB) on alkali-silica reaction (ASR) expansion as well as on mechanical properties of ASR-affected concrete are investigated. Crushed red clay brick originated from demolished masonry was ground in a laboratory ball mill and replaced for portland cement at levels of 15% and 25% by weight in concrete mixes produced with alkali reactive sand. ASR expansion, compressive strength, flexural strength, and modulus of elasticity of the concrete mixes were evaluated. Effect of GCB on ASR gel chemistry was also studied on Pyrex glass-paste specimens using SEM/EDS (scanning electron microscope equipped with energy dispersive X-ray spectroscopy). The results indicate that GCB effectively reduces ASR expansion in concrete: associated cracking and loss on mechanical properties are also significantly reduced. SEM study suggests that GCB alters alkali silica gel chemistry thus resulting in a less expansive product.

1. Introduction

Use of industrial by-products or wastes as supplementary cementitious materials in concrete has become a common and necessary practice for today's concrete industry due to growing economic and environmental concerns. Research has demonstrated that finely ground red clay brick obtained from waste products (e.g., demolished masonry or rejects of brick/tile manufacturing industry) possesses pozzolanic properties and can be used as a supplementary cementitious material in concrete [1,2]. Furthermore, ground clay brick (GCB) was found to improve durability such as increased resistance to sulfate attack [3] and mitigation of alkali-silica reaction (ASR) [4].

ASR manifests itself as a three-dimensional array of cracking. Depending on the degree of reaction, ASR diminishes the engineering properties of concrete such as strength and stiffness. Particularly, tensile strength and modulus of elasticity have been found to be sensitive to ASR cracking; the reductions may be up to 80%. Compressive strength may also be affected but to a lesser extent [5–9]. In ASR studies often expansion is taken as the sole criterion for acceptance/rejection. However, the degree of reaction and expansion may not correlate: sometimes reaction takes place but does not convert to cracking (e.g., some lightweight aggregate).

This paper is an ongoing attempt of the authors to explore the use of GCB in cementitious systems. Previous research has focused on mortar properties, and very limited study has been reported on the effect of GCB on alkali-reactive concrete mixes. An understanding of the effect of GCB as partial cement replacement on deleterious ASR expansion and concrete mechanical properties is sought. Furthermore, the study is extended to the effect of GCB on ASR gel chemistry.

Waste red clay brick originated from demolished masonry was ground employing a laboratory ball mill and replaced for portland cement at levels of 15% and 25% by weight in the concrete made with alkali reactive sand. ASR expansion, compressive strength, flexural strength, and modulus of elasticity of the concrete were evaluated employing ASTM procedures. In order to study the effect of GCB on ASR gel chemistry, microscope study was carried out on Pyrex rod-cementitious paste specimens prepared with and without GCB. The test results are presented in the following sections.

2. Materials and methods

A high alkali ASTM Type I portland cement, whose chemical composition given in Table 1, was used in the study. Crushed red clay brick obtained from various demolishing sites was finely ground in a laboratory ball mill. The Blaine fineness and the residue on 45-μm (ASTM No.325) sieve are 370 m^2/kg and 10.2%, respectively. The chemistry is provided in Table 1. Ground red clay brick is denoted as GCB in this paper.

River sand with known alkali reactivity and nonreactive crushed oolitic limestone were used to produce alkali-silica reactive concrete. Petrographic analysis showed that the sand contains

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[*] Corresponding author.
E-mail address: fbektas@iastate.edu (F. Bektas).

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Table 1
Chemical composition of the cementitious materials.

Composition (%)	Portland cement	Ground clay brick (GCB)
CaO	62.93	0.81
SiO_2	20.34	69.90
Al_2O_3	4.95	15.38
Fe_2O_3	2.35	6.78
MgO	2.41	1.58
SO_3	4.43	0.04
K_2O	1.15	2.78
Na_2O	0.24	1.02
Loss on ignition	0.69	0.16

considerable amounts of volcanic glass (4%) and chert (2%). In addition, andesite, granite and recrystallized quartz particles are also present as potentially reactive constituents. Past experience has proven no ASR activity for the limestone. Aggregate gradations are given in Table 2.

Prior to concrete testing, the effectiveness of GCB in mitigating ASR was assessed using accelerated mortar bar test methods. ASTM C1260 [10] was run for samples with no GCB (i.e., control) and ASTM C1567 [11] was run for samples with GCB (either 15% or 25% by weight replacement of portland cement). The control mortar was tested using both required ASTM sand gradation (Table 2) and as-delivered gradation. GCB was tested using only as-delivered aggregate gradation. Accelerated mortar bar test includes length change determination of 25 by 25 by 285 mm mortar bars which are stored in 1 N NaOH solution at 80 °C. A length change less than 0.10% at the end of 14 days is considered to be a non-expansive mixture according to ASTM C1567.

In concrete testing, the alkali content (as Na_2O equivalent) of the portland cement was adjusted to 1.5% by adding NaOH to the mixing water. Concrete prisms, 75 by 75 by 300 mm, were prepared for ASR expansion measurements and flexural strength determination, and 50 by 150 mm cylinders were cast for compressive strength and static modulus of elasticity determination. After demolding at 24 h, the specimens were cured in insulated tanks maintained at 50 °C and >95% relative humidity in order to accelerate the ASR. The expansion measurements were taken up to 6 months. Prior to measurement/testing, the specimens were taken out of the tank and stored in a moist room at 23 °C in order to eliminate thermal effect. The compressive strength [12], the flexural strength [13] and the modulus of elasticity [14] tests were executed at 14, 28, 56, 91 and 180 days. Furthermore, at 180 days, polished sections were prepared from the control and 25% GCB concretes for scanning electron microscopy (SEM).

ASR gel formation and chemistry were also studied at micro level employing a two-phase specimen—Pyrex glass rod (0.4 mm in diameter) embedded in cementitious paste bar ($25 \times 25\ mm^2$ in cross section). 25% GCB replacement was compared with plain portland cement. The specimens were kept in a curing tank over water at 50 °C. At the age of 6 months, polished sections were prepared from these glass rod-cementitious paste specimens and examined under low/ variable pressure SEM with energy dispersive X-ray spectrometer (EDS). No water was used in cutting and polishing the microscope samples.

Table 2
Fine and coarse aggregate gradations as percent retained on sieves.

Sieve size	Coarse aggregate	Fine aggregate	[ASTM C 1260/1567 grading requirement]
19 mm	30	–	–
12.5 mm	20	–	–
9.5 mm	40	–	–
4.75 mm	10	4	–
2.36 mm	–	12	10
1.18 mm	–	4	25
600 μm	–	17	25
300 μm	–	36	25
150 μm	–	21	15
75 μm	–	5	–
Pan	–	1	–

3. Results and discussions

3.1. ASR expansion

Expansion curves obtained from ASTM C1260 and ASTM C1567 are plotted in Fig. 1. Control-1260, which was cast with the required ASTM aggregate gradation, produced higher expansion compared to control which was cast using as-delivered gradation (1.01% vs. 0.87% at 14 days). As-delivered sand has higher fine content compared to the standard gradation: it is known that smaller the particle size greater the expansion or the reactive constituents might be abundant in the fine fraction. Fig. 1 demonstrates that the GCB significantly mitigates the ASR expansion. ASTM C1567 limits the expansion to 0.10% at 14 days. 15% GCB was not sufficient to suppress the harmful expansion and 25% lies just above the limit. It is worth noting if the tests were run using the required aggregate gradation, which has led to less expansion compared to as-delivered gradation, 25% GCB might fall just below 0.10%. Another level of GCB replacement, 35%, was evaluated in the concrete testing. Material proportions of the control mixture are given in Table 3. In the GCB mixes, portland cement was replaced at 15%, 25% and 35% levels. No air entrainment and no water reducer were used. Fig. 2 gives the expansion measurements of the concrete prisms up to 6 months. The expansions leveled off after 3 months for all the mixes tested. The final expansions in the descending order are 0.235%, 0.043%, 0.023% and 0.017% for the control, 15%, 25% and 35% GCB, respectively.

ASTM C1293 [15], which requires concrete prisms stored over water at 38 °C, limits the expansion to 0.04% for an innocuous concrete mix. Based on this limit, 25% and 35% GCB provide sufficient ASR mitigation and 15% is on the border line. The control specimens had cracking on the surface while GCB specimens showed no visual distress. 15% GCB does not sufficiently suppress the expansion based on the mortar bar test and falls on the line in concrete testing. It is widely accepted that accelerated mortar bar test is over conservative and extremely harsh, and generally used for screening purposes. Effectiveness of 15% GCB replacement should be concluded as inconclusive at this point.

3.2. Mechanical properties

The results of the mechanical testing of concretes are given in Table 4. As the 25% GCB concrete had provided sufficient ASR suppression, 35% replacement was not further pursued.

Between 14 days and 6 months the control mix did not experience a compressive strength loss, if not a slight gain, despite the visual evidence of extensive cracking and gel exudation. 15% and 25% GCB specimens showed no signs of surface cracking, however, a few sites of gel exudation were observed on 15% GCB specimens. For the same age of testing, the compressive strengths of 15% and 25% GCB are higher than that of the control. The positive effect of GCB addition on engineering properties can be observed on the flexural strength and elastic modulus: both 15% and 25% GCB mixes showed superior performance as compared to the control at all testing ages. These results are in good agreement with the expansion measurements. It is evident that the expansion and associated cracking was mostly reflected on flexural strength and modulus of elasticity but not on the compressive strength. Previous studies have also confirmed that tensile strength and modulus of elasticity are more sensitive to ASR cracking [5,7]. Furthermore, the control

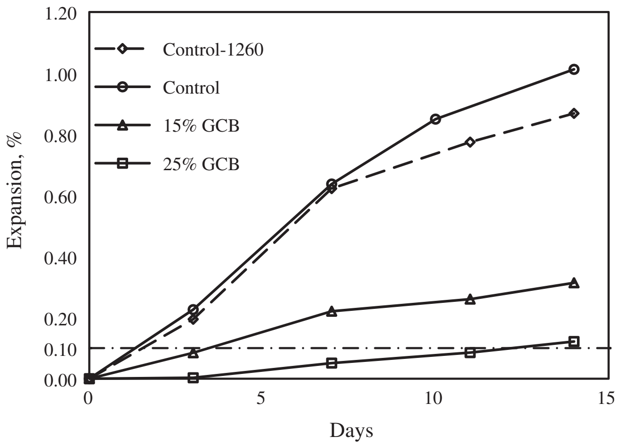

Fig. 1. Expansion curves of the mortar-bars in NaOH solution at 80 °C.

Table 3
Proportions for the control mixture.

Portland cement (kg/m^3)	390
Water (kg/m^3)	195
Reactive sand (kg/m^3)	775
Coarse aggregate (kg/m^3)	925

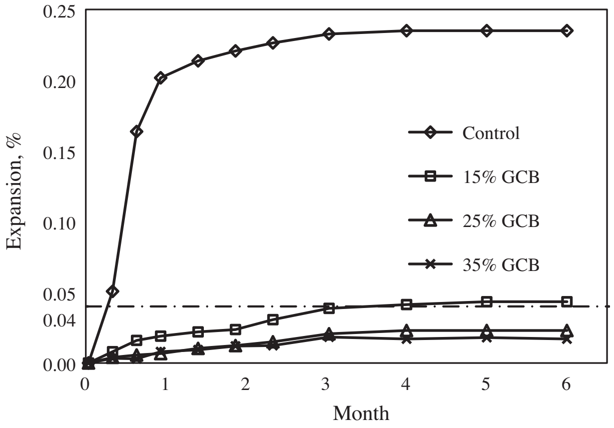

Fig. 2. Expansion curves of the concrete prisms over water at 50 °C.

Table 4
Mechanical properties of the concrete mixtures with and without GCB.

	Control	15% GCB	25% GCB
Compressive strength (MPa)			
14 days	32.3 ± 2.4	31.8 ± 0.7	29.8 ± 0.9
28 days	29.1 ± 1.2	33.2 ± 1.1	30.9 ± 0.4
56 days	30.9 ± 1.6	35.5 ± 2.4	36.6 ± 1.2
91 days	32.4 ± 0.2	36.1 ± 1.2	36.3 ± 1.2
180 days	34.3 ± 0.4	38.3 ± 2.0	34.6 ± 0.7
Flexural strength (MPa)			
14 days	2.6 ± 0.4	4.2 ± 0.2	4.5 ± 0.2
28 days	2.0 ± 0.3	4.9 ± 0.2	4.7 ± 0.2
56 days	1.7 ± 0.2	4.8 ± 0.2	4.7 ± 0.1
91 days	2.7 ± 0.2	4.5 ± 0.4	5.0 ± 0.2
180 days	3.5 ± 0.3	5.4 ± 0.7	5.4 ± 0.3
Modulus of elasticity (GPa)			
14 days	20.7 ± 2.2	29.6 ± 0.7	26.2 ± 0.4
28 days	12.7 ± 0.8	28.4 ± 0.7	28.8 ± 1.3
56 days	12.9 ± 0.3	31.0 ± 1.2	27.9 ± 0.3
91 days	13.9 ± 0.3	32.8 ± 2.7	30.1 ± 1.5
180 days	15.4 ± 0.6	29.0 ± 0.6	29.3 ± 0.5

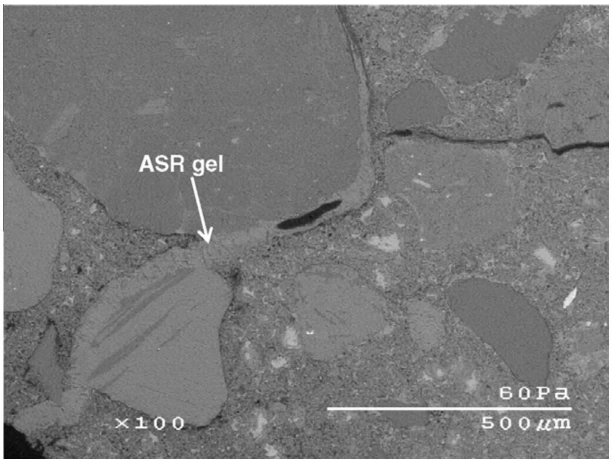

Fig. 3. ASR gel running along the aggregate boundaries in the control sample (EDS point analysis: SiO_2 = 41.05; Al_2O_3 = 3.65; Fe_2O_3 = 0.43; MgO = 0.40; CaO = 33.31; Na_2O = 2.86; K_2O = 2.34; SO_3 = 0.42).

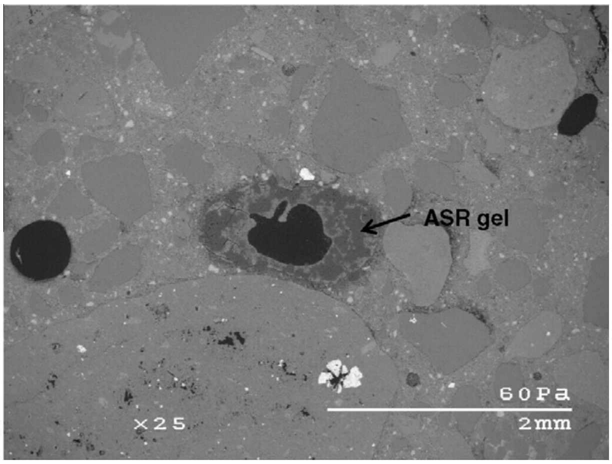

Fig. 4. ASR gel in an air void in 25% ground clay brick concrete (EDS point analysis: SiO_2 = 59.60; Al_2O_3 = 0.51; Fe_2O_3 = 0.11; MgO = 0.32; CaO = 15.35; Na_2O = 6.08; K_2O = 13.38; SO_3 = 0.30).

concrete demonstrated a distinctive behavior that after a drop in flexural strength a recovery occurs at the later ages. The control concrete reached its lowest value at 56 days and then, showed an increase. Initial loss and later recovery is also seen in the modulus of elasticity values. Ahmed et al. [7] reported similar behavior: the phenomenon has been explained on the basis of on-going hydration dominates the detrimental effect of ASR which slows down or stops.

In summary, mechanical testing has proved the beneficial effect of GCB in mitigating ASR and associated deterioration. The ground brick used in the study showed superior performance both at 15% and 25% cement replacement levels compared to the control mix. The results have also provided supplemental information that GCB is probably able to mitigate the expansion at 15% replacement for the material combination used. It is known that higher surface area (i.e., increased fineness) enhances the ASR effectiveness of fine admixtures [16]. The GCB used in the study could be improved by further grinding and the desired expansion reduction would be achieved at low replacement levels.

3.3. Micro-structural investigation

Micro-structural investigation was performed for a better understanding of the role of GCB in ASR. First part included the

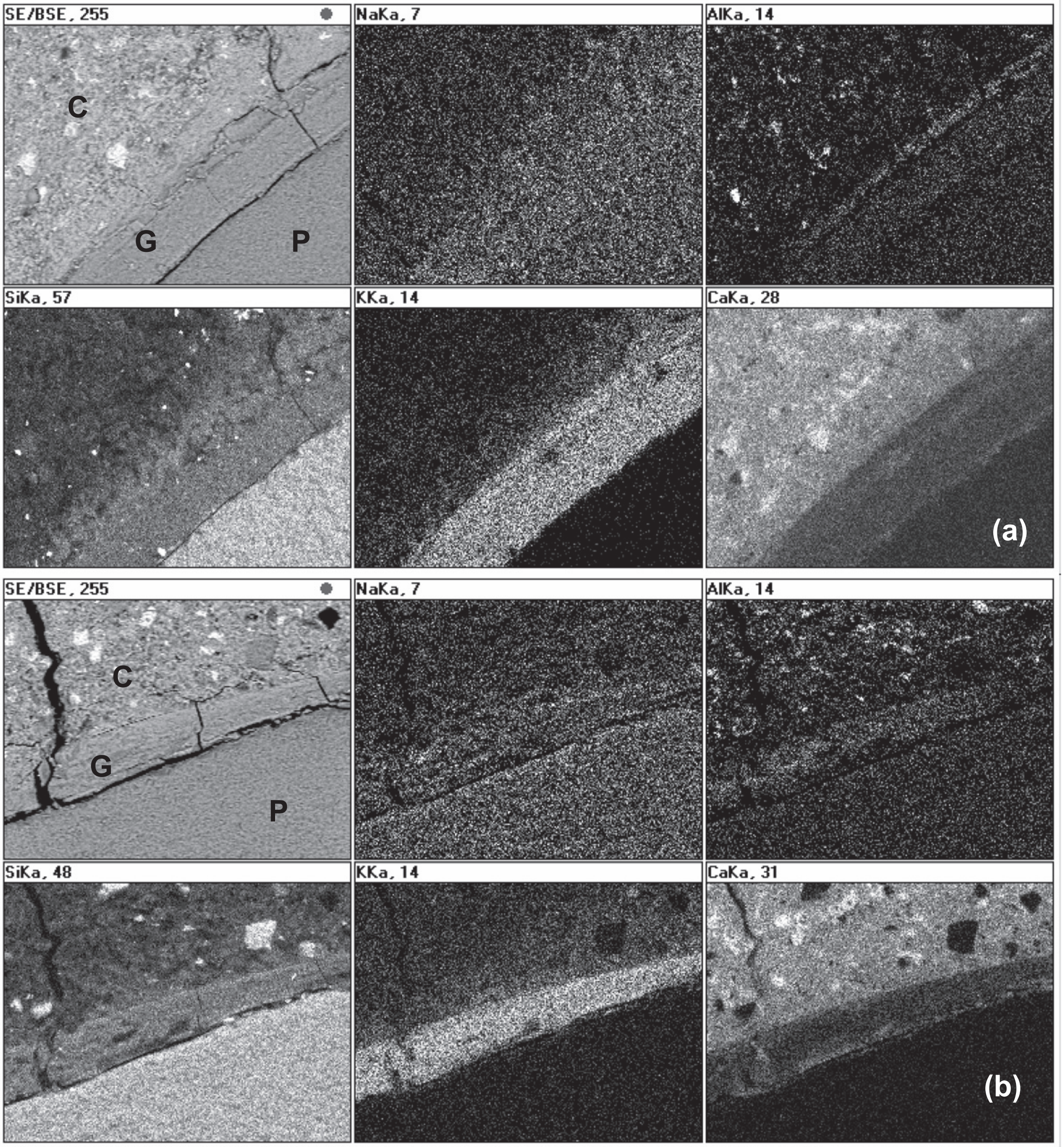

Fig. 5. X-ray mapping of ASR gel in (a) control with no GCB and (b) 25% GCB (C = cementitious paste; G = ASR gel; P = Pyrex).

Table 5
Chemical composition of ASR gel[a].

	Control			25% GCB		
	Average	Std. dev.	Range	Average	Std. dev.	Range
SiO_2	49.70	1.82	47.26–54.60	50.39	1.04	48.76–57.93
Al_2O_3	4.25	2.98	0.81–8.22	5.10	2.36	2.06–7.33
Fe_2O_3	0.12	0.10	0.00–0.30	0.22	0.09	0.11–0.33
MgO	0.27	0.08	0.13–0.40	0.40	0.13	0.27–0.65
CaO	12.21	4.09	6.41–17.43	8.10	1.36	6.34–10.15
Na_2O	5.16	1.06	2.78–6.97	7.37	3.55	3.77–12.78
K_2O	15.39	2.01	12.81–18.63	17.01	1.17	15.24–18.33
SO_3	0.33	0.14	0.15–0.57	0.27	0.07	0.17–0.40
Na_{eq}	15.25	1.73	13.19–17.52	18.53	3.08	15.17–23.42

[a] The values represent the percentage weight oxide.

investigation of concrete samples taken from the expansion prisms (i.e., control and 25% GCB). SEM observations have confirmed the visual condition of the specimens: the control was heavily cracked and showed abundant evidence of reaction products (i.e., ASR gel) whereas the GCB sample showed no internal distress, however, ASR gel was present sporadically. The gel was detected as lining the cracks and filling the air voids (Figs. 3 and 4).

The observations suggested that the ASR gel found in the control sample tended to be rich in calcium and relatively low in alkali compared to the gel in the GCB sample. Wang and Gillot [17] postulated that there is a cycle of cation exchange: alkali is replaced by calcium as the ASR gel matures and a non-swelling lime–alkali–silica complex is formed. In their recent study, Ichikawa and Miura [18] stated that the hard reaction rim surrounding the reactive aggregate is actually a transformation of soft alkali-silica gel into a hard calcium–alkali–silica complex. The observations in this study have confirmed the previous works and suggest that ASR gel exchanges its alkali with calcium from the surrounding cement paste and the resulting calcium-alkali-silica complex is similar to cement hydration products (i.e., calcium-silicate-hydrate gel) and is more stable and harder than its predecessor alkali-rich gel. The recovery observed in the flexural strength and modulus of elasticity can be attributed to this phenomenon: soft and fluid alkali-rich gel initially disperses into concrete matrix through cracks initiated from reaction sites, then, it becomes more viscous and probably more stable through alkali-calcium exchange, and bonds to surrounding paste functioning like a grout filling the cracks and voids, thus, increasing strength and stiffness.

The sand used in the study is composed of various potentially reactive constituents as mentioned in the petrographic description. Therefore, in order to have a homogeneous reactive phase, the study on gel chemistry was further carried out using Pyrex glass. Pyrex rod was embedded in cementitious paste either cast with plain portland cement or 25% GCB replacement. There was evidence of paste cracking in both specimens. ASR gel was found both in the control and in the GCB samples, mostly surrounding the Pyrex, however, the quantity of gel in the control was significantly higher (i.e., a thicker gel band). Fig. 5a and b shows the X-ray mappings taken from the control and 25% GCB, respectively. The upper left corner is the backscattered electron (BSE) image both taken at the same magnification. The elemental mapping suggests that the potassium in the paste was selectively attracted to the reaction site: in both of the images, a potassium band that coincides with the ASR gel is clearly seen. This is not true for the sodium. EDS has showed that the Pyrex is mainly composed of silica (~85–90%), sodium (~4–5%) and aluminum (~2–3%). It is unknown that the alkali from Pyrex might or might not take role in the reaction.

A limited statistical analysis was done on gel chemistry based on the EDS point measurements that were taken along the gel band. Number of the data points taken from each specimen is proportional to the quantity of the gel 12 and 8 points for the control and the GCB samples, respectively. The values, given as oxide compositions, are presented in Table 5. The results indicate a difference in the alkali, as Na_2O equivalent, and calcium contents between the two gel compositions: the calcium is higher and the potassium is lower in the plain portland cement paste. Unpaired *t*-test was run for the alkali and calcium contents and the difference was found statistically significant: two-tailed *P* value equals to 0.021 and 0.029 for the alkali and calcium contents, respectively. Bleszynski and Thomas [19] studied the ASR gel composition in the concrete sections containing plain portland cement and 40% fly ash, and asserted that the high-calcium viscous gel found in the plain portland cement samples produces expansive forces whereas the alkali-rich gels in fly ash samples are less viscous and do not cause expansion. Ichikawa [20] attributed the effectiveness of pozzolanic materials in ASR suppression to the deficiency of calcium which is necessary to form the reaction rim that causes expansion. Bektas et al. [2] showed that GCB reduces the portlandite content of paste. Consumption of calcium hydroxide, thus calcium in the pore solution, could help in the low-calcium gel formation, subsequently, resulting in less expansion. On the other hand, it is worth noting that the detected values for the calcium and alkali contents of the gel lie in a relatively wide band: the coefficient of variations for the calcium and alkali are 34% and 11% for the control sample, and 17% and 17% for the GCB sample, respectively. Therefore, it might be misleading to draw a firm conclusion based on the gel chemistry but alkali and calcium seem to be the key parameters and this area merits further attention in a future study. The ASR associated phenomena present a complex structure and cannot be explained based on a single mechanism. Nonetheless, it is evident that at a given age the quantity of gel produced is less when finely ground red clay brick is introduced as cement replacement to the system. The study has confirmed the previous works of the authors which had implied ground clay brick could be used in concrete as an ASR suppressing component.

4. Conclusion

The study was undertaken as an ongoing attempt of the authors to explore the use of ground clay brick as portland cement replacement in concrete. The effect GCB on engineering properties of ASR affected concrete was investigated. The chemistry of ASR gel in the presence of GCB was also compared to the plain portland cement system by employing SEM/EDS. Based on the results of this experimental work the following conclusions can be drawn:

- Both mortar and concrete expansion tests showed that, when used as a cement replacement at the 15% and 25% levels, GCB significantly reduces the ASR expansion.
- ASR expansion and associated cracking considerably reduce concrete flexural strength and modulus of elasticity. No significant impact is observed on compressive strength.
- GCB replacement significantly mitigates the negative effects of ASR induced cracking on the mechanical properties of concrete (i.e., flexural strength and modulus of elasticity).
- GCB modifies the ASR gel chemistry: GCB incorporated system produces high-alkali and low-calcium gel, which might be less expansive.

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