

THE MECHANISM OF GBFS PREVENTING AAR: A DISCUSSION

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Abstract

In order, three different methods have been applied to study the alkali content of gelpores in cement. In the closed system, the concentration of K^+ , Na^+ and OH^- haven't reduced with the increase of age. In the open system, the diffusion and transferring of K^+ and Na^+ towards free space leads to the decrease of total alkali content. By ESEM the contents of K^+ and Na^+ in the first hydrated layer are very low and the contents of calcium and magnesium are relatively high. So the mechanism of GBFS preventing AAR is: when GBFS is dissolved by alkali medium, SiO_2 and Al_2O_3 are dissolved into the cement matrix, then around GBFS particles form reaction rims rich in Ca and Mg, and the C-S-H gel of positive charges formed in the area repulses K^+ and Na^+ , which are forced to transfer to the mortar's matrix or pore or mortar sample surface. The transferred K^+ and Na^+ form alkali gel products with other dissolved ions, then become evenly distributed in the mortar sample and react with $Ca(OH)_2$ in pore solutions to form $(Na,K)_{x-2z} \cdot zCa \cdot (SiO_2)_y \cdot (OH)_x$ gel products; and thus changes the gel products' structure. The gel products will not expand, and so they can delay expansion destruction.

Keywords: GBFS, AAR, alkali content, preventing mechanism.

1 INTRODUCTION

In general, three different alkali reservoirs can be distinguished in cement: total alkali, water soluble alkali and effective alkali. Total alkali content is the sum of all alkali existing in all forms, which is determined through acid dissolution. Water soluble alkali is the alkali dissolved from the cement when mixed with water for a certain time, which is also called water dissolving alkali. Effective alkali is the alkali existing in pore solutions when cement and water in a certain proportion are hydrated for a certain time [1]. As is known, the effective alkali content in the concrete is one of the factors used to determine the reducing or preventing effect of alkali aggregate reaction (AAR); only the effective alkali in pore solution can react with the silicon aggregate, which leads to AAR. According to the rule, when the aggregate, cement and environmental medium are fixed, if the addition of additive could reduce effective alkali content to within the safety limit (500mmol/L), the harm of AAR can be effectively reduced.

According to the former research, the use of ground granulated blast furnace slag (GBFS) instead of cement can significantly reduce the expansion rate of mortar [2], in other words, GBFS has the capability of clearly reducing AAR. This research has been done to explain the mechanism by which the addition of GBFS to reduce the alkali content of mortar can also reduce AAR.

2 MATERIALS AND METHODS

2.1 Materials

Granulated blastfurnace slag

GBFS is an amorphous material of potential hydration activity. GBFS's broad application to cement and concrete as additive is closely connected with its potential hydraulic activity. German industry standard DIN EN197-1[3] specifies GBFS's amorphous content and $(CaO+MgO) / SiO_2$, which is required to be bigger than one, so that it ensures GBFS' having enough potential hydration

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activity. From Table 1, it can be seen that $(\text{CaO}+\text{MgO})/\text{SiO}_2$ is 1.33 and meets the requirement. $(\text{CaO}+\text{MgO})/(\text{SiO}_2+\text{Al}_2\text{O}_3)$ is 0.97 and $(\text{CaO}+\text{MgO}+\text{MnO})/(\text{SiO}_2+\text{Al}_2\text{O}_3)$ is 0.96. These values mean that GBFS has good potential hydration activity. Besides, in Table 1, the content of amorphous SiO_2 in the GBFS is lower than 66.6%, just 36%, so it belongs to the structure of invert glass. The glassy structure and the XRD analysis of the GBFS are shown in Figures 1 and 2. In this condition, Al_2O_3 and Fe_2O_3 can take part in the forming of networks, but the total content is just about 14wt%, so the amorphous network structure is not regular, and has some silica and alumina tetrahedra existing in the form of chain and islands. The aluminosilicate existing in this form can de-polymerize and react with alkali to form alkali gel products. This means that the high contents of amorphous SiO_2 in GBFS has some advantages as a reducing material of AAR. In other words, when GBFS is used as a reducing material of AAR, high amorphous content and low $(\text{CaO}+\text{MgO})/\text{SiO}_2$ can introduce more active SiO_2 , which produces more reactions between SiO_2 and alkali (NaOH , KOH). The GBFS will be used after sieving and pulverizing. As aggregate grain size is 0.5–2.0mm, as powder its specific surface area is about 335 m^2/kg .

Chert

Chert is the siliceous isolate produced in the Cretaceous period, most of which occurs as condensates in limestone of dark, centimetre or decimetre-size grains, elliptic and non-geometric cryptocrystalline and microcrystalline quartz and other minerals, chiefly characterized by a deep coastal cretaceous shell [4]. In German chert is flint. Chert, freely condensed or expelled by condensates, is like a silicated shell, whose SiO_2 content is reduced from the middle to the surface. There has been much research on chert's alkali susceptibility [5]. The Chert applied in the research is selected from the gravels in the north of Germany, with 4.89% carbonate (by calcium carbonate) and 2.9% water absorption. The chemical compositions of Chert are in Table 1. The chert will be used after crushing to a grain size of 0.5–2.0mm.

Cement

The selected cement is CEM I with high alkali content ($\text{Na}_2\text{O}_{\text{eq}} = 1.3$), whose physical characters are in the Table 2. The chemical compositions of cement are shown in Table 1.

Non-reactive aggregate and additives

The German normsand is used as the experimental fine aggregate with grain size of 0.1–0.5mm. For adjusting alkali equivalent, analytic reagent NaOH and KOH are used as additive alkali to adjust the required alkali equivalent in the fast testing method.

2.2 Test method

Preparation of mortar samples

Mortar samples are prepared according to LMPA (Landesmaterialprüfamt) Magdeburg accelerated testing method [6], of $40\times 40\times 160\text{mm}$. Molding is according to German Industry Standards and European Standards DIN EN196-1 [7]. When formed, the sample is put into a closed container for curing under controlled humidity, samples standing over water. The curing temperature is set according to the experimental requirements, within ± 0.5 °C. So the surface of the sample is always in the dry status, which is proximate to the actual applying situation of mortar curing, and the curing can increase the solubility of silica to form enough reaction products so as to accelerate the chemical reaction resulting from alkali silica reaction [8].

Analysis of alkali content

In the research, three means are used to determine the alkali content in mortar: the first, the changing role of all ions, especially OH^- in the closed cement paste system with the increasing of age when GBFS powder is used as additive to reduce AAR; the second, determining the changes of the internal total alkali content and water soluble alkali content of mortar with addition of GBFS in the open system when water soluble alkali content can be used to demonstrate the changing tendency of effective alkali; the pore solution needed for determination can be obtained by the pressing method after 90-day curing in the experimental conditions, and there is relatively good correspondence relation between effective alkali and water soluble alkali. Hence, many scholars in the world have made

use of water soluble alkali to demonstrate the change of alkali content [9], the difference in the research is that mortar samples are used, not the hardened cement. The last, environmental scanning electron microscope (ESEM) has been used to observe the micro-structure and as an element analysis to micro-area, where the changes of alkali contents in different micro-areas can be compared.

1) The ion concentration of cement paste and hardened cement

The pore solutions of cement paste are tested in clear liquid absorption [10]. The clear liquid applied by the absorption process is directly absorbed from the upper layer of high water: cement ratio. There is delamination of water and lower cement paste in the high water: cement ratio, so that there appears a layer of clear liquid in the upper part of the polymer plastic bottle in the still period or in the latter hydration and hardening stage. The filtered solution obtained in the initial period is the initial concentration, and then the clear liquid in the upper part has ion exchange and diffusion with the paste in the lower part, which leads to the change of concentrations of ions in the solution. The speed of ions' upward diffusion and exchange is relatively low, so the application of clear liquid absorption can make ion concentration a little lower than that in the lower cement stone. This means that the upper layer clear liquid is absorbed by way of clear liquid absorption.

For the same 2.5% Na₂O alkali equivalent in the research system, the alkali in the cement - GBFS system, is a mixture of NaOH and KOH in a molar ratio of 1:6, and is added as basicity regulator. The mix formulation used to determine the ion concentration of pore solution is in Table 3. According W/B = 1.0, Cement, GBFS and water, or alkali solution of NaOH and KOH are mixed in a plastic cup for three minutes. Then filter some fresh paste by a filter paper of 0.45 μm pore, whose filtrate is used as the first stage of pore solution analysis (fresh solution). The remaining fresh paste is put into a plastic cup, sealed by wax and stored at a temperature of 20 °C. Absorbing the upper layer clear liquid at a certain time interval, the solution absorbed is used to determine ion concentration. The ion concentration of solution is determined by Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES). The pH value of solution is determined with a glass electrode by Microprocessor pH/10N Meter, PMX 3000. The ion concentration of OH⁻ is determined with ion-selective electrode by Titro Line/Schott, TW alpha.

2) The chemical compositions of GBFS and mortar

To analyze the chemical compositions of GBFS, raw materials are directly ground in a ceramic mortar and then filtered by a 0.063mm sieve, and the powder gained is used for chemical analysis and testing. The preparation of mortar sample is to grind the sample of set age into powder to pass the 0.063mm sieve. Before the analysis, the powder sample is dissolved by excess concentrated acid. What's worthy of attention is that the sample couldn't be directly selected from the surface of mortar, but from the internal core sample. The mortar powder is used to determine mortar's total alkali content and water soluble alkali content. Chemical analysis and testing instrument is ICP-OES too.

3) Environmental scanning electron microscope analyzing method

In order to observe the micro-structures of GBFS and its hydrated products, Philips Environmental Scanning Electron Microscope, XL-30 ESEM with integral energy dispersive X-ray micro-analysis system are applied. The application of ESEM can realize the direct observation of cement stone or mortar without conductive film, and the analysis is easy and quick without destroying the original form. Before the testing, break the mortar sample and take the fresh fracture surface to have a direct observation. In the normal observation the acceleration voltage is 12.0 kV. With integral energy dispersive X-ray micro-analysis can be applied to determine some certain element's content.

3 RESULTS AND ANALYSIS

3.1 Effective alkali change of pore solution in the closed cement paste

The cement formulation used to determine the ion concentration of pore solution in a closed system is in Table 3. The GBFS for experiment is ground into fine powder as cement and then mixed with cement to make high water containing cement paste for determining the changes of effective alkali content. OH⁻ concentration of pore solution is used to demonstrate effective alkali content. The concentration of GBFS in the cement is 20% and the water cement ratio is 1. The pure cement paste is the reference. Solution ion concentration (Na⁺, K⁺, OH⁻, Ca²⁺) and pH value are determined by

chemical analysis. The testing results are in Figures 3-5.

Comparing cements with and without GBFS, it can be observed that, the concentration of K^+ , Na^+ and OH^- in the pore solution has increased with the increase of age in the first seven days, which arises from the initial alkali dissolution and the fast initial hydration reaction. Besides this general tendency, there were these observations:

By the comparison of ion concentration between pure cement and cement with GBFS, the Figures 3 and Figure 4 show that the ion concentration in the pure cement, especially K^+ , Na^+ and OH^- in the initial period is significantly lower than that of cement with GBFS (mixture of NaOH and KOH of molar ratio 1:6 is used to regulate alkali equivalent to 1.3), which is connected with the dissolution speed of alkali in cement. In the cement are water soluble alkali of 73% K_2O and 36% Na_2O . The soluble alkali, not dependent on the total alkali content of cement, is greatly influenced by the form of the cement. While in cement with GBFS, soluble KOH and NaOH are used as additive alkali, the alkalis are very easily to dissolve into paste so that the concentration of K^+ , Na^+ and OH^- comes to relatively high points in the initial period of hydration, and the difference is not significant at 60 days.

When the alkali equivalent of Na_2O remains constant, observing the pore solution concentration curves of K^+ , Na^+ and OH^- of hardened cement structure in the closed system shows that the ion concentration of pore solution in cement, with or without GBFS, stabilizes with cement hydration and then comes to a dynamically relative balance. The ion concentration changes drastically with cement hydration in the first several hours and the first several days, and changes a little seven days later (almost remains constant); all the ion concentrations have no tendency to reduce with the increase of age. When the alkali equivalent is the same, ion concentrations of cement paste with GBFS after 60-day hydration basically stay at a constant range, for instance, the concentration of K^+ changes 308 mmol/L to 310 mmol/L from 7-days to 60-days; the concentration of Na^+ is 63 mmol/L at seven days and 57 mmol/L at sixty days; and the concentration of OH^- is 363mmol/L at seven days and 369mmol/L at sixty days. When GBFS is mixed into cement in the closed system, the above demonstrates that K^+ and Na^+ in the pore solution do not have the tendency to produce hydrated products 60 days later, and have not significantly consumed some OH^- by the reaction of alkali and SiO_2 in the GBFS. The phenomenon of paste alkali reduction has not significantly taken place. The phenomenon is contradictory to combining theory [11, 12] and reducing effective alkali theory [13, 14], for combining theory thinks that Ca^{2+} in the pore solution could be combined by GBFS. The combining process leads to the reduction of calcium-silicate ratio and makes K^+ and Na^+ stably combined in C-S-H gel phase or existed in an insoluble form in alkali-reach products, such as analcime or zeolite-like structures. The research results show that the concentrations of K^+ and Na^+ have not been decreased, that is, K^+ and Na^+ have not been combined. When K^+ and Na^+ have been combined, the concentrations of K^+ and Na^+ will be relatively decreased, so the phenomenon can't be explained by combination theory.

Reducing effective alkali theory thinks that SiO_2 in GBFS is an active acidic oxide, easy to react with alkali in concrete, so that it consumes effective alkali in concrete and reduces the effective alkali taking part in AAR, which reduces AAR. Alkali equivalent of GBFS is 0.65%, lower than that of cement (1.29%). When GBFS replaces cement, the total alkali content will drop without the adding of alkali, which will lead to the reduction of effective alkali. In the research system, when cement is replaced by GBFS, alkali is added to ensure adequate alkali equivalent. Therefore, the effect of drastic reduction of total alkali content and effective content by direct replacement is not significant. The research results in the closed system also prove that the concentration of hydroxide ion in the pore solution has not been decreased, that is, the content of effective alkali has not been decreased. Therefore, GBFS reducing mechanism of AAR needs to be further explained.

Furthermore, in the closed system, the ions such as Si, Al and Fe, for their limited solubility, are dissolved very little in alkali medium. The results demonstrate that the concentrations of Si and Al are 10^{-2} mmol/L and the concentration of Fe is 10^{-3} mmol/L, which further demonstrates that the pore solution ions that influence AAR mainly are K^+ , Na^+ and OH^- .

3.2 The change of effective alkali in the open system

In the above hardened cement stone in the closed system, the concentrations of K^+ and Na^+ have not been reduced in pore solution with GBFS. Under the testing condition, the system is sealed (a sealed

system), and alkali only circulates in the closed system. However in the actual application, the sample is put in an un-sealed system (open system). In order to observe the actual changes of chemical compositions in the internal structure of the relative paste which is in an open system, the preparation and curing of sample are determined by LMPA fast testing method. In the open system, mortar sample is freely put on the curing water at a certain temperature, when K^+ and Na^+ can dissolve into the water in the process of humidity-preserving and curing, which is similar to the natural environment in the wet status, for the actual application environment of concrete mortar is not in a closed system. Under this condition, the alkali content change of mortar can be determined by total alkali content and soluble alkali content and the changing tendency of soluble alkali content can be used to demonstrate that of effective alkali in the mortar. When determining the chemical compositions of mortar's internal compositions, the sample is only taken from the internal part of mortar, which is demonstrated by Figure 6.

The formulation of mortar sample for determining AAR is in Table 4, Chert sample is used as reference, and GBFS is used as aggregate and additive respectively, whose results are in Table 5. The chemical analysis results of alkali content in mortar without curing, according to the raw materials of their composition, are obtained by calculation in a proportion, while as to the mortar sample of 90-day curing; the result is directly obtained by chemical analysis of core sample.

From Table 5, it can be observed that the amount of potassium in GBFS is relatively decreased, for instance, K_2O content in 1-GBFS reduced from 1.03% to 0.81%, and K_2O content in 2-GBFS reduced from 0.83% to 0.73%. The soluble alkali content in the GBFS system also significantly reduced compared with Chert reference, for instance, Na_2O content reduced from 0.72% to 0.45% in 1-GBFS, while reduced from 0.55% to 0.43% in 2-GBFS. The result shows that the contents of potassium and sodium in GBFS are relatively low. The decrease of soluble alkali content in mortar also shows that alkali's outward diffusion to the surface and pore in the sample makes the relative alkali content in the matrix decrease continually in continuing hydration process.

The research results in the open system show that the total of K^+ and Na^+ in the mortar system added by GBFS has been decreased, that is, the outward diffusion of K^+ and Na^+ in the natural environment will lead to the decrease of their total in the system. This phenomenon also includes leaching. This also shows that K^+ and Na^+ in the system have not been combined into the system.

3.3 Micro-area element analysis of GBFS system

To examine the correctness of the above conclusions, the distribution of alkali in mortar sample is further analyzed, and element analysis is made to the micro-area layer of mortar 1-GBFS (GBFS used as aggregate, Na_2O alkali equivalent is 2.5%, put on the water of 80 °C for 90 days) when observing its micro-structure, the testing instrument is ESEM. The analysis results are in Figure 7.

Figure 7 shows that alkali has a tendency to diffuse out of GBFS particles; in other words, the concentrations of K^+ and Na^+ in the matrix out of GBFS particles are higher than that in the internal of GBFS particles and the interface reaction ring (viz. the first hydration layer). Silicon content in mortar sample 1-GBFS is lowest in the first hydration layer.

Figure 7 shows clearly that, in the first hydration layer, the levels of potassium and sodium can't be observed in the interface reaction ring of GBFS particle through the ESEM test, this means the levels of K^+ and Na^+ in this zone are very low. The levels of potassium and sodium there are lower than that in the internal of GBFS particle. Contrary to K^+ and Na^+ , the concentration of calcium and magnesium is relatively high. From the concentration variations of K^+ and Na^+ in the internal of GBFS particle, the first hydration layer and adjacent cement stone matrix (not including aggregate), it can be found that the concentrations of potassium and sodium in the adjacent cement stone matrix are the highest, and is lower inside the GBFS particle, while the lowest alkali content is in the first hydration layer. Of course, the contents of potassium and sodium in the matrix are lower than that in the surface of the mortar sample and the pore of mortar (Figure 8).

In this research, the rich accumulation of calcium ion is not due to the combination of GBFS with calcium ions in pore solution, but that when GBFS is dissolved by alkali medium, Al^{3+} and Si^{4+} are dissolved and Ca^{2+} and Mg^{2+} are still existing in the first hydration reaction ring of GBFS. The rich accumulation of calcium and magnesium leads to hydrated products' high calcium: silicon ratio in the reaction ring, and according to Glasser [], C-S-H gel phase of high calcium silicon ratio has

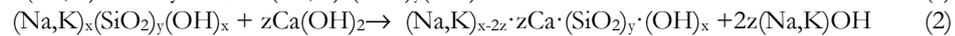
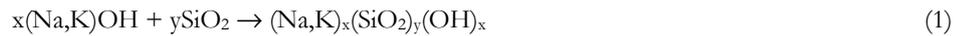
positive charge, which increases the repulsion against K^+ and Na^+ , so that they cannot be combined in the first hydration layer.

So, according to the element micro-area analysis, K^+ and Na^+ can't be absorbed or combined in the hydrated layer of GBFS surface.

4 AN EXPLANATION OF GBFS'S PREVENTION MECHANISM OF AAR

GBFS's reducing alkali aggregate reaction is a comprehensive multi-factor process, such as the active invert glass structure of GBFS, the repulsion of K^+ and Na^+ , the transfer of ions, multi-pore structure of GBFS, even distribution of gel products and change of gel products' structure.

According to the above explanations, the mechanism of GBFS preventing AAR (preliminary model) is the following: GBFS, belonging to active invert glass structure, when dissolved by alkali medium, SiO_2 and Al_2O_3 are dissolved into the cement matrix, then around GBFS particles form reaction rings of rich calcium and magnesium, and C-S-H gel of positive charges formed in the calcium-magnesium-rich area which repulses K^+ and Na^+ , and which are then forced to transfer to the mortar's matrix, pores or mortar sample surface (only when alkali concentration is very high in the outer space, they will transfer into the pore structure of GBFS). The transferred K^+ and Na^+ form alkali gel products with dissolved silicon and aluminium (like Equation 1), then become evenly distributed in mortar sample and react with $Ca(OH)_2$ in pore solution to form $(Na,K)_{x-2z} \cdot zCa \cdot (SiO_2)_y \cdot (OH)_x$ gel products (Equation 2), so causing changes gel products' structure. The gel products will not expand so that they can delay expansion destruction. The chemical reaction equation in the process is the following [15]:



According this chemical reaction, the alkali hydroxide products will be made again and enter into the pore solution of cement paste, and the alkali hydroxide products will react as Equation 1, continue to consume active SiO_2 and produce AAR gel products. So, when the system is in a closed status, the circulation of the two reactions and the rejection of calcium-magnesium-rich layer of slag particle surface against K^+ and Na^+ , ensure the concentration of K^+ and Na^+ has not been decreased in the system. While, in an open system, the diffusion of K^+ and Na^+ will lead to the decrease of total alkali in the system.

This also shows that completely preventing alkali aggregate from reacting by use of slag is not successful. Slag can only deter the production of harmful alkali aggregate reaction expansion by way of its multi-pore structure and evenly distributed calcification gel products phases, whose detailed preventing mechanism should be further studied.

5 CONCLUSIONS

- 1) In a closed system, when Na_2O alkali equivalent is constant, under any condition, in hydrated paste, the cement replaced by GBFS has similar ion concentration changes as pure cement: the concentration of K^+ , Na^+ and OH^- change drastically in the initial hydration period with cement hydration. However with the increase of age up to 60 days, the concentration changes in the relatively closed system are not significant, almost keeping constant, which means the concentrations of all ions have no tendency to reduce with the increase of age. The conclusions obtained in the system couldn't be explained by reducing effective alkali theory or combining theory.
- 2) In an open system, the total alkali content and soluble alkali content of mortar sample with GBFS as aggregate are reduced after 90-day curing when compared with the initial value, which shows ions of potassium and sodium in the open system have the tendency to diffuse and transfer freely towards the free space, that is, towards pore, sample surface or other places of low concentration, leading to the relative reduction of total alkali content and soluble alkali content in the internal of mortar sample.
- 3) Through the micro-area layer element analysis of mortar, it can be observed that alkali also has the tendency to diffuse towards sample surface, that is, the concentrations of K^+ and Na^+ in the surface are higher than that in the internal parts. As to GBFS, in the first hydration layer,

the contents of potassium and sodium are very low, which can't be determined by energy spectrum. This shows that K^+ and Na^+ can't be absorbed or combined in the hydrated layer of slag surface.

- 4) The mechanism of GBFS preventing AAR (preliminary model) is the following: GBFS, belonging to active invert glass structure, when dissolved by alkali medium, SiO_2 and Al_2O_3 are dissolved into the cement matrix, then around GBFS particles form reaction rings of rich calcium and magnesium, and C-S-H gel of positive charges formed in the calcium-magnesium-rich area repels K^+ and Na^+ , which are forced to transfer to the mortar's matrix, pores or the mortar sample surface (only when alkali concentration is very high in the outer space, they will transfer into the pore structure of GBFS). The transferred K^+ and Na^+ form alkali gel products with dissolved silicon and aluminium, then are evenly distributed in mortar sample and react with $Ca(OH)_2$ in pore solution to form $(Na,K)_{x-2z} \cdot zCa \cdot (SiO_2)_y \cdot (OH)_x$ gel products, so causing changes gel products' structure. The gel products will not expand so that they can delay destruction, whose preventing mechanism should be further studied.

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TABLE 1 Selected results by ICP-OES, ISE (only Cl), and ignition loss (LOI) by gravimetric analysis, in wt%. Results < 50× LLD underscored

main elements	material				
	LLD	CEM I	GBFS	chert	Normsand
Na ₂ O	0.01	<u>0.25</u>	<u>0.42</u>	<u>0.04</u>	<u>0.27</u>
K ₂ O	0.01	1.58	<u>0.33</u>	<u>0.17</u>	1.89
CaO	0.1	59.6	36.9	0.7	<u>0.2</u>
MgO	0.1	2.6	10.6	<u>0.1</u>	<u>0.1</u>
MnO	0.01	0.08	0.19	<u>0.05</u>	<u>0.00</u>
Fe ₂ O ₃ -total	0.1	2.9	0.8	1.6	<u>0.3</u>
Al ₂ O ₃	0.1	5.7	13.2	0.7	4.0
SiO ₂	0.1	20.2	35.6	96.5	92.9
TiO ₂	0.01	0.26	0.74	0.12	0.06
LOI ¹⁾	0.1	2.4	1.7	<0.01	<u>0.4</u>
SO ₃	0.1	3.2	<u>0.5</u>	<u>0.1</u>	<u>0.0</u>
P ₂ O ₅	0.01	0.12	-	-	-
Cl ²⁾	0.001	0.068	<u>0.004</u>	<0.001	<0.001
SUM total	100.00	98.96	100.98	100.05	100.12
calculated values					
Na ₂ O _{eq}	-	1.29	0.64	0.15	1.51
CaO+MgO/SiO ₂	-	3.08	1.33	0.10	<0.01

¹⁾: measured gravimetrically at 1000 °C.
²⁾: measured by ISE in solution

TABLE 2: Cement physical indexes

Sample	Density	Surface area	Setting time		Water req.ment	Compressive strength			Flexural strength		
	g/cm ³	m ² /kg	initial	final	wt%	2d	7d	28d	2d	7d	28d
			h:min			MPa			MPa		
Cement	3.127	342	3:50	4:50	27.3	25.7	39.1	48.4	5.9	7.6	8.7

TABLE 3: The cement formulation used to determine the ion concentration

Material	Na ₂ O _{eq}	Slag	Cement	NaOH	KOH	Water	Temperature	Note
	wt%	g	g	g	g	g	°C	
Cement	1.3	-	1000	-	-	1000	20	Control
Cement+ GBFS	1.3	200	800	0.60	4.46	1000	20	

TABLE 4 The formulation of mortar sample to determine AAR

Number	Type	Cement	GBFS powder	Water	Aggregate size		
					0.1~0.5mm Normsand	fine: 0.5~1.0mm	coarse: 1.0~2.0mm
0-Chert	Control	450g	0	225g	450g Sand	450g Chert	
1-GBFS	GBFS-aggregate 80 °C, upon water	450g	0	225g		450g GBFS	
2-GBFS	GBFS-additive 80 °C, upon water	270g	180g	225g		450g Chert	

PS: Na₂O_{eq} is 2.5%.

TABLE 5: Mortar chemical composition changes before and after curing, in wt%.

Number	Time	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	MnO	TiO ₂	K ₂ O	Na ₂ O	w.K ₂ O	w.Na ₂ O
0-Chert	before	77.4	1.9	1.9	15.4	0.7	0.06	0.16	0.52	0.47	0.30	0.41
	after	78.1	2.6	1.5	15.1	0.6	0.02	0.09	0.57	0.34	0.21	0.22
1-GBFS	before	46.1	9.0	1.2	33.4	6.0	0.12	0.45	1.03	0.72	0.30	0.41
	after	50.1	8.4	1.1	31.3	6.4	0.11	0.44	0.81	0.45	0.21	0.21
2-GBFS	before	78.0	3.5	1.4	13.0	1.5	0.06	0.19	0.83	0.55	0.19	0.40
	after	80.0	3.1	1.2	12.5	1.3	0.03	0.13	0.73	0.43	0.20	0.29

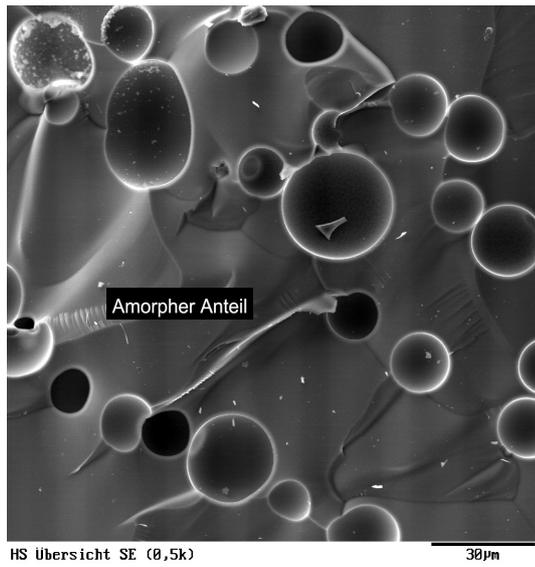


Figure 1 SEM photo of the glassy matrix of GBFS

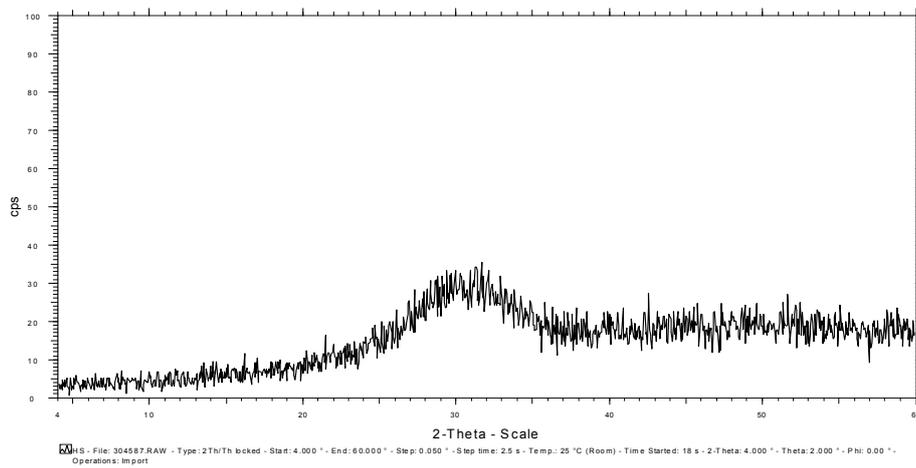


Figure 2: X-ray diffractogram of GBFS

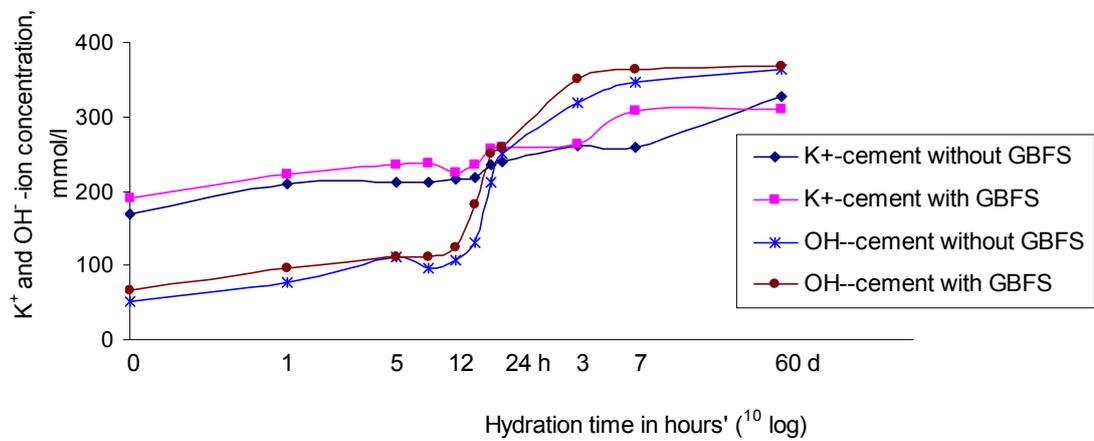


Figure 3: Development of K⁺ and OH⁻ concentrations in cement pore solution over time.

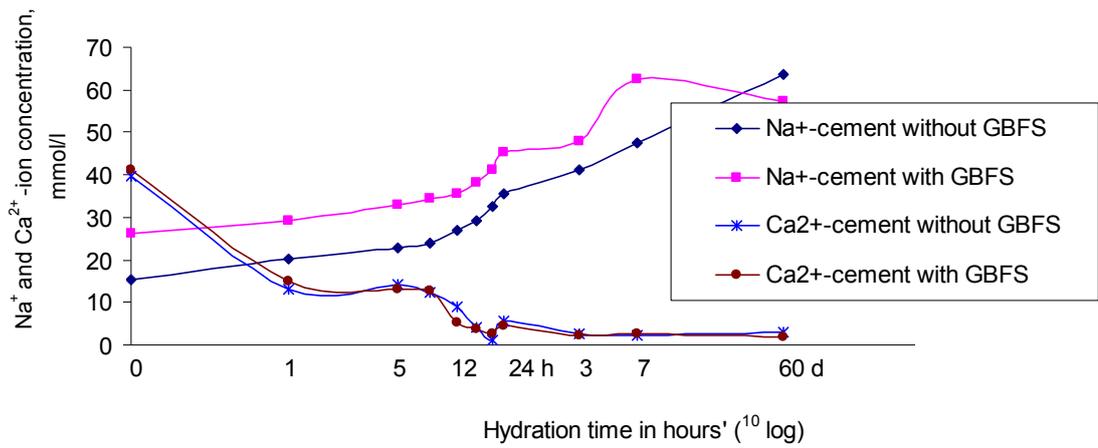


Figure 4: Development of Na⁺ and Ca²⁺ concentrations in cement pore solution over time.

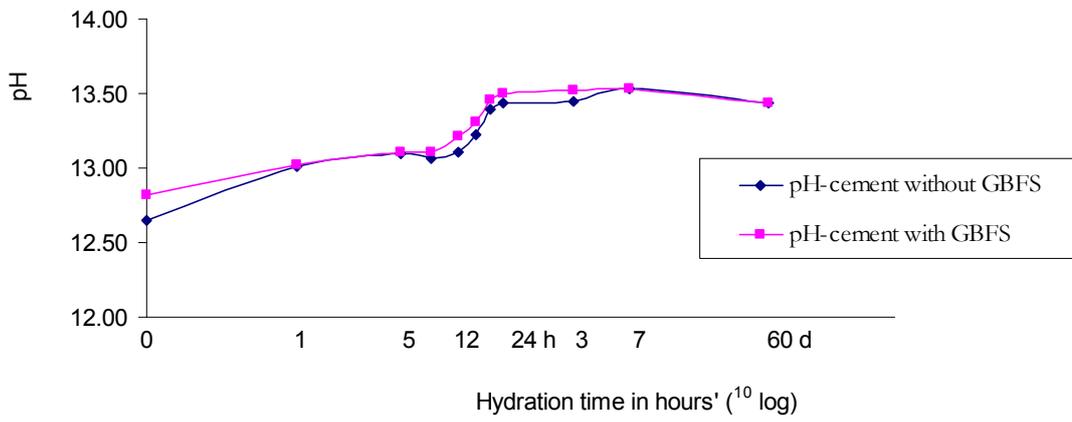


Figure 5: Development of pH in cement pore solution over time.

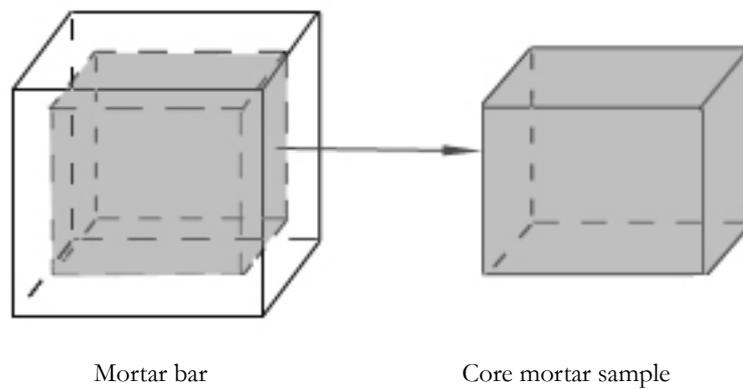


Figure 6: Mortar bars were prepared for chemical assessment by cutting off all faces at 30 mm depth

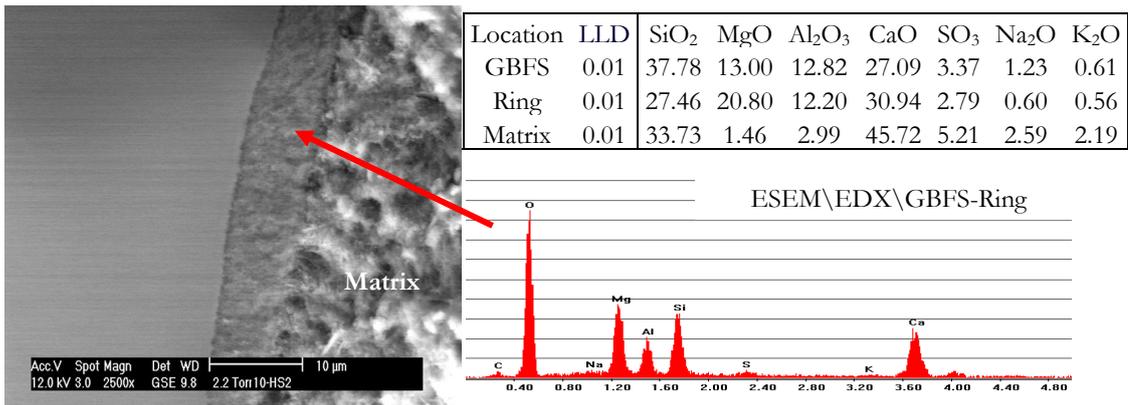


Figure 7: ESEM photo of GBFS-particle interface reaction ring in 1-GBFS mortar (data in wt%).

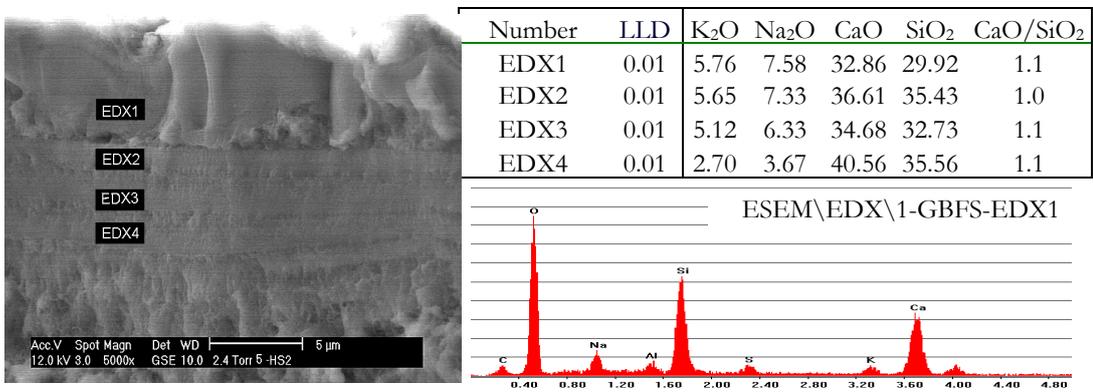


Figure 8: ESEM photo of surface in 1-GBFS mortar (data in wt%).