

Geopolymers and Other Inorganic Polymers

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EFFECT OF EXTERNAL AND INTERNAL CALCIUM IN FLY ASH ON GEOPOLYMER FORMATION

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ABSTRACT

Calcium in fly ash can be present as a glass component or as a free lime. The presence of calcium in fly ash glass so called "internal calcium" can have effect on the leaching of the glass and consequently the availability of Si and Al for geopolymer product formation. Whereas, the presence of calcium as a free lime in fly ash so called "external calcium" would have indirect effect on leaching as this fly ash contains higher Si and Al contents. In addition to the effect of calcium on the leaching, the source of calcium can have effect on the product formation. To study these two effects, the synthetic fly ash glasses with low and high calcium content were prepared to be used for leaching test and for formulating geopolymer. The specimen with external calcium was prepared by adding CaO to the geopolymer made with synthetic fly ash with low calcium. The specimen with internal calcium was prepared by using synthetic fly ash with high calcium content in the geopolymer mix. Synthetic fly ash was used instead of real fly ash to control the glass composition in fly ash and to avoid the effect of calcium from mineral phases. Synthetic fly ash glasses were prepared from lab grade chemical oxide as a starting material for geopolymer matrices. The mole ratio of Si:Al was kept at 1.84:1. The fly ash glass was ground and then mixed with NaOH solution. The products were characterized by FTIR technique to study the polymerization of the gel. The presence of calcium composite gel was determined by the difference in FTIR pattern before and after acid leaching which is specific for calcium composite gel. The compressive strength of geopolymer was investigated to study the contribution of these gels to strength. The percentage of C-S-H gel and N-A-S-H gel formed were determined and correlated with the compressive strength of geopolymer. It was found that the type of glass and the source of calcium have effect on geopolymer product formation. The geopolymer made from low calcium fly ash and external calcium has higher compressive strength than the one made from high calcium fly ash. This can be due to the leaching of the glass as the leaching result shows that low calcium glass can provide more Si and Al content for N-A-S-H and other zeolite formation. As for the effect of the source of calcium on the product formation, the FTIR analysis shows that the internal calcium in the high calcium glass forms more CSH gel than the external calcium in the low calcium glass. This could be because the external calcium might precipitate in high pH solution while the internal calcium does not.

INTRODUCTION

Geopolymer or inorganic polymer is aluminosilicate framework. The term of geopolymer was first applied by Davidovids, 2008¹. Reaction of geopolymer is called geopolymerization which involves a chemical reaction in a highly alkali such as sodium hydroxide, potassium hydroxide and/or sodium silicate, potassium silicate solution with aluminosilicate reactive material such as metakaolin, fly ash. Under strong alkali solution, aluminosilicate materials are rapidly dissolved to form free tetrahedral of Si and Al (SiO_4 and AlO_4). In geopolymerization, water gradually splits out and tetrahedral of Si and Al are linked alternatively to yield polymeric precursors by sharing all oxygen atoms between two tetrahedral units¹. In term of geopolymer, it was proposed that geopolymer is

formed by geopolymerization of individual aluminate and silicate species¹. The major difference between geopolymer and Portland cement is the presence of calcium in their structure. Calcium silicate hydrate (CSH) is the major product of Portland cement while calcium is not essential in any geopolymerization product. Many starting material of geopolymer composed of calcium such as Class C fly ash, and furnace slag.

Class F fly ash is a good candidate for starting material of geopolymer as it can provide alumina as well as silica to the geopolymer process. It is composed of 60-80% amorphous phase and some crystalline phase such as quartz, mullite, hematite and maghettite²⁻⁴. Class C fly ash as it contains higher calcium content can provide calcium in addition to silica and alumina to the matrix. The dissolved calcium can participate in three processes. First, it can be hold in the matrix inside the geopolymer product⁵. This calcium can interfere with geopolymer process and have effect on the property. Second, under strong alkali solution of geopolymer mix, the calcium hydroxide would precipitate as it has low solubility in water at high pH. Third, the remaining of calcium can form CSH gel when the alkalination induces the cleavage of siloxane link (Si-O-Si) that react with Ca(OH)₂ to form Ca-Di-siloxanate tobermorite or CSH gel^{1,6-7}. Some researchers found that, calcium in fly ash improves mechanical property of geopolymer. It accelerates the hardening process and increases the strength^{8,9}. Some groups found that adding Ca(OH)₂ to geopolymer mixture can improve mechanical property^{6,10}. Notice that this property is the combined property of Ca-geopolymer, CSH gel and geopolymer gel. No work has been done to distinguish the ratio of these products. The source of calcium might have effect on the formation of these products. External calcium is the calcium that is added in to the mix while internal calcium is the intrinsic calcium in the fly ash glass. It is believed that the external calcium is more readily available than the internal calcium as the internal calcium inside the glassy phases might not dissolve all out at early age. Thus, the system with external calcium would have more calcium products than the system with internal calcium. Alonso, Palomo, Yip and Kumar found that both internal and external calcium can produce CSH gel, CAH and CASH gel^{9,11-12}.

In this research, the effect of fly ash glass type and the source of calcium on geopolymer production formation were studied. The fly ash with external calcium was prepared by synthesizing fly ash glass with low calcium and adding Ca(OH)₂ to obtain the same Ca(OH)₂ content as fly ash with high calcium, so called, internal calcium. The fly ash glass was synthesized from the chemicals in order to control the chemical composition. The products of geopolymer were characterized by FTIR, XRD and salicylic acid with methanol (SAM solution) leaching test. The compressive strength of geopolymer was also measured and related with other properties.

TECHNICAL APPROACH

Synthesizing fly ash glass

The fly ash glass was batched by lab grade chemical oxide. The glasses with low and high calcium were named SFALC and SFAHC, respectively. The mixture was melted at 1550°C in electric furnace. Fly ash glass was ground and sieved under 45 µm. The chemical composition of fly ash glass was determined by XRF technique. The mineralogy of glass was characterized by XRD technique. The molecular structure of fly ash glass was characterized by FTIR technique.

Reactivity Test

The glass samples were hydrated in 14 M NaOH to determine the reactivity. Initially about 1 g of glass was placed in contact with 100 ml of a 35 °C alkaline solution, leading to a glass surface area to solution volume (S/V) ratio at the beginning of the test of 100 cm². The glass powder was hydrated up to 7 days at 35 °C. At the end of the leaching period the samples was filtered and then dried at room temperature before measuring the weight difference. The remaining fly ash was determined the chemical composition by XRF technique.

Synthesizing geopolymer paste

The geopolymer paste with internal calcium was prepared by mixing SFAHC with 14 M NaOH solution while that of external fly ash was prepared from the mix of SFALC with Ca(OH)₂ and 14 M NaOH solution. The mole ratio of Si:Al was 1.84:1. Calcium hydroxide 13.2 wt% was added into SFALC mixture to maintain the same molar content of Ca²⁺ in both mixtures. Both were continuously stirred for 5 minutes and, casted in cylindrical mold (30 mm in diameter and 60 mm in height). They were cured at 60°C for 2 hours. The hardened paste was demolded and kept at 36°C until the test age. The compressive strength of these specimens was tested at the age of 3, 7 and 28 days. The tested samples were ground and characterized by FTIR, XRD and SAM solution leaching.

Salicylic acid with methanol (SAM solution) leaching test

This test was first introduced by Takashima who used this technique to dissolve alite and belite in Portland cement. The solution of salicylic acid with methanol was prepared from 7 grams of salicylic acid and 40 ml of methanol. It was used to dissolve calcium bearing phase in geopolymer paste and report as the percentage of mass dissolved¹³.

This leaching test was modified to study product of geopolymer pastes made from fly ash with high and low calcium content (GHC-internal and GLC-external in shorthand). The geopolymer pastes were ground and stirred for 3 hours. Then, it was filtered and dried at 100°C. Part of insoluble residue of geopolymer pastes after SAM solution leaching was characterized by XRF, FTIR and XRD to determine the product formed in geopolymer pastes. The soluble part was used to study the percentage of mass dissolved including calcium compound and new phases of GHC-internal and GLC-external by weight loss.

FTIR technique

Fourier transform infrared spectroscopy was chosen to study the gel products of geopolymer. FTIR was obtained from PerkinElmer instrument. The specimen was prepared by 0.001 mg of sample in 0.04 mg of KBr. Spectra analysis was performed over the range 4,000–400 cm⁻¹ at the resolution of 4 cm⁻¹.

Steps to determine the product of geopolymer are as follows.

1. Synthetic fly ash glass was characterized by FTIR.
2. GHC-internal and GLC-external were characterized by FTIR and subtracted with FTIR spectra of fly ash glass. The possible products found in resultant FTIR spectra are calcium silicate hydrate gel (CSH gel), calcium aluminate silicate hydrate gel (CASH gel), geopolymer gel (NASH gel) and Zeolite as shown in Eq.(1)

$$\text{Geopolymer Pastes} - \text{Unreacted Fly Ash Glass} = \text{CSH gel} - \text{CASH gel} - \text{NASH gel} + \text{Zeolite} \quad (1)$$

3. Insoluble residue of GHC-internal and GLC-external after SAM solution leaching was characterized by FTIR. They were subtracted with FTIR spectra of their fly ash glass. The possible products found from FTIR spectra are NASH gel and Zeolite as shown in Eq. (2)

$$\text{Insoluble Residue after SAM Sol}^n - \text{Unreacted Fly Ash Glass} = \text{NASH gel} + \text{Zeolite} \quad (2)$$

4. FTIR spectra of CSH gel and CASH gel was obtained by subtracting FTIR spectra obtained from Eq. (1) and Eq. (2) as shown Eq. (3).

$$\text{CSH gel} + \text{CASH gel} = (\text{CSH gel} + \text{CASH gel} + \text{NASH gel} + \text{Zeolite}) - (\text{NASH gel} + \text{Zeolite}) \quad (3)$$

XRD technique

The XRD pattern was obtained using Thermo-Fisher X-TRA with CuK radiation. Specimens were scanned at 2θ from 5° to 80° as 0.02° step size at the rate of 2 sec per step. This data was used to provide fundamental information of GHC-internal, GLC-external and insoluble residue of GHC-internal and GLC-external after SAM solution leaching at the age of 28 days.

RESULT AND DISCUSSION

Properties of Glass

Fly ash glass was synthesized in order to control the glass composition in fly ash, particle size distribution and avoid inert particle of mineral phases. The chemical composition of glass was analyzed by XRF as shown in Table 1. The high calcium Class F fly ash (SFAHC) has SiO₂ + Al₂O₃ – Fe₂O₃ of 82.72% and CaO of 14.35%. The low calcium Class F fly ash (SFALC) has SiO₂ + Al₂O₃ – Fe₂O₃ of 92.55% and CaO of 4.04%. They are considered to be Class F fly ash as described by ASTM C618¹⁴. Particle size distributions of synthetic fly ashes (SFAHC and SFALC) are shown in Fig.1. SFAHC and SFALC were ground and sieved to pass 45 μm sieve. Geopolymer prepared from fine fly ash and strong alkali solution is expected to have high performance. Fig. 2 presents XRD pattern of SFALC and SFAHC, respectively. There are amorphous silica peaks around 20 to 30° at 2θ. There is no evidence of crystalline phase. FTIR spectra of SFAHC and SFALC glasses are shown in Fig. 3. The major broad peak of SFALC at 1074 cm⁻¹ is associated with Si-O asymmetric stretching vibration Q₃ units. The main spectra peak of SFAHC shifts to lower wavenumber at around 970 cm⁻¹, typical of Si-O Q₂ units¹⁵.

Table 1 The chemical composition of low and high calcium fly ash glass

ID	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	SiO ₂
SFAHC	22.98	14.35	12.30	1.65	0.626	0.544	47.44
SFALC	25.87	4.04	13.70	1.84	0.70	0.732	52.98

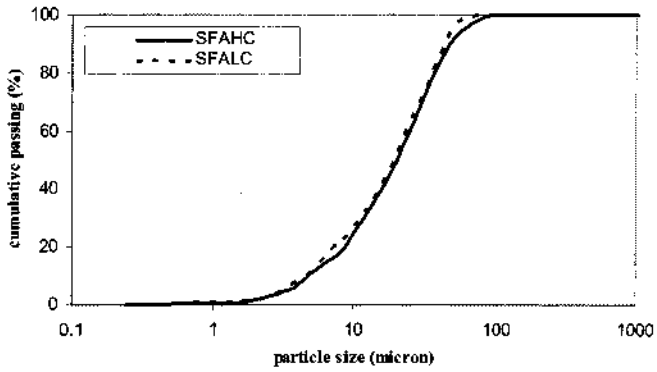


Figure 1 Particle size distribution of SFALC and SFAHC

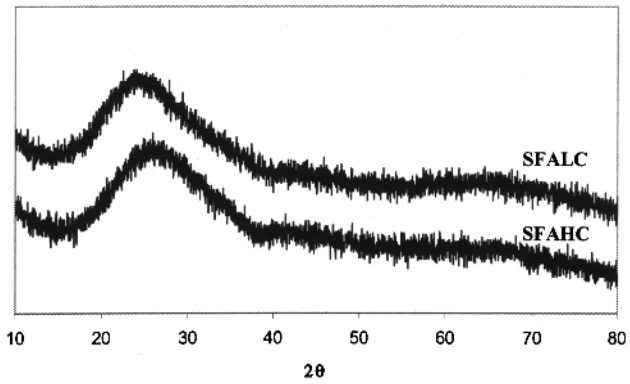


Figure 2 XRD patterns of SFAHC and SFALC

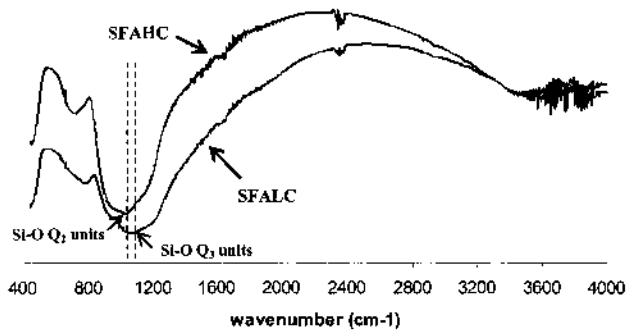


Figure 3 FTIR of synthetic fly ash glasses; SFAHC and SFALC

Reactivity of Fly Ash

The chemical analysis of the hydrated fly ash glass is shown in Table 2 below. The result shows that there is high percentage of Na in the solid part which was not present in the initial fly ash glass. This suggests that the sodium product was formed. The XRD patterns of both hydrated glasses indicate the presence of Na₂CO₃. Since sodium was not present in initial glass, all of the sodium content in the composition of hydrated glass can be removed. By subtracting the percentage of Na₂O out, the remaining is the composition of the hydrated glass. As Si is the main network component of the glass, the percentage of Si removal from glass is used as a measure of fly ash reactivity. The result is shown in Table 2. SFAHC glass is 14.4% reactive while SFALC glass is 28.7 % reactive.

Table 2 Normalized composition of SFAHC and SFALC without Na and the percentage of Si removal

ID	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	SiO ₂	%Si removal
SFAHC-N	16.57	20.80	19.63	1.72	0.86	0	40.42	14.4
SFALC-N	18.38	8.00	31.58	2.69	1.58	0	37.77	28.7

FTIR analysis

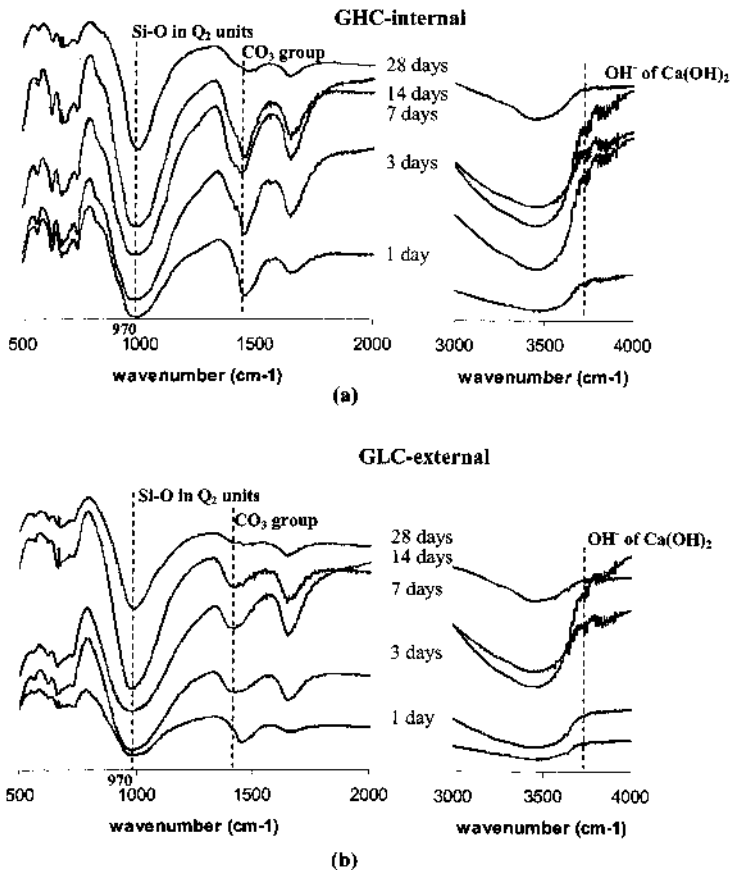


Figure 4 FTIR spectrum of geopolymer pastes after subtract by FTIR spectra of fly ash glass
(a) GHC-internal and (b) GLC-external

FTIR spectra of GHC-internal and GLC-external with time are shown in Fig. 5 (a) and Fig. 5 (b), respectively. In this research, 14.4% of SFAHC and 28.7% of SFALC are reactive. Thus 85.6% of SFAHC and 71.3% of SFALC in fly ash spectra intensity was used to subtract to geopolymer paste spectra in order to remove the unreacted fly ash glass spectra from the geopolymer spectra. After subtracted by FTIR of unreacted fly ash glass, the remaining FTIR spectra is the spectra of geopolymer products i.e. CSH gel, CASH gel, NASH gel and Zeolite.

The spectrum shows a main narrow band at around 966 cm^{-1} at the early age (1 day) as a result of Al effect which changes Si-O-Si into Si-O-Al linkage. It causes the broadening of the band around 970

cm^{-1} ¹⁶. This peak became somewhat appear sharper after the curing age increased due to there was an increasing Si leached out of fly ash, typical of the Si-O asymmetric stretching vibration generated by Q_2 units¹⁵. There is also sharp peak at 3640 cm^{-1} in GLC-external, corresponding to $\text{Ca}(\text{OH})_2$, which came from both calcium in CSH product and crystalline $\text{Ca}(\text{OH})_2$. So CH peak cannot be used to support the formation of the CSH gel. The narrow band is also visible at around $1400 - 1450 \text{ cm}^{-1}$, typical of CO_3 group is attributed to CaCO_3 or Na_2CO_3 from reaction between $\text{Ca}(\text{OH})_2$ or Na_2O and CO_2 in the atmosphere⁷.

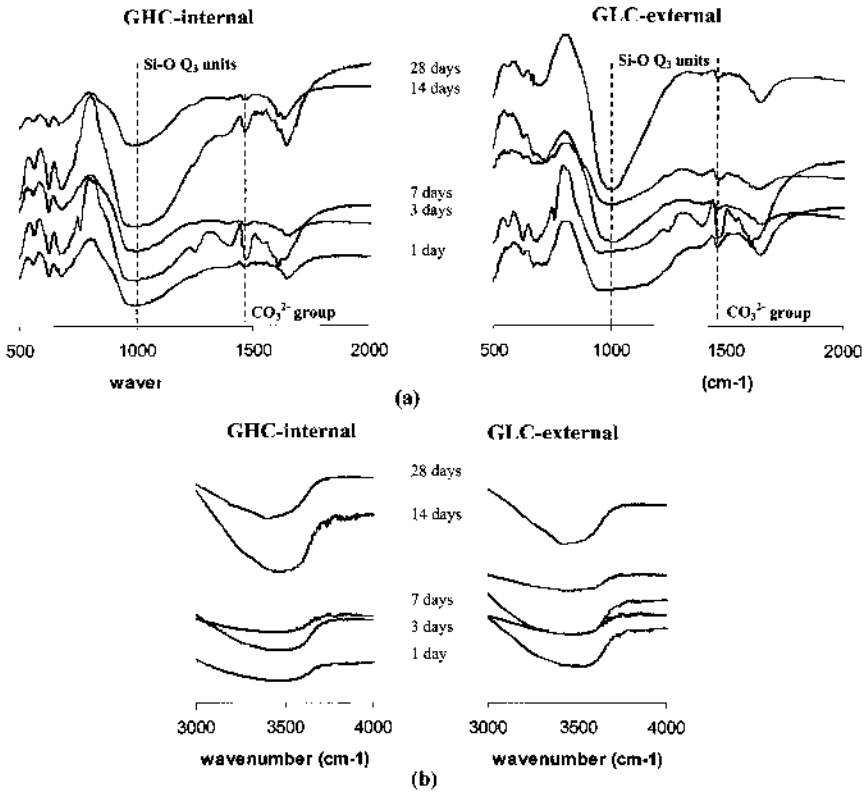


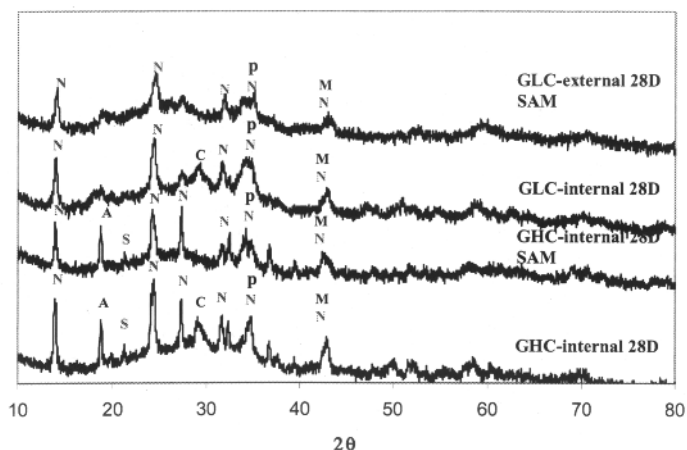
Figure 5 FTIR spectra of insoluble residue of geopolymer after SAM solution leaching and subtracted by FTIR spectra of fly ash glass
 (a) GHC-internal and GLC-external at low wavenumber ($400 - 2000 \text{ cm}^{-1}$)
 (b) GHC-internal and GLC-external at high wavenumber ($3000 - 4000 \text{ cm}^{-1}$)

Fig. 5 (a) and Fig. 5 (b) show FTIR spectra of insoluble residue of GHC-internal and GLC-external after SAM solution leaching and subtracted by FTIR spectra of 85.6% and 71.3% of fly ash glass at low wavenumber ($400 - 2000 \text{ cm}^{-1}$) and high wavenumber ($3000 - 4000 \text{ cm}^{-1}$), respectively.

In our work, it was found that SAM solution can dissolve Ca-compound such as CSH gel, CASH gel, $\text{Ca}(\text{OH})_2$ and some Na compound such as remaining NaOH and Na_2CO_3 . This procedure is based on the formation of a soluble calcium complex with Ca in CSH gel CASH gel and $\text{Ca}(\text{OH})_2$. CaCO_3 cannot be dissolved by SAM solution due to its less solubility in water. It is extremely stable as a solid and water doesn't have sufficient solvating capability to cause the ions to separate and come into solution. In addition, both NASH gel and Zeolite is complex structures, SAM solution cannot attack their structure. Consequently, the resultant FTIR spectra of insoluble residue of geopolymer after SAM solution leaching and subtracted by FTIR spectra of fly ash glass could be the spectra of NASH gel and Zeolite.

There is a broad band appearing in high wavenumber at around 1000 cm^{-1} , indicating Si-O-Si stretching vibrations of geopolymerization¹⁷. It is possible be NASH gel occurring in the geopolymer. The intensity of the major peak (around 1000 cm^{-1}) slightly increased as the curing age increased. At 28 days, GLC-external has higher intensity at 1000 cm^{-1} than GHC-internal due to high Si and Al content in SFALC. As such, the GLC-external could produce more NASH gel than GHC-internal. There is the band characteristic of carbonate group at around 1450 cm^{-1} . It was supposed to be CaCO_3 from reaction between $\text{Ca}(\text{OH})_2$ and CO_2 in atmosphere which cannot be dissolve by SAM solution due to low solubility property.

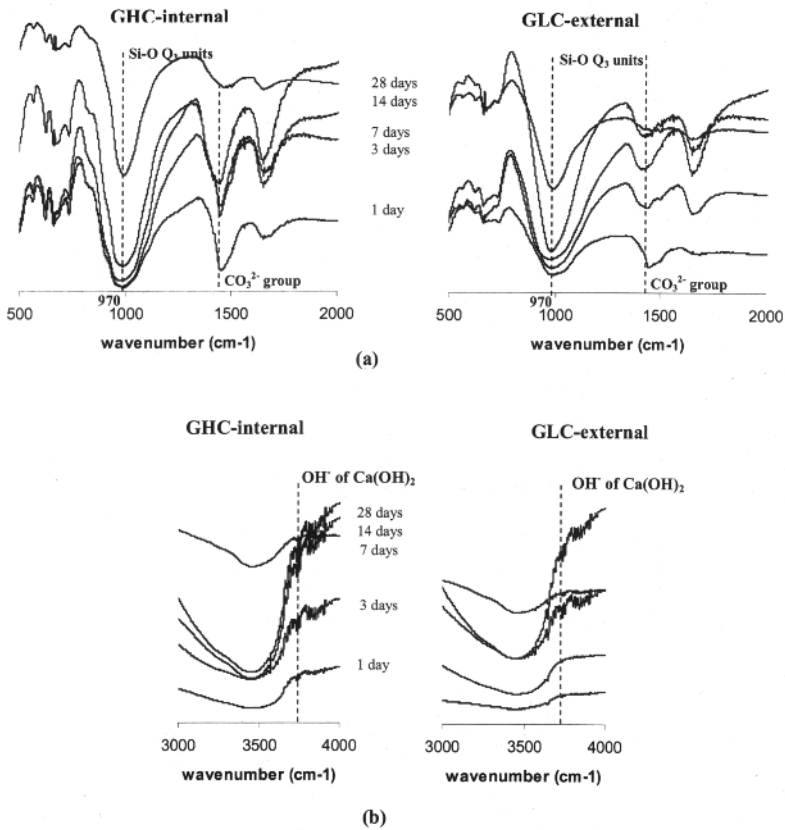
In addition, Fig.6 presents XRD pattern of GHC-internal, GLC-external and insoluble residue of GHC-internal and GLC-external after SAM solution leaching at the age of 28 days. Crystalline phase of Zeolite was found in both XRD pattern of geopolymer pastes and XRD pattern of insoluble residue geopolymer paste after SAM solution leaching in form $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 1.7\text{SiO}_2 \cdot 1.7\text{H}_2\text{O}$. Zeolite is aluminosilicate mineral which possibly came from the amorphous geopolymeric products when the reaction condition is suitable¹⁸. It should be noted that SAM solution can not dissolve NASH gel and Zeolite due to both the structure of NASH gel and Zeolite have Si-O in Q_3 units (tetrahedral).



N = Sodalite S = Laumontite P = Portlandite M = Periclase
C = Sodium Silicate A = Aluminum Hydroxide

Figure 6 XRD pattern of GHC-internal, GLC-external and insoluble residue of GHC-internal and GLC-external after SAM solution leaching

Effect of External and Internal Calcium in Fly Ash on Geopolymer Formation



Figures 7 FTIR spectra resulting from subtracting the spectra in Figure 5 from Figure 4
 (a) GHC-internal and GLC-external at low wavenumber (400 – 2000 cm^{-1})
 (b) GHC-internal and GLC-external at high wavenumber (3000 – 4000 cm^{-1})

Fig. 7 shows the FTIR spectra resulting from subtracting the spectra insoluble residue (Figure 5) from geopolymer (Figure 4). The resultant FTIR spectra in this part are the spectra of CSH gel and Ca(OH)₂ gel.

The major peak of this part is shift to lower wavenumber at around 970 cm^{-1} , corresponding to the Si-O asymmetric stretching bands in Q₂ units, typical of CSH gel¹⁵. Both GHC-internal and GLC-external have peak of at 970 cm^{-1} at the early age to 28 days. At the early age, GHC-internal has higher intensity at 970 cm^{-1} than GLC-external. This could be because SFAHC released Si and Ca more rapidly to form CSH gel at the early age while SFALC released Si slowly to react with the external calcium that was readily available outside the glass. Some external calcium might precipitate as

evidenced from $\text{Ca}(\text{OH})_2$ band in its FTIR spectra. At the age of 28 days, GHC-internal has higher intensity at 970 cm^{-1} than GLC-external because high Ca content in glass could produce more CSH gel or CASH gel than GLC-external sample that Ca was added in the mix. It was also found peak at around 3640 cm^{-1} which attributed to $\text{Ca}(\text{OH})_2$ from both CSH gel and crystalline $\text{Ca}(\text{OH})_2$. It supports the presence of CSH gel in both samples. In addition, the peak at 1450 cm^{-1} corresponds to carbonate group (CO_3) which could be Na_2CO_3 . This sodium salt can be dissolved by SAM as it has weak ionic bond and high solubility in water. SAM solution cannot dissolve CaCO_3 as it has stronger bond and is more stable as solid phase. Thus, SAM solution can dissolve calcium compound including CSH gel, CASH gel and $\text{Ca}(\text{OH})_2$ and sodium compounds including sodium silicate and Na_2CO_3 .

In summary, the products of GHC-internal and GLC-external can be determined by FTIR spectra. NASH gel and Zeolite were found by FTIR spectra of insoluble residue of geopolymer after SAM solution. By measuring the intensity of major peak at around 1000 cm^{-1} which is the sign of NASH gel and Zeolite, GLC-external has higher NASH gel than GHC-internal. This can be because SFALC has high Si and Al content for the formation of NASH and Zeolite. The CSH gel and CASH gel can be determined from FTIR spectra of the part of gel dissolved by SAM solution. The relative amount of CSH and CASH gel is determined from the intensity of major peak at around 970 cm^{-1} . It was found that GHC-internal has higher CSH gel or CASH gel than GLC-external due to the high calcium content in SFAHC.

Analysis of C-S-H, C-A-S-H gel by SAM solution

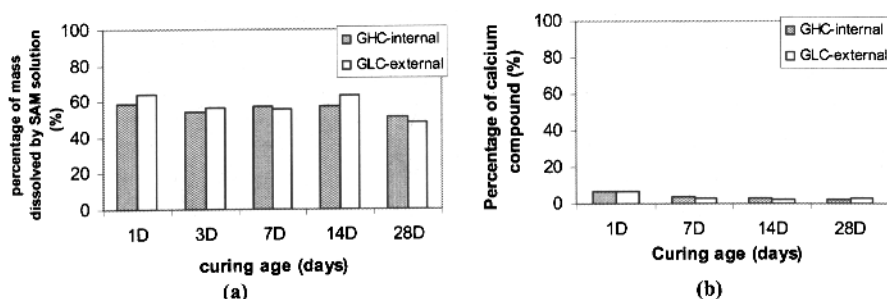


Figure 8 Percentage of mass dissolved by SAM solution (a) Percentage of mass dissolved, (b) Percentage of calcium compound

The percentage of mass dissolved by SAM solution of GHC-internal and GLC-external geopolymer are shown in Fig. 8(a). The percentage of mass dissolved in both GHC-internal and GLC-external is around 50-60%. The analysis of mass dissolved by SAM solution was intended to determine the CSH and CASH gel content in the geopolymer pastes. To determine the major elements in the product dissolved from the matrix, the soluble part was analyzed by XRF. High percentage of Na_2O around 45 to 60% was found in soluble part. Thus the percentage of mass dissolved by SAM solution cannot be used to determine CSH and CASH gel. To confirm that NASH gel cannot be dissolved by SAM solution, the synthetic NASH gel was prepared by sol-gel method by mixing 1 M of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ for aluminum with 1 M of sodium metasilicate for sodium and silica. Aluminum nitrate was dissolved in water and slowly added into sodium silicate solution. NASH gel was characterized by FTIR and measured the mass loss after SAM solution leaching. It was found that NASH gel and Zeolite cannot be dissolved by SAM solution. Insoluble residue of NASH gel after

SAM solution leaching was also characterized by FTIR and found both FTIR spectra of NASH gel and insoluble residue of NASH gel after SAM solution present Si-O Q₃ units, typical geopolymer or Zeolite form. Thus, the Na compound that was dissolved out can be the remaining NaOH and Na₂CO₃ or the new Na phase formed in the reaction. It also shows that not all Na participates in geopolymerization of NASH gel. The percentage of Na was subtracted by percentage of mass dissolved to obtain the percentage of Ca compound as shown in Fig. 9(b). There are small amount of Ca compound dissolved. It was found that the dissolved calcium from GHC-internal is higher than that of GLC-external. It cannot be concluded from this result that GHC-internal has higher CSH gel as the Ca(OH)₂ can be dissolved by SAM solution also.

Compressive Strength

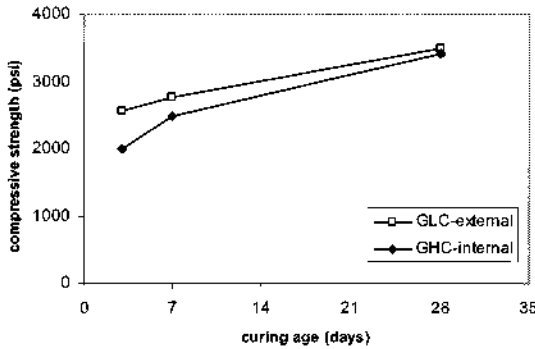


Figure 9 Compressive strength of GHC-internal and GLC-external

Fig. 9 shows the compressive strength of GHC-internal and GLC-external. The data of compressive strength was correlated with intensity of FTIR spectra products of GHC-internal and GLC-external as shown in Fig. 5 and Fig.7. The compressive strength of GLC-external is higher than that of GHC-internal. According to FTIR of GLC-external, it has higher intensity of NASH product than GHC-internal while GHC-internal has higher intensity of CSH gel. It could be because this Class F fly ash with low calcium (SFALC) released more silica and alumina to produce NASH gel than that of GHC-internal as shown in FTIR spectra (Fig.5 (a)). Theoretically, this SFALC fly ash should dissolve Si, Al slowly as this glass contains high Si and Al which are network former of the glass. However, it is evidently shown that the geopolymer made from SFALC fly ash has higher strength and higher intensity of NASH gel. This shows that it can release more Si and Al for geopolymer reaction. The additional strength at the early age could be the contribution from CSH gel which was formed from the reaction between dissolved silica and external calcium. Its compressive strength then increased at later age as the geopolymer reaction continued to proceed. The compressive strength of GHC-internal was lower than that of GLC-external at all ages although it has higher intensity of CSH gel and CASH gel. This can be because it has lower Si and Al content to form NASH gel. GHC-internal which has calcium in fly ash glass can form CSH gel and NASH gel, simultaneously as evidenced by CSH gel and NASH gel in FTIR spectra at early age.

SUMMARY

FTIR was used together with XRD and SAM leaching to identify the product of geopolymer i.e. CSH gel, CASH gel, NASH gel and Zeolite. Both of GHC-internal and GLC-external have CSH gel CASH gel, NASH gel and Zeolite. Both glass type and calcium source have the effect on geopolymer product formation. The low calcium fly ash (GLC-external) has higher Si removal percentage in alkali solution than the high calcium fly ash (GHC-internal). This dissolved silica can react with Na or Ca that are available in the solution to form NASH or CSH gel respectively. The geopolymer made of GLC-external has higher strength than the one made of GHC-internal. This is because its glass has higher silica and alumina that can release out to form NASH gel. It is not because of CSH gel as the FTIR analysis shows that GLC-external system has lower intensity of CSH gel than GHC-internal even though it has calcium added to the system. The added calcium might precipitate in this high pH solution and does not form CSH gel. In GHC-internal sample, its internal calcium was more readily available to react with silica. Thus, the dissolved silica was consumed by this calcium to form CSH gel. This indicates that the presence or location of calcium designates the formation of CSH gel in geopolymer. In conclusion, both glass components and the source of calcium has an effect on the formation of geopolymer products in which the low calcium (high Si and Al) glass has higher Si removal percentage than the high calcium (low Si and Al) glass and the internal calcium can react with dissolved Si to form more C-S-H gel than external calcium.

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