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1 **Alkali-treated incineration bottom ash as supplementary cementitious materials**

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7 **Abstract**

9 Municipal solid waste incineration bottom ash (IBA) contains metallic aluminum
10 which generates gas when in contact with cement paste. To increase the utilization
11 potential of IBA, alkali treatment for removal of metallic aluminum is proposed. This
12 paper investigated the effects of alkalinity, reaction temperature, and alkali type on
13 the properties of alkali-treated IBA and the resulting IBA blended cement mortars.
14 Results showed that alkali treatment effectively removes the metallic aluminum in
15 IBA and minimizes aeration in IBA blended cement mortars. Furthermore, alkali
16 treatment enhances pozzolanic properties of IBA and the resulting alkali-treated IBA
17 possessed pozzolanic reactivity similar to coal fly ash. The strength activity indices
18 (SAI) of the resulting alkali-treated IBA blended cement mortars were above 75% of
19 the control at the age of 28 days and beyond. In particular, the mix incorporating IBA
20 treated with NaOH (pH=14) at 25 °C has a strength comparable to that of control at
21 the age of 90 days. The proposed method provides an effective, efficient, and fast
22 means for the removal of metallic aluminum in IBA and the alkali-treated IBA can
23 potentially be used as supplementary cementitious materials for concrete production.

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Keywords: incineration bottom ash (IBA); supplementary cementitious materials;
alkali treatment; density; compressive strength

1 Introduction

With economic development and population growth, generation of municipal solid waste (MSW) around the world has increased over the years. Compared to direct landfill of MSW, incineration provides effective means to reduce the mass and the volume of MSW by 80% and 90%, respectively [1] and to convert waste into green energy. The incineration ash residues, however, still need to be managed and are often disposed of by landfill. For land and resource scarcity cities or countries like Singapore, utilization of incineration ash residues to diverge them from landfill is of great interest and significance [2].

Two types of ash residues are commonly found after incineration, the incineration bottom ash (IBA) which is the non-combustible residue of combustion that falls on the bottom of incinerator [3] and the incineration fly ash (IFA) which is the fine residue that is driven out from the incinerator with flue gases [3]. Compared to IFA, IBA is much less hazardous [4] and is classified as a non-hazardous waste according to the European Waste Catalogue [5]. Furthermore, IBA represents about 75~80% of the total ash residue after incineration [6] while IFA only accounts for the remaining 20%. As such, IBA has much higher potential to be used for civil engineering applications [7] and successful use of IBA creates greater impact on resource creation and extension of lifespan of landfill.

Supplementary cementitious materials (SCMs) possess cementitious and/or pozzolanic properties [8], which are often used to replace cement in the production of concrete. SCMs contribute to the hardened properties of concrete and certain SCMs also improve the fresh properties [9] of concrete. SCMs greatly reduce the demand on cement and significantly lower the greenhouse gas emissions [10] associated with cement clinker production. Common SCMs such as coal fly ash, ground granulated blast-furnace slag, and silica fume are by-products from different industry sectors [11].

It has been reported that IBA possesses pozzolanic properties and can be a potential cement supplement and replacement [12, 13]. However, IBA contains certain amount of metallic aluminium due to the presence of aluminium products, such as aluminium cans, foil, container, and packaging [14], in municipal solid waste. When IBA is mixed with cement, it reacts with hydroxide ions to generate hydrogen gas as follows [15].

Generation of hydrogen gas may lead to aeration [7], expansion and cracking of concrete [15-17] and even explosion [18] in some extreme cases. Removal of metallic aluminium from IBA to prevent hydrogen generation is therefore crucial for the successful application of IBA as supplementary cementitious materials. Bertolini et al. [19] used wet grinding to remove metallic aluminium in IBA before it can be used as cement supplements. However, results showed that the removal efficiency is low and long rest time from days to months is required for the depletion of metallic aluminium in IBA.

In this paper, alkali treatment was proposed to remove metallic aluminium in IBA. X-ray fluorescence (XRF), X-ray powder diffraction (XRD), collection of gas over water, and saturated lime test were used to characterize chemical composition, mineralogy composition, gas generation, and pozzolanic reactivity of IBA, respectively, before and after alkali treatment. The alkali-treated IBA was then used to prepare IBA blended cement mortars in accordance with ASTM C311/C311 M for the determination of dry density, compressive strength, and strength activity index. The influence of alkali treatment conditions including alkalinity, temperature, and alkali type, on the properties of IBA and the resulting IBA blended cement mortars were reported.

2 Experimental program

2.1 Raw materials

Incineration bottom ash (IBA) was collected from a local Waste-to-Energy (WTE) incineration plant capable of treating 800 tons of solid waste daily and generating 22MW of green energy. An advanced grate combustion system including a multi-stage grate furnace was designed and biofuel is used for waste incineration. Municipal solid waste is burned consistently without pre-processing. The burning temperature is between 800 and 1,000 °C. Granular size of IBA ranges from micrometers to decimeters. Once collected from the incineration plant, the IBA was oven-dried immediately at 105 °C for 24 hours. After that, the dried IBA particles without sieving and crushing were directly introduced into a ball miller at predetermined time span of 10 minutes with a rotation rate of 300 rpm. The planetary ball miller has 4 bowls and 100 g steel milling balls are used to grind 400 g IBA in each bowl (i.e., the mass ratio of milling balls to IBA is 1:4). **Fig. 1** shows the gradation of the ground IBA. As can

be seen, the ground IBA has an average particle size of around 30 microns with a maximum particle size of about 150 microns.

Laboratory grade pure sodium hydroxide solids or calcium hydroxide solid were used for the preparation of alkaline solution. Ordinary Portland cement (OPC, clinker content more than 80%), fine aggregates, tap water, and superplasticizer (SP) were used to prepare IBA blended cement mortars. OPC conforming to the Singapore Standards SS 26 was used in this study. XRF test was carried out to reveal the chemical composition of OPC. Sequential X-ray spectrometer (Bruker S8 TIGER) was used in this study for XRF test and the chemical composition is showed in the form of weight percentage of oxidation (**Table 1**). Sample was weighed and mixed with 20 wt% of binding material CH_2O , pre-grind and mixed, and pelletized on an aluminum cup using a Herzog manual press at 15 tons for 20s. After the measurements, all peaks in the spectra were carefully checked. The elements present in the sample are subjected to an evaluation process based on pre-calibrated element lines coming from a line library. Fine aggregates were normal river sand with particle size less than 5 mm. Water reducing admixture used in this study was a 3rd generation polycarboxylate-based superplasticizer (SP).

2.2 Alkali treatment of IBA

Table 2 summarizes the five treatment conditions investigated in the study where alkaline solution (sodium hydroxide or calcium hydroxide) was used at pre-determined alkalinity (PH=12 or 14) to react with IBA at specific temperatures (25 or 70 °C) for a duration of 120 minutes. The first treatment condition in water was tested as the control. Alkaline solution was prepared by dissolving pre-determined amount

of alkali into distilled water. A hot plate stirrer was used to condition the solution to the pre-determined temperature. After which, ground IBA was added into the solution with a solution-to-IBA ratio of 10 and stirred for a pre-determined duration of 120 minutes. Surface foaming as shown in **Fig. 2a** was observed when IBA was added into the alkaline solution due to gas generation from IBA via chemical reaction between metallic aluminum and alkali. With prolonged treatment duration (i.e., 2 hours in the current study), the foaming was reduced and a clear solution can be obtained which suggests seizing of further gas generation from IBA as shown in **Fig. 2b**. The IBA solution was then centrifuged, followed by filtration to separate IBA from filtrate. IBA was washed 2-3 times to remove alkalis after treatment. The alkali-treated IBA was then oven dried at 105 °C for 2 hours prior to further characterization and usage as cement supplements.

2.3 Mix design of IBA blended cement mortars

Table 3 summarizes the mix design of IBA blended cement mortars. In accordance with ASTM C311/C311M, 20% of cement in the control mortar should be replaced by the pozzolans of interest. A control mix without the addition of IBA (Mix 1) and another mix with the replacement of 20% cement by the original untreated IBA (Mix 2) were prepared for comparison.

To prepare the mortar specimens, cement, IBA and sand were dry-mixed first for 3 minutes in a planetary mixer. After which, water was slowly added into the mixture and mixed for another 5 minutes until a homogenous and consistent paste was achieved. The fresh mortar was poured into 50 mm cubic moulds and vibrated for 30 seconds. The surface of moulds was then covered with plastic sheet to prevent water

evaporation. The specimens were cured at room temperature and demolded after 24 hours. After demolding, samples were cured in saturated lime water until the pre-determined age for testing at 7 days, 28 days and 90 days.

2.4 Test methods

XRF and XRD were used to characterize chemical and mineralogy composition of IBA, respectively, before and after alkali treatment. XRF technique was used to analyze the type and content of element in sample. The measurements were performed with Bruker wavelength dispersive S8 TIGER sequential X-ray spectrometer in this study. The IBA samples in loose powder form were analyzed as pressed pellets with pre-calibrated standardless method. XRD technique is widely used as a technique for quantitatively and/or qualitatively identifying the crystalline phase in a mixture such as mineral substances, metallic alloy and hydrated cement. In current study, XRD was used to qualitatively identify different crystal phases and compounds in IBA. The XRD analysis was performed with a Bruker D8 powder diffractometer by using Cu K α radiation. The XRD patterns were measured from 10° to 90° (2 θ) at a scan rate of 2°/min. Inductively coupled plasma mass spectrometry (ICP-MS) was used to determine content of trace element in the filtrate solution after the alkali treatment.

Gas generation from the original and the alkali-treated IBAs was measured by means of a collection of gas over water apparatus (**Fig. 3**) to evaluate the effectiveness of the alkali treatment on the removal of metallic aluminum. The setup involved a sealed conical flask in which the reaction took place and a measuring cylinder filled with water and inverted in a water trough. The gas evolved from the sealed conical flask is

collected by attaching one end of a hose to the sealed conical flask and inserting the other end up into the inverted measuring cylinder. As the gas was created, it displaced water from the measuring cylinder. The volume of gas can be determined by the amount of water that was displaced by the gas. In the test, 1 g of IBA was added into 1 M NaOH solution at ambient condition (23 ± 1 °C and 1 atm), which was agitated with a magnetic stirrer at 300 rpm. The amount of gas generated was recorded in every 5 min until the completion of reaction with no further gas generation.

Saturated lime test was adopted in this study to evaluate pozzolanic reactivity of IBA by mixing IBA with saturated lime solution and monitoring the change of calcium content in the solution to identify the degree of pozzolnaic reaction. Saturated $\text{Ca}(\text{OH})_2$ solution was prepared in an environmental chamber at 40 °C. 20 g IBA was mixed with 100 ml saturated $\text{Ca}(\text{OH})_2$ solution followed by vigorous shaking. After that, the IBA suspension was cured in the environmental chamber at 40 °C for 15 days. The consumption of calcium ion was determined by means of inductively coupled plasma optical emission spectrometry (ICP-OES). Pozzolanic reactivity of silica fume (Elkem Microsilica® Grad 920 ASTM) was also evaluated with the same method as the control test. The silica fume used is undensified with bulk density of 200-350 kg/m^3 and specific surface area beyond 15 m^2/g . The content of SiO_2 of the silica fume is more than 85 %.

Dry density of IBA blended cement mortar samples was recorded to evaluate efficiency of metallic aluminium removal by alkali treatment. The sample was first dried in oven at 105 °C for 24 hours. Dry density was then calculated by taking the ratio of mass to volume (50mm×50mm×50mm) of the sample. At least 3 samples

were tested for each mix and the average density and standard deviation were reported. Compressive test was conducted to determine the strength of IBA blended cement mortars. A minimum of four samples were tested for each mix. The pozzolanic reactivity of alkali-treated IBAs were evaluated through the concept of SAI, which is defined as

$$SAI = (B/A) \times 100\% \quad (2)$$

in accordance with ASTM C311/C311M, where A is the compressive strength of control sample without the presence of IBA and B is the compressive strength of mortar-IBA sample where 20% of cement was replaced by IBA.

3 Results and discussion

3.1 Effect of alkali treatment on chemical and mineralogical composition of IBA

Table 4 summarizes the oxide composition of the IBA before and after alkali treatment. As can be seen, calcium (~32% CaO) accounts for the largest proportion of chemical elements in the original untreated IBA and the total content of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and iron oxide (Fe₂O₃) is around 42%. This is close to the definition of class C fly ash where the sum of SiO₂+Al₂O₃+Fe₂O₃ should be more than 50% according to ASTM C618, and thereby indicating potential of IBA as a supplementary cementitious material. After treatment, the Na₂O and K₂O contents are greatly reduced while the total potential “pozzolan” fraction, i.e. SiO₂+Al₂O₃+Fe₂O₃, increases. Sodium and potassium in IBA exist in the form of salt, such as sodium chloride (Halite) as shown in the XRD results, which are easily dissolved and washed away. The composition percentage of other components increases correspondingly in treated IBA due to the removal of Na₂O and K₂O. In this

regard, alkali treatment may enhance the pozzolanic potential of IBA as supplementary cementitious materials.

Fig. 4 shows the XRD diffractogram of IBA before and after alkali treatment. As can be seen, the main crystal phases of the original IBA are quartz (SiO₂), calcite (CaCO₃), magnetite (Fe₂O₃), aluminum oxide (Al₂O₃), Halite (NaCl) and some compounds of calcium, silicon, and aluminum, such as gehlenite (Ca₂Al₂SiO₇), calcium silicate (CaSiO₃) and calcium aluminate oxide (Ca₃Al₂O₆). After treatment, most crystal phases remain unchanged while peaks between 31° to 34° are less sharp as compared to the original IBA. This may be attributed to the dissolution of sodium chloride and reaction of aluminum oxide with sodium/calcium hydroxide to form sodium/calcium aluminate as follows,

In addition, a new peak at around 28° associated with aluminum silicate appears in the sodium hydroxide treated IBA samples. This peak is more pronounced when IBA was treated by NaOH with lower alkalinity (Na12T70) or lower reaction temperature (Na14T25). This is mainly due to the solubility of aluminum silicate increases with the increase of alkalinity and temperature [21].

3.2 Effect of alkali treatment on IBA gas generation and pozzolanic reactivity of IBA

Fig. 5 shows the gas generation from the original and alkali-treated IBAs in 1 M NaOH solution. As can be seen, untreated IBA generated about 5.7 ml gas per gram IBA, and no detectable gas was generated from all four types of alkali-treated IBAs.

This indicates alkali treatment in the current study effectively removed metallic aluminium in IBA.

Fig. 6 shows the percentage of calcium removed from the saturated lime water mixed with the original untreated and alkali-treated IBA. Result of silica fume (SF) is also plotted in the figure as a reference pozzolan. As can be seen, IBAs treated at lower temperature (Na14T25) or lower alkalinity (Na12T70, Ca12T70) showed higher Ca removal capacity than the untreated IBA. This suggests the pozzolanic property of the three alkali-treated IBAs was enhanced. However, IBA treated at high alkalinity and temperature (Na14T70) has slightly lower Ca removal capacity than the untreated IBA, which suggests that high alkalinity and reaction temperature may diminish the pozzolanic property of IBA. Among the four treated IBAs, Na12T70 possesses the highest pozzolanic reactivity followed by Ca12T70, Na14T25, and Na14T70. While the pozzolanic reactivity of Na12T70 is not as strong as silica fume, it is comparable to (or slightly lower than) the class F fly ash which has a calcium removal capacity of 78% at 28 days as reported in [20].

3.3 Trace element analysis in filtrate solution from alkali treatment

Table 5 shows the content of trace elements in the filtrate solution from alkali treatment and from pure water treatment (H₂O T70). As can be seen, content of heavy metals in the filtrate solution from alkali treatment is much reduced than that from pure water treatment, which suggests the alkali treatment of IBA is more environmental friendly as compared to water treatment in terms of disposal of filtrate solution after treatment. This may be attributed to the reaction between metal ions and hydroxyl ion which forms metal hydroxide precipitates as shown below.

where M is metal ion. The formation of metal hydroxide effectively immobilizes heavy metals and reduces leaching potential of IBA.

Comparing the four alkali treatment conditions, higher alkalinity seems to be more effective to immobilize certain heavy metals such as Fe, Mg, Ni, Se and Mo while some other trace elements such as Sb and Cu, show a reverse trend. Different treatment temperature does not seem to have significant influence on trace element content in the filtrate solution of Na14T70 and Na14T25. As for the effects of types of alkalis, it seems that calcium hydroxide treatment is more effective to immobilize heavy metal than sodium hydroxide treatment as the heavy metal content in the filtrate solution of Ca12T70 is less than that of Na12T70. This may be attributed to that the reaction between IBA and calcium hydroxide produces calcium compounds, e.g. calcium aluminate hydrate, which is less soluble as compared to the sodium compounds [22]. As a result, the precipitation of calcium compounds on IBA may further hinder the leaching of heavy metals.

3.4 Dry density of IBA blended cement mortars

Fig. 7 compares the dry density of the control cement mortar, the untreated IBA blended cement mortar, and the alkali-treated IBA blended cement mortar mixes. Density ratio, i.e. ratio between the density of the IBA blended cement mortar to the density of the control cement mortar, is also given in the figure. As can be seen, the untreated IBA blended cement mortar possesses the lowest density due to gas generation from the untreated IBA [23]. It has been reported by the authors that untreated IBA can be used as gas-forming agent to replace costly aluminium powder

for the production of lightweight aerated materials [24, 25]. Mixtures with alkali-treated IBA, on the other hand, have a much higher density of above 95% of the control. This indicates alkali treatment can effectively remove metallic aluminium and to minimize aeration in IBA blended cement.

Among the four treatment conditions, Na14T70 IBA (i.e., high alkalinity and high temperature NaOH treatment) blended cement mortar possesses the highest density comparable to the control. The slightly reduced density may be attributed to the partial replacement of cement with IBA where the specific gravity of IBA (2.65) is lower than that of cement (3.15). Reduced alkalinity (Na12T70) or reaction temperature (Na14T25) causes slight reduction of density of the resulting IBA blended cement mortar which suggests higher alkalinity or reaction temperature favors the removal of metallic aluminium. Furthermore, samples incorporating Ca(OH)₂ treated IBA (Ca12T70) shows the lowest density among the four treatment conditions.

Tests were carried out to measure gas generation from IBA during the Ca12T70 and the Na12T70 treatment conditions and the results are shown in **Fig. 8**. As can be seen, less gas was generated during the Ca12T70 treatment condition than that during the Na12T70 treatment condition. This suggests Ca(OH)₂ treatment is less effective than the NaOH treatment for metallic aluminium removal at the same alkalinity (pH=12) and reaction temperature (70 °C). This may be due to the formation of calcium compounds, e.g. calcium aluminate [26], which precipitate on IBA and hinders further reaction of metallic aluminium in IBA with Ca(OH)₂ solution during treatment. The calcium aluminate layer in IBA may be broken by the mechanical force during mixing

of IBA blended cement mortar which enables further reaction of IBA with cement paste and gas generation from IBA, resulting in slightly lower density. Further study is needed to confirm this hypothesis.

3.5 Compressive strength of IBA blended cement mortars

Fig. 9 shows the compressive strength of IBA blended cement mortars at different age up to 90 days. The general trend shows that the strength of all mixes increases with increasing age. The control cement mortar (w/o IBA) has the highest strength followed by the alkali-treated IBA blended cement mortars ($\text{Na14T25} > \text{Na12T70} > \text{Ca12T70} \approx \text{Na14T70}$). The untreated IBA blended cement mortar possesses the lowest strength due to lower density caused by gas generation from the untreated IBA. It is noted worthy that while increased alkalinity and reaction temperature (Na14T70) favors the removal of metallic aluminium in IBA and the resulting IBA blended cement mortar has the highest density comparable to the concrete cement mortar, the 90-day compressive strength of the Na14T70 cement mortar is the lowest among all treated IBA blended cement mortar. This is attributed to high alkalinity and reaction temperature diminish the pozzolanic property of IBA as discussed in **Sec. 3.2 (Fig. 6)**. An optimum treatment alkalinity and reaction temperature is necessary to remove metallic aluminium in IBA as much as possible while keeping its pozzolanic properties. Further studies (additional data) are required to fully reveal the effects of alkalinity and reaction temperature on pozzolanic properties of IBA and to discover the underlying mechanisms. **Table 6** summarizes the strength activity index (SAI) of the alkali-treated IBA blended cement mortars. Except at early age, the SAIs of all alkali-treated IBA blended cement mortars are above 75% of the control. In particular, the strength of Na14T25 specimen is comparable to that of control at the age of 90

days. Bertolini et al [19] reported a similar result, in which mortar with 30% cement replacement by wet-ground IBA can achieve a comparable strength with the control mortar. This suggests the alkali-treated IBA can potentially be used as supplementary cementitious materials in accordance with ASTM standard C618.

4 Conclusions

This paper studied the effects of alkali treatment conditions including alkalinity, reaction temperature, and alkali types, on the properties of IBA and the resulting IBA blended cement mortars. The alkali treatment effectively removes the metallic aluminum in IBA and minimizes aeration in IBA blended cement mortars. Furthermore, alkali treatment enhanced the pozzolanic properties of IBA and the resulting alkali-treated IBA possessed pozzolanic reactivity similar to coal fly ash. The SAIs of all alkali-treated IBA blended cement mortars are above 75% of the control at the age of 28 days and beyond. In particular, the mix incorporating IBA treated with NaOH (pH=14) at 25 °C has a strength comparable to that of control at the age of 90 days. High alkalinity and reaction temperature; however, diminish the pozzolanic reactivity of IBA. An optimum treatment alkalinity and reaction temperature is necessary to remove metallic aluminium in IBA as much as possible while keeping its pozzolanic properties. The proposed method provides an effective, efficient, and fast means for the removal of metallic aluminum in IBA and the alkali-treated IBA can potentially be used as supplementary cementitious materials for concrete production.

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Table 1 Chemical composition of cement (% by mass)

Oxide	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	P ₂ O ₅
Cement	62.2	24.3	4.6	4.0	3.3	0.6	0.2	0.2

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Table 2 Alkali treatment conditions

No.	ID	Treatment conditions					
		Temp. (°C)		Alkalinity (PH)			Alkali type
		25	70	7	12	14	NaOH Ca(OH) ₂
1	H ₂ OT70		✓	✓			
2	Na14T70		✓			✓	✓
3	Na14T25	✓				✓	✓
4	Na12T70		✓		✓		✓
5	Ca12T70		✓		✓		✓

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Table 3 Mix design of IBA blended cement mortars

Mix No.	Mix ID	Cement (g)	Untreated IBA (g)	Treated IBA (g)	Sand (g)	Water (g)	SP (ml)
1	Control (w/o IBA)	500	0	0	1375	242	5
2	Untreated IBA	400	100	0	1375	242	5
3	Na14T70	400	0	100	1375	242	0
4	Na14T25	400	0	100	1375	242	0
5	Na12T70	400	0	100	1375	242	0
6	Ca12T70	400	0	100	1375	242	0

447 * SP: superplasticizer

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Table 4 Oxide composition of IBA before and after treatment

Oxide	Original IBA (%)	Alkali-treated IBA (%)			
		Na14T70	Na14T25	Na12T70	Ca12T70
CaO	32.47	34.93	34.50	34.90	33.47
SiO ₂	25.89	29.02	28.99	29.17	30.16
Fe ₂ O ₃	9.92	12.52	12.62	11.49	11.89
Al ₂ O ₃	6.47	6.51	6.77	7.24	7.15
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	42.28	48.05	48.36	47.90	49.20
Na ₂ O	10.90	2.77	2.89	3.40	3.53
K ₂ O	1.53	0.78	0.76	0.82	0.79
P ₂ O ₅	7.75	8.07	8.01	7.64	7.64
MgO	2.38	2.23	2.33	2.34	2.44
TiO ₂	1.18	1.42	1.39	1.39	1.33
CuO	0.45	0.53	0.53	0.45	0.46
ZnO	0.45	0.40	0.40	0.47	0.48
Cr ₂ O ₃	0.22	0.28	0.27	0.27	0.26
PbO	0.15	0.24	0.21	0.17	0.19
MnO	0.11	0.15	0.15	0.19	0.18
SrO	0.06	0.10	0.10	0.06	0.06

Table 5 Content of trace elements in filtrate solution from alkali treatment and water treatment

Trace elements	Content in filtrate solution (ppb)				
	Water treatment		Alkali-treatment		
	H ₂ OT70	Na14T70	Na14T25	Na12T70	Ca12T70
Ag	0.02	0.01	0.00	0.01	0.00
As	7.02	2.77	2.68	2.01	1.15
Cd	0.70	0.15	0.15	0.18	0.09
Co	1.79	0.62	0.63	0.56	0.31
Cr	5.55	1.87	1.58	7.35	2.77
Cu	1909.00	1148.00	1107.00	512.00	379.00
Fe	1500.00	16.20	16.90	288.00	234.00
Hg	3.12	0.76	0.67	1.03	0.52
Mo	142.56	29.14	28.05	50.33	30.89
Ni	31.40	2.77	2.95	6.28	3.81
Sb	83.15	28.51	24.81	11.17	7.34
Se	12.60	1.23	1.31	3.94	2.10
Mg	48.60	1.00	1.03	9.48	4.56

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Table 6 Strength Activity Index of treated IBA blended cement mortars

Mix ID	Strength Activity Index (%)		
	7 days	28 days	90 days
Na14T70	70	81	79
Na14T25	73	76	99
Na12T70	70	79	94
Ca12T70	81	82	76

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Fig. 1 Gradation of the ground IBA

(a)

(b)

Fig. 2 Alkali treatment of IBA for (a) 15 and (b) 120 minutes

Fig. 3 Collection of gas over water apparatus

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Fig. 4 XRD diffractogram of IBA before and after alkali treatment

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Fig. 5 Gas generation from the original and alkali-treated IBAs in 1 M NaOH solution

Fig. 6 Percentage of calcium removed from the saturated lime water mixed with IBA
(silica fume as the control test)

Fig. 7 Dry density of IBA blended cement mortars

Fig. 8 Gas generation during the alkali-treatment

Fig. 9 Compressive strength of IBA blended cement mortars