Alkali-Activated Aluminium-Silicate Composites as Insulation Materials for Industrial Application

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Abstract. The article reports on the study of thermal stability of alkali-activated aluminium-silicate composites (ASC) at temperature 800–1100°C. ASC were prepared by using calcined kaolinite clay, aluminium scrap recycling waste, lead-silicate glass waste and quartz sand. As alkali activator, commercial sodium silicate solution modified with an addition of sodium hydroxide was used. The obtained alkali activation solution had silica modulus $M_s=1.67$. Components of aluminium scrap recycling waste (aluminium nitride (AlN) and iron sulphite (FeSO$_3$)) react in the alkali media and create gases – ammonia and sulphur dioxide, which provide the porous structure of the material [1]. Changes in the chemical composition of ASC during heating were identified and quantitatively analysed by using DTA/TG, dimension changes during the heating process were determined by using HTOM, pore microstructure was examined by SEM, and mineralogical composition of ASC was determined by XRD. The density of ASC was measured in accordance with EN 1097-7. ASC with density around 560 kg/m$^3$ and heat resistance up to 1100°C with shrinkage less than 5% were obtained. The intended use of this material is the application as an insulation material for industrial purposes at elevated temperatures.

1. Introduction

Heat-resistant concrete is a widely used material in high temperature conditions for industrial machinery. It is constantly subjected to operating and deterioration under combined thermo-chemo-hydro-mechanical effects, which often cause chemical and physical alteration of the concrete and result in excessive cracking, spalling and loss of strength [2]. In the industry, there is a need for
insulation materials stable at the elevated temperatures in order to preserve equipment from heating and cooling processes, and to satisfy the safety requirements, such as protecting personnel from hot or cold surfaces.

Studies have shown that scientists all over the world are searching to upgrade heat-resistant concretes and are looking for new materials, which can be applied at the elevated temperatures. The proposed alkali activated materials could also be used as an alternative to concrete; they have emerged as solutions to overcome the problem of massive usage of virgin raw materials and reduce CO$_2$ emissions [3]. Useful utilisation of the industrial waste is a much more attractive alternative than depositing it on the waste sites. Recycling of industrial waste into new materials reduces possible pollution of the environment and decreases the costs of waste deposits, as well as saves resources for manufacturing new materials and building units.

Alkali activation is a type of geosynthesis that involves naturally occurring aluminium-silicates; it is based on the chemistry of alkali-activated inorganic binders. These amorphous, three-dimensional aluminium-silicate binder materials, the formation process of which was first explained by Glukhovsky, were first introduced to the world of inorganic cementations materials by Davidovits [3]. Alkali activated materials may be synthesized at room temperature or at slightly elevated temperatures by the alkaline activation of aluminium-silicates obtained from industrial wastes, calcined clays, natural minerals or mixtures of two or more of these materials as well as different types of inert fillers. In a strong alkaline solution, aluminium-silicate reactive materials rapidly dissolve to form free SiO$_4$ and AlO$_4$ tetrahedral units [4,5]. During the polycondensation reaction, the tetrahedral units are linked in an alternating manner to yield amorphous structure.

A key attribute of alkali activation technology is the robustness and versatility of the manufacturing process; it enables products to be tailor-made from a range of aluminium-silicate raw materials so that they have specific properties for a given application at a competitive cost [6]. It is clear that alkali activated materials can exhibit performance properties such as high compressive strength [7]; high level of resistance to a range of different acids and salt solutions and high freeze–thaw resistance [8]; not subject to deleterious alkali–aggregate reactions [8]; low shrinkage [9]; low thermal conductivity [10]; good adhesion to steel [11]; inherent protection of steel reinforcing due to high residual pH and low chloride diffusion rates [12]; high stability when exposed to high temperatures [8]; effective solution for the stabilization of industrial by-products and the immobilization of heavy metals [13]. Although several researchers demonstrated an excellent durability of alkali activated materials in their experiments, the major unsolved problem in the development and application of alkali activation technology is still related to the durability, because it seems to depend strongly on the adequate curing regimes and composition.

This study attempts to respond to both issues: industrial waste and by-product usage in the production of alkali-activated aluminium-silicate composites (ASC), thus minimizing the usage of non-renewable natural resource and obtaining improved heat resistance of materials, while adjusting dimensional changes by adding quartz sand fillers, and secondly, porous aluminium-silicate composite suitability as thermal insulation material for industrial production purposes.
2. Materials and test methods

2.1. Test methods
Chemical composition of raw materials – calcined kaolinite clay (MK), waste from aluminium scrap recycling factory (ASRW) and lead-silicate glass waste (LSG) from glass recycling factory was determined according to LVS EN 196-2 with precision +/- 0.5%. The analysis of ASRW elements was carried out with the help of inductively coupled plasma optical emission spectrometry (ICP-OES), atomic absorption spectroscopy (AAS) and potentiometer titration analyses. Particle size distribution in powder materials was determined by laser diffraction. Specific surface area was detected by BET method (‘Nova 1200 E-Series, Quantachrome Instruments’). Effective diameter was detected by Zeta potential (‘90 Plus’ and ‘MAS Zeta PALS Brookhaven Instr’).

Mostly instrumental methods were used for investigation of aluminium-silicate binders without quartz filler to avoid dominance of quartz. Thermogravimetrical research was carried out by using High temperature DTA / DSC Baehr DTA 703. The mineralogical composition by X-ray diffraction (XRD) (PAN analytical X’Pert PRO) was determined for raw materials and ASC. Thermal conductivity test was performed with heat flow meter instrument LaserComp FOX. The upper and lower plate temperatures were 0°C and 20°C with average temperature of 10°C. High temperature microscopy (HTOM) EM201, HT163 was used to determine heat resistance and shrinkage of ASC in temperatures up to 1400°C. The sample has been tested by heating rate 80°C/min up to the temperature of 500°C and then switched to 15ºC/min while reaching the temperature of 1400°C. Alkali-activated aluminium-silicate binders (ASB) and composites (ASC) with quartz sand filler were observed using scanning electron microscope (‘TESCAN Mira / LMU Field-Emission-Gun’).

2.2. Raw materials
Raw materials used in this study were calcined kaolinite clay (MK), aluminium scrap recycling waste (ASRW), lead-silicate glass waste (LSG) received from recycling industry and quartz sand (Q). Alkali-activation of raw material composition was done by modified sodium silicate solution with an addition of sodium hydroxide. MK, ASRW and LSG were ground in the laboratory planetary ball mill Retsch PM 400 for 30 min with speed of 300 rpm to obtain homogenous powder raw material.

In the current study, MK was obtained in the laboratory furnace by sintering commercially available kaolinite clay at the temperature of 800°C. Sintering process of calcined kaolinite clay lasted approximately 3 hours with the temperature increase of 15°C/min. After additional grinding specific surface area of MK was 15.86 m²/g, whereby effective diameter of MK particles was 743.1 nm. Chemical composition of MK is given in table 1. According to XRD analysis, MK used is largely amorphous, with a small quantity of quartz (SiO₂) as an impurity phase, and minor kaolinite. Crystalline layer structure, which is a common characteristic of clay minerals, leads to a fine particle size (1-3 µm) and plate like morphology in MK, it was determined by SEM. ASRW is the final waste in the aluminium scrap recycling process (chemical composition is given in table 1). The content analysis of ASRW shows the following results: aluminium (Al) – 34.40%, silicon (Si) – 4.4%, magnesium (Mg) – 2.4%, calcium (Ca) – 1.3%, sodium (Na) – 1.7%, potassium (K) – 2.3%, sulphur (S) – 0.1%, chlorine (Cl) – 4.2%, iron (Fe) – 3.6%, copper (Cu) – 1.0%, lead (Pb) – 0.1% and zinc (Zn) – 0.6%. These data correspond to the chemical composition of ASRW. In terms of chemical composition, the analysed ASRW contained also aluminium nitride (AlN) – on average 5 wt.%, aluminium chloride (AlCl₃) – on average 3 wt.%, potassium and sodium chloride (NaCl + KCl) – total 5 wt.% and iron sulphite (FeSO₃) – on average 1 wt.%. According to the XRD analysis, the ASRW
contained metallic aluminium (Al), iron sulphite (FeSO₃), aluminium nitride (AlN), corundum (Al₂O₃), aluminium iron oxide (FeAlO₃), magnesium dialuminium (MgAl₂O₄), quartz (SiO₂), aluminium chloride (AlCl₃) and aluminium hydroxide (Al(OH)₃) [1, 16].

Table 1. Chemical composition of ASRW, MK, LSG and Q [wt. %].

| Chemical component | ASRW | MK   | LSG  | Q   |
|--------------------|------|------|------|-----|
| Al₂O₃              | 63.19| 25.55| 1.03 | 1.42|
| SiO₂               | 7.92 | 63.66| 68.07| 96.8|
| CaO                | 2.57 | 3.47 | 1.39 | -   |
| SO₃                | 0.36 | -    | -    | -   |
| TiO₂               | 0.53 | -    | -    | -   |
| MgO                | 4.43 | 1.97 | -    | -   |
| Fe₂O₃              | 4.54 | 0.51 | 0.19 | 0.34|
| PbO                | -    | 20.02| -    | -   |
| Na₂O               | 3.84 | 3.75 | 8.02 | -   |
| K₂O                | 3.81 | 0.45 | 1.17 | -   |
| Other              | 2.60 | 0.53 | 0.11 | 0.49|
| LOI, 1000°C        | 6.21 | 0.21 | -    | -   |

LSG was obtained from fluorescent lamp recycling process, which includes lamp classification, glass separation, cleaning from harmful components and glass grinding. The results of grading analysis showed that additionally ground material contains a wide range of particles in dimensions from 8 µm to 30 µm with the average grain size of 26.3 µm. It is comparable with the data obtained from the investigation made by SEM. Ground LSG particles have smooth surface. The specific surface area of LSG ground for 30 min was 1.126 m²/g.

Quartz sand (Q) was used as an available filler to reduce deformations and dimensional changes of ASC at elevated temperatures. Chemical analysis of Q is given in table 1. The mass ratio between solid raw materials of ASC and Q was from 1:1 to 1:1.67.

Alkali activator was prepared by modification of commercial sodium silicate solution (Ms = 3.22). To obtain alkali activation solution with the required chemical composition (Ms = 1.67), the modification with an addition of sodium hydroxide was performed. Commercially available sodium hydroxide flakes with 97% purity were used.

2.3. Sample preparation and curing conditions

Two series of samples were prepared. Compositions without quartz filler (ASC binders) are presented in Table 2, but with quartz filler (called composites) – in Table 3. Fresh mixtures were cast in 40x40x160 mm prismatic moulds and curing conditions were kept constant at temperature 80°C for 24h. The optimal curing temperature of 80°C was selected for 24 hours to obtain specimens with as few cracks as possible. Components of ASRW – aluminium nitride (AlN) and iron sulphite (FeSO₃) – react in the alkali environment and create gases – ammonia and sulphur dioxide, which provide porous structure of material before setting [16]. After 24 hours, samples were demoulded and kept in the ambient environment. To determine dimensional changes at the elevated temperatures, samples were sawn into smaller pieces with dimensions 10x40x40 mm. Density was tested before and after heat treatment at temperatures 800, 900, 1000 and 1100°C.
3. Results and discussion

3.1. Alkali-activated aluminium-silicate binders (ASB)

Due to the chemical reactions and gas evaporation from the mixture before setting, highly porous material was obtained [1]. Selected alkali-activated aluminium-silicate binders (ASB) provided density in the range from 300 to 340 kg/m$^3$ (table 2). After heat treatment, density of binders did not change significantly except for A10-A1-G1 with bigger amount of glass (LSG) in the composition.

| Batch     | Composition, mass ratio | Treatment temperature [°C] | Mass changes after heating, [%] | Density, [kg/m$^3$ ] before heating | Density, [kg/m$^3$ ] after heating |
|-----------|-------------------------|----------------------------|---------------------------------|-------------------------------------|-----------------------------------|
| A10-A1-G0 | MK 1 ASRW 1 LSG 0       | 800                        | -14.8                           | 340                                 | 330                               |
|           |                         | 900                        | -14.4                           | 340                                 | 330                               |
|           |                         | 1000                       | -13.6                           | 340                                 | 320                               |
|           |                         | 1100                       | -12.8                           | 340                                 | 340                               |
| A10-A1-G0.5 | MK 1 ASRW 1 LSG 0.5  | 800                        | -14.5                           | 324                                 | 320                               |
|           |                         | 900                        | -14.4                           | 324                                 | 320                               |
|           |                         | 1000                       | -15.3                           | 323                                 | 304                               |
|           |                         | 1100                       | -14.9                           | 323                                 | 311                               |
| A10-A1-G1 | MK 1 ASRW 1 LSG 1      | 800                        | -14.0                           | 300                                 | 300                               |
|           |                         | 900                        | -14.2                           | 310                                 | 310                               |
|           |                         | 1000                       | -13.7                           | 330                                 | 340                               |
|           |                         | 1100                       | -14.0                           | 328                                 | 300                               |

Density of A10-A1-G1 decreased from 328 to 300 kg/m$^3$ after heat treatment at temperature 1100°C (table 2). Bloating of the specimen and volume increase was observed.

DTA and TG tests for the binder specimens with bigger amount of glass (LSG) additive (A10-A1-G1) and samples without glass (LSG) additive (A10-A1-G0) in the composition were performed to explain the dimensional changes during heating process (figure 1 and figure 2). Endoeffect at the temperature of 110°C is explained by lost mechanically associated water and dehydration of N-A-S-H or Si(OH)$_4$ gel, because in the temperature interval 90-130°C up to 80% of water is intensively evaporating from the sodium silicate solution used as activator for production of alkali activated materials. The dehydration of N-A-S-H or Si(OH)$_4$ gel continues till 300-400°C.
There are indications that commercial sodium silicate solution used for preparation of alkali activator releases chemically bonded water in the temperature interval till 600°C - 700°C and the formation of crystals of sodium disilicate is possible. According to XRD, ASRW contains Al(OH)$_3$, as well as aluminium nitride (AlN), which reacts with water vapour and creates additional Al(OH)$_3$ and NH$_3$ in the temperature interval from 120 to 150°C. Endoeffect observed in the temperature range of 220 to 280°C indicates decomposition of Al(OH)$_3$ (figures 1 and 2). Both exoeffects found in the temperature interval 800-900°C indicate formation of new minerals. It is possible that part of Al(OH)$_3$ and metallic Al reacts with NaOH and creates new mineral NaAlOH$_4$ at the temperature around 800°C (figure 1) and albite (Na$_2$OˑAl$_2$O$_3$ˑ6SiO$_2$) at the temperature around 900°C. The small endoeffect detected at the temperature 573°C is associated with structural transition of the α-quartz SiO$_2$ to β-quartz.

According to the data obtained by high temperature microscopy, specimen A10-A1-G0 shows practically no changes before heat treatment up to 800°C (figure 3). Dimensional shrinkage of binders is observed in the temperature interval from 800°C to 1000°C, which compiles around 20% from the total area. In the temperature interval from 1000°C to 1300°C material expands and melts afterwards.
Sample A10-A1-G0.5 has medium LSG amount in the mixture (table 2). Up to temperature 800°C the sample shows practically no changes. In the temperature range from 800°C to 900°C shrinkage of the material is observed, it constitutes around 10% from the total relative area (figure 4). In the temperature range 900°C - 1080°C material shows no visual changes and shrinkage is constant (10% of the total area). Reaching temperature above 1080°C, the material expands and melts afterwards.

Sample A10-A1-G1 reaches shrinkage around 5% from the total relative area after heat treatment in the interval from 100°C to 750°C. At the elevated temperature 750°C till 800°C the material has lost 10% of the total area, but then from 800°C till 860°C the material expands for about 20%. From 860°C till 950°C the material loses around 15% of the total relative area and then from around 950°C till 1050°C it expands and melts afterwards. It is possible to use this particular material without any volume changes at the working temperature up to 850°C.

![Figure 3](image)

**Figure 3.** High temperature microscopy curve: relative area change of ASB during heating.

It was concluded that glass (LSG) additive has significant influence on the heat resistance of alkali activated materials. LSG has 8% of Na2O, sodium oxide is a known flux, if sodium content is increased in the composition, the formation of a melt at a lower temperature is favoured. The binder (A10-A1-G0) has 5% shrinkage of relative area at temperature 840°C, 7.5% –at 868°C and 10% shrinkage –at 887°C, 20% –985°C (figure 3). By increasing the amount of glass (LSG) in the composition, shrinkage of material increases –for specimens A10-A1-G1 shrinkage of 5% is observed already at the temperature of 770°C, but in case of increasing the temperature up to 1000°C, shrinkage of material does not exceed 5%.

| Composition      | Deformation range, °C | Sphere T, °C | Shrinkage |
|------------------|------------------------|--------------|-----------|
| A10-A1-G0        | 1196                   | 1357         | 840 868 887 985 |
| A10-A1-G0.5      | 1169 1169-1349         | 1272         | 826 850 878 -    |
| A10-A1-G1        | 974 974-1286           | 1174         | 770 - - -        |
| A10-A1-G0-Q3     | 1186 1186-1199         | 1199         | 660 680 1051 1150 |
| A10-A1-G0-Q5     | 1165 1165-1200         | 1200         | 730 1120 1160 1150 |
| A10-A1-G1-Q3     | 1066 1066-1134         | 1102         | 680 720 745 1051 |
| A10-A1-G1-Q5     | 1165 1165-1234         | not defined  | 1119 1139 1149 1174 |

**Table 3.** Relative area changes of samples at different temperatures.
By increasing the temperature over 1000°C, expansion of specimens A10-A1-G1 is observed. Comparing the resulting material to the composition without additive in the material it was concluded that glass (LSG) additive causes shrinkage of the material at lower temperature and therefore reduces material working temperature to 770°C degrees. Mass changes of samples after heat treatment (table 2) correspond to the data obtained by DTA/TG (figures 1 and 2) and HTOM (figures 3 and 5).

3.2. Alkali-activated aluminium-silicate composites (ASC)
Binder compositions (A10-A1-G0, A10-A1-G0.5, A10-A1-G1) with satisfactory dimension changes in the temperature interval from 800 till 1000°C were supplemented with quartz sand filler (Q) and alkali-activated aluminium-silicate composites (ASC) were prepared for the further investigations. Microstructure of hardened ASC looks amorphous and homogenous (figure 4). Additional research was done regarding the investigation of the correlation between curing conditions and microstructure of ASC. However, some micro cracks have been observed in the material structure (figure 4, b). This could be caused by the temperature regime during hardening process of specimens or could have appeared during sample preparation procedure. Micro cracks do not affect strongly the functional properties of ASC due to its high total porosity (82-83%), and low compressive strength (up to 2 MPa).

Figure 4. Photographs of ASC A10-A1-G0-Q5 composition’s pore structure: a) optical microscopy, b) SEM (magnification 5000x).

The density of alkali-activated aluminium-silicate composites (ASC) with quartz filler is between 510 and 590 kg/m³ (table 4). Mass loss after heating of all samples containing quartz in the composition was 8-28% depending on the heating temperature.

As the previous studies indicate, quartz sand filler (Q) limits the expansion of the alkali activated material at temperatures above 1000°C, the subsequent high-temperature microscopy studies were also performed for samples A10-A1-G0-Q3, A10-G1-Q3, A10-A1-G1-Q5 and A10-G1-Q5 (figure 5).

Alkali activated binders with different amounts of glass (LSG) additive had been chosen for preparing aluminium-silicate composites (ASC). Quartz sand filler (Q) was added to the mixture in the amount of 3 and 5 weight parts to limit the expansion of materials at the temperature up to 1000°C (table 4). Relative area changes of ASC at different temperatures are given in figure 5. Results show that ASC with increased amount of glass (LSG) and quartz sand filler (Q) in the composition (A10-A1-G1-Q5) have 5% shrinkage at the higher temperature – 1119°C, 7.5% – at 1139°C, 10% – at 1149°C and 20% shrinkage – at 1174°C (figure 5).
### Table 4. ASC compositions and their physical properties before and after heat treatment.

| Batch          | Reactive components (mass ratio) | Filler | Treatment temperature [°C] | Mass changes after heating [%] | Density, [kg/m$^3$] before heating | Density, [kg/m$^3$] after heating |
|----------------|---------------------------------|--------|-----------------------------|---------------------------------|-----------------------------------|---------------------------------|
|                | MK ASRW LSG Q                   |        |                             |                                 |                                   |                                 |
| A10-A1-G0-Q3   | 1 1 0 3                         |        | 800                         | -8.66                           | 550                               | 520                             |
|                |                                 |        | 900                         | -8.63                           | 560                               | 540                             |
|                |                                 |        | 1000                        | -8.20                           | 540                               | 520                             |
|                |                                 |        | 1100                        | -8.08                           | 540                               | 520                             |
| A10-A1-G0-Q5   | 1 1 0 5                         |        | 800                         | -12.08                          | 550                               | 520                             |
|                |                                 |        | 900                         | -27.49                          | 580                               | 460                             |
|                |                                 |        | 1000                        | -27.45                          | 580                               | 440                             |
|                |                                 |        | 1100                        | -26.58                          | 590                               | 470                             |
| A10-A1-G1-Q3   | 1 1 1 3                         |        | 800                         | -18.71                          | 560                               | 540                             |
|                |                                 |        | 900                         | -26.19                          | 510                               | 530                             |
|                |                                 |        | 1000                        | -26.59                          | 570                               | 540                             |
|                |                                 |        | 1100                        | -26.99                          | 540                               | 420                             |
| A10-A1-G1-Q5   | 1 1 1 5                         |        | 800                         | -28.37                          | 540                               | 400                             |
|                |                                 |        | 900                         | -27.87                          | 590                               | 450                             |
|                |                                 |        | 1000                        | -27.08                          | 590                               | 470                             |
|                |                                 |        | 1100                        | -28.04                          | 560                               | 480                             |

**Figure 5.** High temperature microscopy curve: relative area change of ASC containing quartz sand filler (Q) during heating.
3. Conclusion
The new type of porous alkali activated aluminium-silicate composite (ASC) was obtained by using alkali activated aluminium-silicate binder (ASB) made of industrial by-products such as aluminium scrap recycling waste and lead-silicate glass waste (LSG) from recycled fluorescent lamps and natural filler.

It was concluded that glass waste (LSG) additive plays ambiguous role in the composition of alkali activated binders (ASB). On the one hand, it promotes significant shrinkage (5%) and volume changeability already at low temperatures (770°C) and afterwards samples are expanding, when temperature is raised just up to 975°C, but on the other hand, the volume changeability does not increase 5% till expansion temperature. That finding was combined with the results of previous investigation and the quartz sand filler (Q) was selected as an additive for the reduction of expansion. Therefore, alkali activated binders (ASB) with glass (LSG) in the composition were selected as most promising mixture for obtaining heat resistant ASC.

The most important conclusion of this study is that quartz sand filler (Q) slows down the expansion of alkali activated binder (ASB) at temperature higher than 1000°C and significantly prolongs working application of the material. With an addition of quartz sand filler (Q) in the composition (5 weight parts), ASC with density between 540-590 kg/m^3 and shrinkage less than 5% at elevated temperatures up to 1119°C was obtained. Density can be controlled by moulding fresh mixture and alkali content in activator solution. However, due to the low density and specific pore structure development, mechanical properties of the material were limited.

Finally, new material with heat resistance up to 1100°C was obtained. The essential indicator is the ability of quartz sand filler (Q) to slow down the influence of lead-silicate glass waste (LSG) and to prolong working applicability of this material. Therefore, it was concluded that ASC could be used as a new insulation material in the production industry.

4. References
[1] Bajare D, Bumanis G and Korjakins A 2014 New Porous Material Made from Industrial and Municipal Waste for Building Application Materials Science 20 333
[2] Prakash S B, Chang V and Li M 2014 Effect of elevated temperature on strain-hardening engineered cementitious composites Construction Building Materials 69 370-380
[3] Prud'homme E, Michaud P, Joussein E, Clacens J M, Arii-Clacens S, Sobrados I, Peyratout C, Smith A, Sanz J and Rossignol S 2011 Structural characterization of geomaterial foams - Thermal behaviour J. of Non-Crystalline Solids 357 3637
[4] Xu H and Van Deventer J S J 2000 The Geopolymerisation of Alumino-silicate minerals Int. J. of Mineral Processing 59 247
[5] Wu J P, Boccaccini A R, Lee P D and Rawlings R D 2007 Thermal and mechanical properties of a foamed glass-ceramic matrix produced from silicate wastes European J. of Glass Science and Technology 48 133
[6] Duxson P, Provis J L, Lukey G C and Van Deventer J S J 2007 The role of inorganic polymer technology in the development of ‘green concrete’ Cement&Concrete Research 37 1590
[7] Lee W K W and Van Deventer J S J 2002 The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements Cement&Concrete Research 32 577
[8] Pacheco-Torgal F, Abdollahnejad Z, Camões A F, Jamshidi M and Ding Y 2012 Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue Construction Building Materials 30 400
[9] Elimbi A, Tchakoute H K and Njopwouo D 2011 Effects of calcination temperature of kaolinite clays on the properties of geopolymer cements *Construction Building Materials* **25** 2805

[10] Arellano Aguilar R, Burciaga Díaz O and Escalante García J I 2010 Lightweight concretes of activated metakaolin-fly ash binders with blast furnace slag aggregates *Construction Building Materials* **24** 1166

[11] Temuujin J, Minjigmaa A, Rickard W, Lee M, Williams I and Van Riessen A 2009 Preparation of metakaolin based geopolymer coatings on metal substrates as thermal barriers *Applied Clay Science* **46** 265

[12] Lloyd R R, Provis J L and Van Deventer J S J 2010 Pore solution composition and alkali diffusion in inorganic polymer cement *Cement&Concrete Research* **40** 1386

[13] Zheng L, Wang C, Wang W, Shi Y and Gao X 2011 Immobilization of MSWI fly ash through geopolymerization: effects of water-wash *Waste Management* **31** 311

[14] Abdullah M M A B, Hussin K, Bnhussain M, Ismail K N, Yahya Z and Abdul Razak R 2012 Fly Ash-based Geopolymer Lightweight Concrete Using Foaming Agent *Int. J. of Molecular Sciences* **13** 7186

[15] Zuda L and Cerny R 2009 Measurement of linear thermal expansion coefficient of alkali-activated aluminosilicate composites up to 1000°C *Cement & Concrete Composites* **31** 263

[16] Bajare D, Korjakins A, Kazjanovs J and Rozenstrauha I 2012 Pore structure of lightweight clay aggregate incorporate with non-metallic products coming from aluminium scrap recycling industry *J. of the European Ceramic Society* **32** 141

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