Effect of cement kiln dust on Geopolymer composition and its resistance to sulphate attack

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ABSTRACT

Utilization of cement kiln dust (CKD) with its high alkali content in the activation of geopolymer specimens to create nonconventional cementitious binders was investigated. Relatively high alkaline content of CKD is predominant factor preventing its recycling in cement manufacture. It was observed that depending on the water-soluble alkalis and sulfate compounds, CKD could provide the necessary environment to activate geopolymer materials. Materials used in this investigation are ground granulated blast furnace slag (GGBFS), air cooled slag (ACS), cement kiln dust (CKD) and calcined kaolin. Calcinations process was done by kaolin firing at 750°C for 3 hours. Alkaline activation by 2 % NaOH along with the added cement dust was studied as compared with that not activated by sodium hydroxide. Curing was performed at 38°C under 100 % relative humidity. Results showed that 25% CKD is the optimum ratio for geopolymer formation and activation of ggbfs by 2 % NaOH along with 25% CKD results in best enhancement in mechanical as well as microstructural characteristics. Activation of low iron metakaolin by 50 % CKD and 2 % NaOH has the lowest mechanical properties due to calcium deficiency that bind geopolymer matrix. Effect of 5 % magnesium sulfate on alkali activated water cooled slag and metakaolin (high iron content) by cement kiln dust results in an enhancement in their mechanical properties up to three months, while subjected to a strength loss up to six months.

Keywords: Geopolymer, GGBFS, ACS, Mk, Alkali, Sulfate.

1. Introduction

Environmental concerns related to Portland cement production, emission and disposal of cement kiln dust (CKD) is becoming progressively significant. CKD is a fine-grained, particulate material readily entrained in the combustion gases moving through the kiln. It is composed primarily of variable mixtures of calcined and uncalcined feed materials, fine cement clinker, fuel combustion by-products, and condensed alkali compounds (ASTM D 5050). CKD generation is responsible for a significant financial loss to the cement industry in terms of the value of raw materials, processing, energy usage, dust collection and disposal. Cement manufacturing plants generate approximately 30 million tons of CKD worldwide per year (Dyer et al. (1999)).

The relatively high alkaline content of CKD is the predominant factors that preventing its recycling in cement manufacturing. All CKD frequently contain alkalis (Na₂O, K₂O) and sulfates in much higher percentages than those in Portland cement. The large amount of free lime in CKD make it a substitute for fertilizers and lime in stabilizing waste water streams. Furthermore, studies have shown that CKD can be effectively used in soil and sludge
stabilization. It has also been successfully used as inorganic filler in bituminous paving and asphaltic roofing (Collins and Emery (1983)).

However, its high alkalis, sulfate contents as well as large amounts of free lime make it an excellent activator for pozzolanic materials. The dissolution rate of materials with latent pozzolanic properties such as slag materials generally depends on alkalis concentration of the reacting system (Wang et al. (1995)). Latent hydraulic materials as Ground Granulated Blast-furnace slag (GGBFS) is a finely ground material that is produced by rapid chilling and results in the formation of amorphous or glassy phases. Cooling with a slow rate forms crystalline materials with low reactivity known as air cooled slag. The solubility of Si, Ca, Al, and Mg is functions of the pH. At a pH lower than 11.5, the equilibrium solubility of silica is low and slag does not dissolve. As a result, more Ca\(^{2+}\) and Mg\(^{2+}\) enter into the solution and an impermeable aluminosilicate coating covers the surfaces of the slag grains, inhibiting further hydration (Song and Jennings (1999)). Sprouse (1984) applied and received a patent for cement that combined ground blast furnace slag with CKD.

Use of slag as supplementary cementitious material improves the concrete durability by reducing concrete permeability and significantly inhibits the ingress of sulfates (Osborne (1991)). Reduction in chloride penetration achieved by GGBS has been confirmed by many different investigators (Page et al. (1981) & Arya and Xu (1995) & Roy et al. (2000)). Deja and Malotepszy (1989) carried out tests on AAS mortars and reported high resistance to sulfates and chlorides. Roy et al. (2000) reported very low chloride diffusion in alkali-activated cement pastes.

Glukhovsky (1980) showed also that the strength of alkali activated slag mortars increased after 1 year in 1–2% MgSO\(_4\) solution and stayed constant for 2 years in dilute acids, HCl and H\(_2\)SO\(_4\), while OPC samples deteriorated in six months. Neville (1995) stated that blended cement with high replacement levels of slag exhibits high carbonation rate. But since carbonation and pore structure are interrelated, good curing, which resulted in a more compact structure, helped to reduce carbonation. This also means the higher the strength, the lower the carbonation.

Metakaolin is an anhydrous aluminosilicate produced by thermal decomposition of kaolin (at temperatures in excess of 550°C); this thermal decomposition improves mechanical strength (Ambroise et al. (1994)), reduces the transport of water and salts through the sample (Kostuch et al. (1993)) and prevents the alkali-aggregate reaction from occurring (Walters and Jones (1991)). Metakaolin has also been used for other different purposes. For example; it has been found that alkali activation of metakaolin is a way of making new cementitious materials (hydroceramics-ceramic-like materials synthesized from a solid aluminosilicate and an alkali-rich solution at low temperatures, 100°C).

The purpose of the paper is to investigate the effect of CKD on the specimen’s behaviour, as it can positively promote geopolymerization reaction. Alkaline activation of alumino-silicate materials (GGBFS, ACS, low iron Mk, high iron Mk) using alkalis lies within cement kiln dust along with 2% sodium hydroxide so as to elucidate the optimum mix composition as revealed from its mechanical and microstructural characteristics. Geopolymer stability up on immersion in 5% magnesium sulfate solution will be also studied.

2. Experimental procedures
2.1 Materials

Materials used in this investigation are water cooled ground granulate blast furnace slag (GGBFS) as well as air cooled slag (ACS) sourced from Iron and Steel Factory- Helwan, Egypt. Two types of kaolin are used: one with high iron content and the other with low iron content both provided from Aswan governorate, Egypt. Both types were thermally treated at 750°C for 3 hrs with a heating rate of 5°C/min to produce metakaolin (Mk). Sodium hydroxide (NaOH) as alkali activator purchased from SHIDO Company with a purity of 99%. Cement kiln by-pass dust CKD is a fine, highly alkaline powder that produced from cement manufacture sourced from Beni-Suef Cement Factory. The chemical composition of the starting raw materials was illustrated in Table (1).

Table 1: Chemical composition of starting materials (Mass, %)

| Material                        | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | K₂O | Na₂O | TiO₂ | MnO₂ | Fe₂O₃ | Cl⁻ | LOI | Total | Notes               |
|---------------------------------|------|-------|-------|-----|-----|-----|-----|------|------|------|-------|-----|-----|--------|---------------------|
| Water-Cooled Slag (GGBFS)       | 36.95| 10.01 | 1.48  | 33.07| 6.43| 3.52| 0.74 | 1.39 | 0.52 | 3.44 | 0.1  | 0.05| 0.00 | 97.69 | BaO=3.0             |
| Metakaolin (Low Iron)           | 66.60| 27.44 | 0.86  | 0.57 | 0.00| 0.08| 0.14 | 0.06 | 2.66 | 0.01 | 0.06 | 0.06| 1.61 | 99.98 |                     |
| Metakaolin (High Iron)          | 56.32| 25.19 | 12.20 | 0.69 | 0.34| 0.21| 1.07 | 0.00 | 1.75 | 0.27 | 0.22 | 0.06| 1.59 | 99.92 |                     |
| By-Pass Cement Kiln Dust (CKD)  | 8.29 | 2.84  | 2.07  | 51.90| 0.57| 2.09| 3.42 | 2.63 | 0.14 | 0.13 | 0.13 | 6.12| 19.59| 99.90 | Free Lime, CaO=15.5  |
| Air-cooled Slag (ACS)            | 3.01 | 10.35 | 0.56  | 34.76| 0.06| 0.42| 0.03 | 0.15 | 0.03 | 0.43 | 0.01| 0.01| 0.00 | 99.99 | BaO=0.34            |

2.2 Specimen preparation and test conditions

Geopolymer mixes made by hand mixing raw materials of each mix passing a sieve of 90 µm for 10 min and a further 5 min using mixer. Some specimens were activated using 2% NaOH, while others use alkalis from CKD for geopolymerization process. Water-binder ratio (w/b) about 0.35 by mass for mixes included slag, while it increases to 0.45 for metakaolin mixes. The paste mixture was cast into 25×25×25 mm cubic-shaped moulds, vibrated for compaction and sealed with a plastic cover to minimize loss of evaporable water.

All mixes were left to cure undisturbed under ambient temperature for 24 hours and subjected to curing at 38°C with 100% relative humidity. At the end of the curing regime, the specimens were subjected to the compressive strength measurements, where the resulting crushed specimens were subjected to stopping of the hydration process using stopping solution of alcohol/acetone (1:1) followed by washing with acetone as recommended by different investigators (Saikia et al. (2004) & Taha et al. (1981)) for preventing further hydration and for further analysis followed by drying of the crushed specimens for 24 hrs at 80°C, then preserved in a well tight container until time of testing.

On the other hand, sulfate attack measurements for optimum mixes were done according to ASTM-C1012 (2009). Specimens were cast, cured in a fog room for 28 days, and then immersed in a solution containing 0.352 M of MgSO₄ (about 5% Mg SO₄ solution). The solution in the container was renewed every 2 weeks for the first 3 months, while the compressive strength was measured periodically (monthly) over 6 months.
2.3 Methods of investigation

Chemical analysis was carried out using Axios, WD-XRF Sequential Spectrometer (Panalytical, Netherland, 2009). Compressive strength tests were carried out using five tones German Brüf pressing machine with a loading rate of 100 kg/min determined according to ASTM-C109 (2007). Microstructure of the hardened alkali activated water cooled slag was studied using SEM Inspect S (FEI Company, Netherland) equipped with an energy dispersive X-ray analyzer (EDX). Removal of free water was accomplished by using alcohol/acetone method as recommended by different investigators (Saikia et al. (2004)). Bonding characteristics of alkali activated specimens were analyzed using Jasco-6100 Fourier transformed infrared spectrometer FTIR. Test sample was ground and uniformly mixed with KBr at a weight ratio KBr: specimen=200:1. The mixture, 0.2 g was pressed to a disk of 13 mm in diameter for analysis at 8 t/cm². The wave number was ranging from 400 to 4000 cm⁻¹ (Panias et al. (2007)).

3. Results and discussion

3.1 Effect of cement kiln dust on geopolymeric behaviour

FTIR spectra for the geopolymer mixes activated with various cement dust as well as those activated using 2% NaOH cured in 100% relative humidity, at 38°C for 28 days are shown in Figure (1). FTIR Bands are as follows: Stretching vibration of O-H bond in the region 3434-3480 cm⁻¹, bending vibrations of (HOH) in the region 1628-1635 cm⁻¹, stretching vibration of CO₂ located at about 1430 & 875 cm⁻¹, asymmetric stretching vibration (T–O–Si) at 1007-1042 cm⁻¹ where T=Si or Al, symmetric stretching vibration (Si–O–Si and Al–O–Si) in the region 711-713 cm⁻¹ and bending vibration (Si–O–Si and O–Si–O) in the region 460-488 cm⁻¹.

Pattern of WCS-NaOH, cured up to 28 days in 100% R.H. at 38°C indicates broadness of H₂O and hydration materials bands at 3434 & 1635 cm⁻¹ giving an indication about the highest hydration products contribution upon using 2% NaOH as a results of dissolution of calcium ions within WCS forming CSH that acts as a nucleating agent for geopolymer precipitation of dissolved species, so that leading to rapid hardening and forming a fine and homogeneous structure (Temuujin et al. (2009)). This is accompanied by increased intensity of the main asymmetric bands of (T–O–Si) and bending vibrations bands (Si–O–Si and O–Si–O), so that reflecting high geopolymeric content. CKD can also enhance slag dissolution and geopolymerization using its high alkalis and high free lime which is 15%.
Figure 1: FTIR spectra of 28 days cured (38°C and 100% RH) geopolymer specimens having various cement dust content (1,2: Stretching vibration of O-H bond, 3: Bending vibrations of (HOH), 4: Stretching vibration of CO₂, 5: Asymmetric stretching vibration (T-O-Si), 6: Symmetric stretching vibration of CO₂, 7: Symmetric stretching vibration (Si-O-Si and Al-O-Si), 8: Bending vibration (Si-O-Si and O-Si-O).

Hydration products bands are also sharp in case of high iron MK-mix but not broad as WCS-NaOH mix, whereas intensity of asymmetric bands of (T–O–Si) as well as bending vibration bands (Si–O–Si and O–Si–O) decreases as compared with the last mentioned mix. Using CKD alone for activation of water cooled slag lead to incomplete dissolution and geopolymerization of slag material that in turn reflected on both hydration and asymmetric bands intensities.

In low iron MK-NaOH, the situation is different where higher content of hydration products is formed as compared with the last mentioned mix but with decreased intensity of asymmetric (T–O–Si) and bending vibration (Si–O–Si and O–Si–O) band, so providing an indication about lower reactivity of MK in addition to increased alkalis contribution from CKD and sodium hydroxide that will consume geopolymer surface and decrease chemical bonding between insoluble solid particles and geopolymeric framework.

It is noticed an increased intensity of the carbonation bands located at 1429 and 875cm⁻¹ in low iron MK as compared with other mixes. This is explained by lower reactivity of the used metakaolin and low iron content that leads to low geopolymer stabilization, so most of free lime in CKD exposed to carbonation in addition to carbonate content lies within CKD. On contrary, WCS-NaOH geopolymer specimen has the lowest intensity of carbonate band reflecting propagation and precipitation of geopolymer products up on alkali addition leaving little free alkalis to be susceptible to carbonation.

Using high iron content metakaolin along with CKD leads to increase in intensity of carbonation band indicating insufficient geopolymerization of reacting materials, where alkalis from excess CKD present as chlorides and not in the form of hydroxide will be susceptible to carbonation forming sodium bicarbonate and does not necessarily lead to a
high pH value of the pore solution; besides they cause efflorescence (Buchwald and Schulz (2005)). Water cooled slag geopolymer without NaOH seems somewhat with little difference reflecting lower efficiency of geopolymerization reaction that surpassed by the absence of hydroxide solution that provide necessary pH values for geopolymerization reaction; so part of unreacted alkalis will be carbonated leading to an increase in the carbonation band. Other indication about increased carbonation with CKD addition is the shift of the asymmetric band (T–O–Si) to a higher value at about 1043 cm\(^{-1}\) in case of higher CKD dose than recorded at the lower dose of cement dust mix at about 1013 cm\(^{-1}\) implying the formation of CSH with smaller calcium content as a result of carbonation (Puertas et al. (2006)).

The results of compressive strength for hardened geopolymer mixes, cured for 90 days in 100 % R.H. at 38\(^\circ\)C are shown in Figure (2). Results show strength increase in all mixes along with hydration age due to propagation of pozzolanic reaction, also the strength decreases with CKD as the excess alkalis that are in the form of chloride consume geopolymer surface, on which the chemical bonding between the insoluble solid particles and the geopolymeric framework takes place in the final stage of the geopolymerization process. Thus, the resulted geopolymeric materials have low mechanical strength (Skoufadis et al. (2003)). There are two main factors that can initiate and propagate the geopolymerization reaction are alkali hydroxide and/or heating to <100\(^\circ\)C that can form amorphous geopolymer, while >100-150\(^\circ\)C forms zeolite of crystalline behaviour.

It is observed that WCS-NaOH achieves the highest strength as confirmed by its broadest hydration band revealed from slag hydration as well as increased intensity of the main asymmetric band of (T–O–Si) and bending vibration bands (Si–O–Si and O–Si–O) giving high geopolymeric contribution. WCS geopolymer mix without sodium hydroxide suffers from a decreased intensity of hydration products as alkali within cement dust that in the form of chloride than hydroxide not able to completely dissolve the Ca, Si, Al ions within WCS.

Strength lowering was observed when using high iron MK than WCS-NaOH. This is attributed to the fact that Ca\(^{2+}\) as well as Fe\(^{3+}\) are capable of acting as charge-balancing cations within the geopolymeric binder structure (Davidovits (1991) & Davidovits (1999)), so up on using NaOH a great content of calcium ions are produced that may contribute to the formation of CSH as mentioned before in case of WCS-NaOH mix. While, Alkalis within CKD as well as free lime lead to dissolution of the iron within MK so act as a charge balance cations forming a more stable geopolymer network as appeared from higher intensity of geopolymer T–O–Si bands; while it decreases as compared with WCS-NaOH mix due to the incomplete dissolution of Mk by the added CKD alone. Finally, low iron MK-CKD possess the lowest strength values in spite of using NaOH which may be due to two factors: one is the excess alkalis in the high CKD and NaOH that may consume geopolymer surface which accompanied by lower reactivity of MK, while the other is lack of iron as well as calcium (as compared with high iron MK) that acts as a charge balance in the network leading to the formation of a less stable geopolymer composition.
The cement dust behavior upon using various slag types is shown Figure (3), where strength decreases with cement dust more than 25%, so the last mentioned dose can be considered as a suitable ratio for best geopolymer behavior. High alkalis content in CKD as mentioned latter, do not necessarily lead to a high pH value of the solution. Also, the excess alkalis in the cement dust hinder the progress of geopolymer formation by increasing matrix porosity and so lead to lowering in mechanical properties. WCS activated by sodium hydroxide possess the best strength performance as compared with mixes with no hydroxide solution as discussed before. It is also noted that WCS mix exhibit higher strength values as compared with ACS one as revealed from higher reactivity of WCS and its amorphous characteristics as compared with the crystalline ACS.

Morphology and microstructure of 28 days cured geopolymer specimens are shown in Figure (4). Morphology of WCS-NaOH specimens illustrate that geopolymer configuration are tightly bound with matrix composition and hydration materials, as the structure topography seems smooth and free from pores (Figure 4a). High iron Mk geopolymer mix shows a low
content of the geopolymer plates in the matrix structure, while increased Mk content leads to overcome the dilution effect over its pozzolanic activity and so leads to spreading of the excess Mk grains over the matrix surface as the alkaI within CKD alone unable to completely incorporate all Mk constituents in the geopolymer structure; so excess MK act as a barrier against the geopolymer matrix cohesion (Figure 4b).

Figure (4c) on the other hand, shows the difference between WCS with no alkali mix as compared with WCS-NaOH, where mix heterogeneity is predominant as the alkaI within the mix composition are not sufficient to completely dissolve Ca, Al, Si from slag constituent, so medium heterogeneity favours low mechanical strength properties as compared with that activated by NaOH. Figure (4d) shows low iron MK-NaOH, as morphology possess low compaction between matrix composition as revealed from low calcium content in Mk that decrease the formed CSH and increase carbonate contribution. The increased carbonation resulted from excess alkalis accompanied by decrease geopolymer participation; while increased alkalis content consume the surface species leading to decrease in oligomer structure and its stability upon time (Panias et al. (2007)). It is known that the formation of oligomeric precursors is enhanced by the increased contents of Si and Al in the aqueous phase caused by the increased dissolution rates, but it is inhibited under extremely high alkalis concentrations.

![Figure 4](image_url)

**Figure 4:** SEM micrograph of 28 days alkali activated geopolymer specimens having (a) 75% WCS and 25% CKD activated by 2% NaOH, (b) 50% MK (high iron) and 50% CKD, (c) 75% WCS and 25% CKD and (d) 50% MK (low iron) and 50% CKD activated by 2% NaOH

### 3.2 Sulfate attack on cement dust geopolymer mix

Based on latter section, two geopolymeric mixes were chosen as revealed from their mechanical and microstructural properties for measuring their stability up on sulfate solution; high iron MK-CKD and WCS-CKD mixes. In spite of lower mechanical properties of the latter mix than WCS-CKD-NaOH, it was chosen to avoid high alkali content as well as to its economical application.
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FTIR spectra of 6 months geopolymer specimens immersed in 5 % MgSO₄ are shown in Figure (5). Bands are as follows: Stretching vibration of O-H bond in the region 3434-3480 cm⁻¹ and 2925-2977 cm⁻¹, bending vibrations of (HOH) in the region 1628-1635 cm⁻¹, stretching vibration of CO₂ located at about 1430 & 875 cm⁻¹, asymmetric stretching vibration (T–O–Si) at 1007-1043 cm⁻¹ where T=Si or Al, symmetric stretching vibration (Si–O–Si) between 711-786 cm⁻¹, symmetric stretching vibration (Si–O–Si and Al–O–Si) in the region 676-688 cm⁻¹ and bending vibration (Si–O–Si and O–Si–O) in the region 410-480 cm⁻¹.

It is shown from IR bands that WCS-geopolymer specimen possess a high intensity of hydration bands at 3415 & 2977 and 1626 cm⁻¹. Asymmetric vibration band of (T–O–Si) at 1141 cm⁻¹ is branched to double bands reflecting geopolymer destabilization up on sulfate immersion at later ages. While high iron MK mix suffers from lower hydration bands at 3434 & 2925 and 1598 cm⁻¹ as explained by dilution effect of Mk, as not all metakaolin constituents can be dissolved and involved in geopolymer formation and not all alkalis in the CKD is in the form of hydroxide. Asymmetric bands of Mk mix appear of low intensity as the lower pH medium produced by magnesium ions can also destabilize geopolymer composition that requires an alkaline medium for geopolymer propagation in addition to the lower stabilization of its geopolymeric constituents.

Finally, band broadness of CO₂ located in FTIR spectra of WCS indicates the presence of sodium bicarbonate that is suggested to occur due to atmospheric carbonation of alkalis lies within CKD and free lime in CKD that not incorporated in geopolymerization reaction. Formed carbon dioxide may contribute to an improvement in the strength by enhancing mix cohesion at a later ages only, possibly as a result of the precipitation of greater amounts of calcium carbonate in the pores, causing a decline in total porosity, average pore size and consequently an increase in mechanical strength as mentioned by Puertas et al.(2006). Mk geopolymer mix specimen exhibit a higher CO₂ band intensity as the increased content of cement dust lead to increase of the free alkalis which will be subjected to carbonation.
Scanning electron microscope of 28 days (zero time), 1 and 6 months magnesium sulfate immersed geopolymer specimens are shown in Figure (6). Microstructure of WCS-geopolymer not immersed in sulfate solution (Figure 6a) seems somewhat dense with spreading of geopolymer constituents in the matrix. On prolong exposure up to 6 months (Figure 6b); geopolymer structure is still possess high resistivity toward sulfate ingress as appeared from its morphology where the geopolymer constituents spread allover the surface with higher content than at zero time reflecting an enhancement in microstructural properties. There are also some pores on the surface of the specimens but not penetrated into the matrix structure confirming high resistivity against sulfate attack.

MK mix in spite of low geopolymer contribution (Figure 6c) turns from dense structure at zero time of immersion into porous one that filled with bundles of needle shaped grains of ettringite (3CaO·Al₂O₃·3CaSO₄·32H₂O) at one month of immersion leading to expansion and structure deterioration (Figure 6d). The formed ettringite reflects the lower stabilization of the formed CSH whereas the low C/S in CSH shows the high resistivity to ettringite formation. Increasing immersion time up to 6 months leads to the formation of wide pores within matrix beside ettringite presence and so decreasing structure homogeneity as well as its mechanical strength than unimmersed specimens (Figure 6e).

The results of compressive strength of geopolymer pastes having various cement dust content and immersed in 5 % MgSO₄ are represented in Figure (7). Strength increases in WCS-mix up to 4 months followed by slight decrease up to 6 months but still higher than that at zero time (28 days) as the sulfate may enhance geopolymer formation at the early age, but at later age the decreased pH from the formed brucite destabilize the geopolymer structure and so mechanical properties. Increased WCS’s strength may be attributed to stability of that mix to
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sulfate attack and also formed CSH from pozzolanic reaction acting as a nucleation center for geopolymer propagation and so lead to strength propagation.

MK mix on the other hand suffers from strength decrease beyond one month of immersion due to alkalis increase so that the formed geopolymer destabilized by surface consumption by alkalis, so the matrix will be more prone to sulfate attack. The role of sulfate is significantly clear in structure deterioration by the formation of ettringite due to sulfate attack that is very expansive since these elements could absorb moisture so that their volume of solid phase could increase to about 124 % and 227 % from the original volume (Wallah and Rangan (2006)) as represented from the following equations:

\[
\text{Ca(OH)}_2 + \text{MgSO}_4 \rightarrow \text{CaSO}_4 + \text{Mg(OH)}_2 
\]

and

\[
3 \text{CaSO}_4 + 3\text{CaO.Al}_2\text{O}_3 + 32\text{H}_2\text{O} \rightarrow 3\text{CaO.Al}_2\text{O}_3.3\text{CaSO}_4.32\text{H}_2\text{O} \quad \text{(Ettringite)} 
\]

Ettringite formation is quite clear in SEM mapping of 1 and 6 months metakaolin sulfate immersion (Figure 6 d, e) so that giving an explanation about strength loss with time. While slag possess a homogeneous structure with a little evidence about ettringite formation as represented from its microstructure as well as its FTIR behaviour.

![Figure 7: Compressive strength of alkali activated geopolymer specimens immersed in magnesium sulfate solution](image)

In metakaolin mix, there might be a direct replacement between CaCO_3 and MgSO_4 forming gypsum that leads to increase in ettringite formation. Moreover, Mg(OH)_2 can on the other hand cause destabilization of hydration materials by lowering the alkalinity provided from brucite formation during exposure to a high concentration of magnesium sulfate solution and will eventually decompose to gypsum. Magnesium ions with its lower solubility decrease medium pH forming M-S-H instead of C-S-H; which is known by its non-cementitious properties and leads to softening on prolong exposure time leading to destabilization of the hydration materials.
4. Conclusions

1. Addition of 2% NaOH positively affects the geopolymerization process and increase in an enhancement in mechanical and microstructure properties. Also, WCS possess higher geopolymer reactivity than metakaolin constituents

2. High iron MK affects geopolymer process where iron (III) can acts as a charge balance in the geopolymer composition and so forms a more stable geopolymer materials.

3. Increases of cement kiln dust over 25% for air and water cooled slag lead to matrix dilution as well as increase in alkalis that are in the form of chlorides than hydroxides, leading to increase in the carbonation content of matrix and so weaken its mechanical as well as microstructural characteristics.

4. WCS mix exhibit higher strength values as compared with ACS one as revealed from higher reactivity of WCS and its amorphous characteristics.

5. WCS specimens exhibit high resistance to sulfate attack as there are little deterioration beyond six months of exposure in 5% MgSO₄ solution, while metakaolin with its unstable CSH forms ettringite that known with its expansive behaviour as well as its damage to microstructure and mechanical properties.

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