ENGINEERING OF LOW COST GEOPOLYMER BUILDING BRICKS APPLIED FOR VARIOUS CONSTRUCTION PURPOSES

H. M. Khater, M. Ezzat and A. M. El Nagar
Housing and Building National Research Centre (HBRC), 87 El-Tahrir St, Dokki, Giza, P.O. Box 1770 Cairo, Egypt

ABSTRACT
The aim of this article is to demonstrate various ways in producing geopolymer brick specimens with low production cost through using various sand ratios as well as decreasing the concentration of the added alkalis by utilizing cement kiln dust as a source of high free alkalis that can initiate and propagate geopolymerization reaction. Activators used are sodium hydroxide, sodium silicate and cement kiln with its high alkalis content, all calculated from the total binder weight. Geopolymer bricks prepared by partial binder substitution of metakaolin/slag by various sand ratio from 15 to 50 %, while other mixes are water cooled slag based incorporating various cement kiln dust in the ratio from 25 up to 75 %. The properties of the produced geopolymer bricks have been studied through measurement of compressive strength, water absorption, FTIR, XRD and SEM imaging. Results demonstrate the possibility of producing low cost geopolymer bricks with volunteer properties and possess high mechanical and microstructural characteristics by increasing the used sand ratio as well as cement kiln dust in producing geopolymer bricks with superior properties giving compressive strength values exceed that required for heavy duty bricks (more than 40 MPa) for mostly all the studied specimens except those incorporating high ratios of cement kiln dust which gives values near to 20 MPa for 50 % CKD and reaches to about 15 MPa for 75 % CKD after 90 days of curing.

Key words: Slags, Metakaolin, Cement Dust, Bricks, Eco-Friendly, Low cost.

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1. INTRODUCTION

Geopolymers are a class of largely X-ray amorphous aluminosilicate materials, generally synthesized by activation of an aluminosilicate powder with a concentrated alkali metal silicate or hydroxide solution. Geopolymers have been the subject of a great deal of research interest, particularly during the last decade owing to their good properties and as they are low emission CO$_2$ materials. It may be synthesized at an ambient or elevated temperature by alkaline activation of aluminosilicate obtained from industrial wastes [1–5], metakaolin [6–9], melt-quenched aluminosilicate [10], natural minerals such as volcanic scoria [11–15], or mixtures of two or more of these materials [16,17]. Activation is achieved by addition of highly concentrated alkali metal hydroxide or silicate solutions.

Clay bricks are the oldest and the most commonly used building materials in masonry construction. However, the production process of clay brick consumes high amounts of energy and releases enormous amounts of dangerous emissions (greenhouse gases) into the atmosphere of our planet. In addition, there are diminishing supplies in natural resources of raw materials (natural clay, silt, sand, etc.) used to fabricate these clay bricks. Accordingly, there is a worldwide need to find an effective alternative that is also environmentally friendly. The recycling of waste products, by incorporating them into building materials, is considered an appropriate solution to this pollution crisis. Many attempts have been made to incorporate waste in the production of bricks, including rubber, limestone dust, sawdust, processed waste tea, fly ash, polystyrene and sludge [18].

The chemical reaction between an aluminosilicate source and an alkaline solution, when formulated in adequate proportions, produces a mechanically strong material referred to as an alkali-activated binder, or ‘geopolymer’ [19]. Metakaolin (MK)-based geopolymers have been widely studied over the past decades [20–22], but one of the main drawbacks of these binders is a tendency towards a large degree of drying shrinkage and cracking [23]. This is associated with the high water demand of the reacting mixes, as a consequence of the high surface area and particle shape of MK due to calcination [24]. This affects the mechanical strength development and stability of these materials, which does not always compare well with the performance of other alkali-activated binders based on industrial by-products, such as granulated blast furnace slag (GBFS) or with lower cost and higher potential for large-scale industrial applications than MK. Other than the lower aspect ratio of the particles, the main difference between these precursors is the presence of calcium in the GBFS which leads to the development of a microstructure enriched in stable and high density phases such as C-S-H gels, which promotes high compressive strengths [25, 26]. The effect of calcium inclusion in geopolymers based on MK has been studied using different sources such as calcium hydroxide [27-29], GBFS, natural calcium silicate materials [30], and carbonates [31, 32].

Recently research attempts have been to produce Geopolymer bricks with pronounced characteristics and can be applied in various construction purposes; Ezzat et al. [33] demonstrated several scientific ways in producing geopolymer bricks form water cooled slag, and clay brick waste (grog) in a ratio ranging from 0 up to 100%, and with a fine sand ratio of 15% of the total weight with 8 % sodium hydroxide activator. Results revealed the feasibility of substituting water cooled amorphous slag with grog in synthesis of Geopolymer brick and Resulting in superior quality, where the compressive strength values, with a substitution of slag with up to 40% grog, exceeds 40 MPa and so can be used in production of heavy duty bricks that can...
withstand against sever weathering conditions. However, further substitution leads to the lowering of mechanical properties of the brick, as a result of increased crystalline content and deficiency of activator to dissolve all crystalline fractures.

Khater et al. [34] also studied Alkaline activation of slag – metakaolin binder of geopolymer brick results in formation of C-A-S-H as well as N-A-S-H gel, which adopts different structures depending on the nature of the alkaline activator. Activators used are 10% NaOH solution in addition to 5% liquid sodium silicate both used from the total binder weight. Geopolymer bricks prepared by partial binder substitution of metakaolin (fired kaolin) by water cooled slag in the ratio from 0 up to 100 %, while the used fine sand(passing 1 mm) in the ratio of 15% from the total weight. Results demonstrate the possibility of substitution of metakaolin by water cooled amorphous slag materials in producing geopolymer bricks with superior properties where an increase in mechanical strength with water cooled slag increase up to 40 % was noticed giving compressive strength values exceed 70 MPa which can be used for production of heavy duty bricks which can be applied in a severe weathering condition as well as special purposes building applications, however further increase results in lowering strength values as a but still exceed 30 MPa after 28 days of hydration.

However, several ways has been demonstrated for production of low cost geopolymer building materials and specially building bricks; among of which are lowering the percentage of added alkaline activators, uses of abundant low cost waste materials, and replacing the used activator by waste materials that incorporate high alkaline materials which can initiate the polymerization reaction. Khater [35] studied the utilization of cement kiln dust (CKD) in activation of ground granulated blast furnace slag (water cooled slag (WCS)), air cooled slag, CKD, and calcined kaolin. Calcinations process was done by kaolin firing at 750 C for 3 h. Alkaline activation by 2% NaOH along with the added cement dust was studied as compared with that not activated by sodium hydroxide. Results showed that 25% CKD is the optimum ratio for WCS-geopolymer formation and activation using 2% NaOH along with 25% CKD results in best enhancement in mechanical as well as microstructural characteristics. Activation of metakaolin by 50% CKD has the lowest mechanical properties due to calcium deficiency that bind geopolymer matrix. Effect of 5% magnesium sulfate on WCS and metakaolin activated by CKD results in an enhancement in their mechanical properties up to 3 months, while subjected to a strength loss up to 6 months.

The main purpose of this article is to fulfill various ways in producing geopolymer brick specimens with low production cost through using various sand ratios as well as decreasing the concentration of the added alkalis by utilizing cement kiln dust as a source of high free alkalis that can initiate and propagate geopolymerization reaction. The hardened geopolymer bricks tested using by X-ray diffraction (XRD), FTIR, SEM, compressive strength testing and water absorption are conducted on pastes of Geopolymer based sample, in order to elucidate the various ways in producing low cost product with more economic benefits.
2. EXPERIMENTAL PROCEDURES

2.1. Materials

Materials used in this investigation are water cooled slag as a type from ground granulated blast furnace slag (GGBFS) supplied by the Iron and Steel Factory-Helwan, Egypt; kaolin collected from El-Dehesa, South Sinai, Egypt and cement kiln dust brought from El-Sweedy Cement Co., Egypt. Sodium hydroxide (NaOH) with purity 99 % in the form of pellets used as alkali activators, obtained from SHIDO Co., Egypt, while liquid sodium silicate (LSS, Na$_2$SiO$_3$.9H$_2$O) from Fisher company consists of 32 % SiO$_2$ and 17 % Na$_2$O with Silica modulus SiO$_2$/Na$_2$O equal 1.88 and density 1.46 g/cm$^3$. The used sand dunes for mortar preparation are sourced from fine sand (<1 mm) from Oases (Wahat)-Road, Egypt.

The chemical compositions of the starting raw materials are given in Table (1). Mineralogical characterization of the raw materials was done using X-ray diffraction analysis in powder form as represented in (Fig. 1). Water cooled slag is a rich aluminosilicate material and composed from the dominant content of SiO$_2$, CaO, Al$_2$O$_3$, Fe$_2$O$_3$, and MnO as illustrated from table (1), while its mineralogical composed of amorphous materials.

On the other hand, chemical composition of used kaolinite contains high percentage of alumina of about 56% with about 27% of silica, in addition to small content of calcium and magnesium as presented in table (1), however the mineralogical composition shows that it composed of 70 % kaolinite mineral with minor amount of quartz minerals (30%) as shown Figure (1). This kaolinite material was thermally treated at 800°C for 2 hrs with a heating rate of 5°C/min., to produce metakaolin (Mk). This temperature was chosen on the basis of an earlier research works, where calcinations below 700°C results in a less reactive metakaolinite with more residual kaolinite, above 850°C crystallization occurs and reactivity declines [36-39].

The chemical composition of used cement kiln dust illustrated that it composed of about 58% CaO, with high free lime content of about (18.22%) and high alkalis where CKD can be used as an economical calcium additive material for geopolymerization where the high free lime content favours utilization in geopolymer formation, while the main mineralogical content of cement dust are calcite, anhydrite, portlandite, lime and a minor content from sylvite and halite.

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>SO$_3$</th>
<th>K$_2$O</th>
<th>Na$_2$O</th>
<th>TiO$_2$</th>
<th>MnO</th>
<th>P$_2$O$_5$</th>
<th>Cl$^-$</th>
<th>L.O.I.</th>
<th>SrO</th>
<th>BaO</th>
<th>Total</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolin</td>
<td>56.33</td>
<td>27.61</td>
<td>1.32</td>
<td>0.18</td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
<td>0.08</td>
<td>3.73</td>
<td>--</td>
<td>0.13</td>
<td>--</td>
<td>10.17</td>
<td>--</td>
<td>--</td>
<td>99.97</td>
<td>--</td>
</tr>
<tr>
<td>Metakaolin (800 °C for 2hrs)</td>
<td>57.50</td>
<td>35.10</td>
<td>1.59</td>
<td>0.64</td>
<td>0.17</td>
<td>0.25</td>
<td>0.15</td>
<td>0.12</td>
<td>2.85</td>
<td>0.00</td>
<td>0.13</td>
<td>0.06</td>
<td>1.14</td>
<td>--</td>
<td>--</td>
<td>99.70</td>
<td>--</td>
</tr>
<tr>
<td>Water Cooled Slag (GGBFS)</td>
<td>36.67</td>
<td>10.31</td>
<td>0.50</td>
<td>38.82</td>
<td>1.70</td>
<td>2.17</td>
<td>1.03</td>
<td>0.48</td>
<td>0.57</td>
<td>4.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.12</td>
<td>0.18</td>
<td>3.28</td>
<td>99.96</td>
<td>--</td>
</tr>
<tr>
<td>Fine Sand (Sand dunes)</td>
<td>89.91</td>
<td>2.00</td>
<td>1.45</td>
<td>1.56</td>
<td>1.91</td>
<td>0.87</td>
<td>0.37</td>
<td>0.06</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.12</td>
<td>1.65</td>
<td>--</td>
<td>--</td>
<td>99.98</td>
<td>--</td>
</tr>
<tr>
<td>By-Pass Cement Kiln Dust (CKD)</td>
<td>5.53</td>
<td>2.16</td>
<td>4.58</td>
<td>58.00</td>
<td>0.84</td>
<td>5.53</td>
<td>2.89</td>
<td>0.98</td>
<td>0.29</td>
<td>0.15</td>
<td>0.18</td>
<td>3.45</td>
<td>15.03</td>
<td>0.22</td>
<td>3.50</td>
<td>99.90</td>
<td>Free lime= 18.22</td>
</tr>
</tbody>
</table>

Table (1): Chemical composition of starting raw materials. (Mass, %)
2.2. Geopolymerization and Curing

Geopolymer mixes were made by hand-mixing raw materials of each mixture passing a sieve of 90 \( \mu \text{m} \) with the alkaline activator for 10 min and a further 5 min with an electronic mixer as represented in Table (2). The water-binder ratio (w/b) was illustrated in details in the mix design table. The used fine sand passes sieve of 1 mm used in the ratio of 15 to 50 \% from the total weight depending on the composition of the studied mix as clarified in the table. The paste mixture was cast into 25×25×25 mm cubic-shaped moulds, vibrated for compaction and sealed with plastic sheet to minimize any loss of evaporable water.

The mix design of the materials used in was tabulated in details in Table (2); where the water content increases with sand increase as the porosity of the matrix increase and so acquire much water content [40]. On the other hand there is a gradual increase in water content with cement dust addition as related mainly to the increased free lime content as well as increased calcium oxide source in cement dust that require more water content.

The table also illustrate the oxide ratios of the reacting raw materials, where the silica/alumina is constant for sand mixes while decreases from 3.56 to 3.17 with cement dust increase, where the optimum range of oxide molar ratios [41, 42]: \( 0.2<\text{M}_2\text{O}/\text{SiO}_2<0.48, \ 3.3<\text{SiO}_2/\text{Al}_2\text{O}_3<4.5, \ \text{H}_2\text{O}/\text{M}_2\text{O}, \ 10–25 \) resulting in three dimensional networks with a more branched structure and so homogeneous and compact structure formed and \( \text{M}_2\text{O}/\text{Al}_2\text{O}_3 \), 0.8 to 1.6 [43]. It can be noticed also that there is a sharp increase in the total alkalis with cement dust reaching to about 2.2 up on using 75 \% cement dust.

Figure (1): XRD analysis of the starting raw material.
All mixes were left to cure undisturbed at ambient temperature for 24 hours, and then cured at a temperature of 40 °C and 100 % relative humidity. At the end of the curing regime, the specimens were subjected to the compressive strength measurements and then the resulted specimens were subjected for stopping of the hydration process by drying the crushed specimens for 24 hrs at 105ºC [44, 45] and then preserved in a well tight container until the time of testing.

2.3. Methods of Investigation

Chemical analysis was carried out using Axios, Wave Length Dispersion X-ray Fluorescence (WD-XRF) Sequential Spectrometer (Panalytical, Netherland, 2009). The X-ray diffraction -XRD analysis was carried out using a Philips PW3050/60 Diffractometer. The data were identified according to the XRD software. Bonding characteristics of the alkali activated specimens were analyzed using a 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 [46, 47].

Water absorption measurements of the bricks were carried out according to ASTM C140 [48]. The percentage absorption was calculated using the equation:

$$\text{Absorption (\%)} = \left(\frac{W2 - W1}{W1}\right) \times 100$$

where \(W1\) = weight of specimen after complete drying at 105°C, \(W2\) = final weight of surface dry sample after immersion in water for at least 24 hours.

Compressive strength tests were carried out using five tones German Brüf pressing machine with a loading rate of 100 Mpa/s determined according to ASTM-C109 [49]. The microstructure of the hardened specimens was studied using Scanning Electron Microscopy - SEM Inspect S (FEI Company, Netherland) equipped with an energy dispersive X-ray analyzer (EDX). Removing of the free water was accomplished by using drying of the crushed specimens for 24 hours at 105°C [44, 45].

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**Table (2): Composition of the geopolymer mixes. (Mass, %)**

<table>
<thead>
<tr>
<th>Mix no.</th>
<th>MK</th>
<th>slag</th>
<th>CKD</th>
<th>Sand dunes</th>
<th>NaOH</th>
<th>Na₂SiO₃</th>
<th>Water/binder</th>
<th>T.M.O/Al₂O₃</th>
<th>SiO₂/Al₂O₃</th>
<th>T.M.O/SiO₂</th>
<th>T.W/T.M.O</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3-15</td>
<td>60</td>
<td>40</td>
<td>-</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>0.348</td>
<td>0.454</td>
<td>2.02</td>
<td>0.225</td>
<td>10.63</td>
</tr>
<tr>
<td>M3-25</td>
<td>60</td>
<td>40</td>
<td>-</td>
<td>25</td>
<td>10</td>
<td>5</td>
<td>0.367</td>
<td>0.454</td>
<td>2.02</td>
<td>0.225</td>
<td>11.21</td>
</tr>
<tr>
<td>M3-50</td>
<td>60</td>
<td>40</td>
<td>-</td>
<td>50</td>
<td>10</td>
<td>5</td>
<td>0.400</td>
<td>0.454</td>
<td>2.02</td>
<td>0.225</td>
<td>12.22</td>
</tr>
<tr>
<td>C1</td>
<td>100</td>
<td>-</td>
<td>25</td>
<td>3</td>
<td></td>
<td></td>
<td>0.213</td>
<td>0.666</td>
<td>3.56</td>
<td>0.110</td>
<td>17.58</td>
</tr>
<tr>
<td>C2</td>
<td>75</td>
<td>25</td>
<td>25</td>
<td>3</td>
<td></td>
<td></td>
<td>0.325</td>
<td>0.920</td>
<td>3.49</td>
<td>0.155</td>
<td>24.19</td>
</tr>
<tr>
<td>C3</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>3</td>
<td></td>
<td></td>
<td>0.379</td>
<td>1.341</td>
<td>3.38</td>
<td>0.233</td>
<td>25.69</td>
</tr>
<tr>
<td>C4</td>
<td>25</td>
<td>75</td>
<td>25</td>
<td>3</td>
<td></td>
<td></td>
<td>0.453</td>
<td>2.169</td>
<td>3.17</td>
<td>0.402</td>
<td>28.19</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

3.1. Effect of sand to binder ratio

XRD pattern of 28 days alkali-activated MK/slag geopolymer brick specimens (60:40 wt., %) and having various ratio of fine sand (<1mm), activated with 10% sodium hydroxide and 5% sodium silicate in the ratios, illustrated in Figure (2). The pattern illustrate a broad band in the region of 6° to 10° 2θ for aluminosilicate gel and broad bands in the region of 17° to 35° 2θ characterizing glassy phase of geopolymer constituents. It can be seen that there a broad band for amorphous geopolymer lying in the last region, however this amorphous constituents diminished with adding 25% fine sand increments with the presence of sharp peak for CSH binder phase, this is in addition to an increased intensity of feldspar minerals, this may be aroused either from the increased feldspar within quartz content and/or the transformation of amorphous geopolymer structure into crystalline feldspars as a results of increased aggregate that hinder the interaction between the geopolymer chains and so subjected to crystallization into feldspars with time [50].

On increasing the quartz ratio up to 50%, predominant intense increase in the feldspar peaks as well as calcite at 29.4° along with the decreased CSH phases as a result of binder decrease, also there is an intense peak at about 11.44° for hydrotalcite which is one of the slag minerals; this confirm the segregation of binder by sand grains and so inhibit complete dissolution of the aluminosilicate materials by the added alkalies, so the added free alkalies will be subjected to carbonation confirming the appearance of calcite peaks with the increased sand content.

![XRD pattern of 28 days alkali-activated MK - Geopolymer brick specimens having 40% slag and incorporating various fine sand ratios.](http://www.iaeme.com/IJCIET/index.asp)

**Fig. (2):** XRD pattern of 28 days alkali activated MK - Geopolymer brick specimens having 40% slag and incorporating various fine sand ratios. [Q: Quartz, F: Feldspars, C: Calcite, Fj: Fajausite, CSH: Calcium silicate hydrate, Ht: Hydrotalcite]

FTIR spectra of 28 days alkali-activated MK/slag geopolymer brick specimens and having various ratio of fine sand are shown in Fig. (3). The characteristics bands for the present geopolymer structure are: hydration groups and combined water
allocated for stretching vibration of O-H bond at about 3450 cm$^{-1}$ and bending vibration for H-O-H at about 1630 cm$^{-1}$, stretching vibration of CO$_2$ located at about 1430-1450 cm$^{-1}$, asymmetric stretching vibration (Si–O–Si) at about 1060 cm$^{-1}$ for non-solubilized silica, asymmetric stretching vibration (Ti–O–Si) at 960 cm$^{-1}$ where T=Si or Al, out of plane bending vibration of CO$_2$ at about 870 cm$^{-1}$, symmetric stretching vibration (Al–O–Si) at about 773 cm$^{-1}$, symmetric stretching vibration (Si–O–Si) in the region 660-698 cm$^{-1}$ and bending vibration (Si–O–Si and O–Si–O) in the region 430-450 cm$^{-1}$.

The pattern indicates an increased growth in the stretching vibration of O-H band for combined water at about 3450 while decreases for bending vibration at about 1630 cm$^{-1}$ with increasing the fine sand ratio, where the increased of the first band reflects the increased water content in the matrix and so increased porosity, while the second band that decrease with sand reflects the decrease in the formed CSH as a results of dilution by added sand.

The decrease in CSH binder phase confirmed by the splitting of the carbonate vibration band at about 1430 cm$^{-1}$ into two peaks which may be due to the carbonation of the formed CSH binder phases by increased porosity and entrained air indicates the distorted nature of CO$_3$ mineral [51, 52]. This could be attributed to partial carbonation of C-S-H gel in air atmosphere. It can be seen also, an increase in the intensity of the carbonate 867cm$^{-1}$($\delta$ C–O) with sand increase confirming the increased porosity leading to more air entraining causing carbonation as well as carbonation of the free alkalis that not shared in the geopolymer formation by sand segregation. The main asymmetric band for T-O-Si related to amorphous geopolymer structure decreased sharply with sand increase as a results of dilution effect and segregation within the matrix, this accompanied by an increased intensity of the non-solubilized silica at about 1100 cm$^{-1}$, this confirmed previously by XRD analysis where the an increased in feldspar with the decrease in the amorphous geopolymer as well calcite increase are the main features. This increased intensity of the amorphous geopolymer peak with sand decrease is in alignment with the decreased bands intensity at about 777, 694 and 440 cm$^{-1}$for symmetric vibration band of (Al-O-Si), symmetric band of (Si–O–Si) and bending vibration (Si–O–Si and O–Si–O) [47] which emphasize the increased dissolution of the unreacted silica and forming additional geopolymer chains.
Microstructure of 28 days alkali-activated MK/slag geopolymer brick specimens and having various ratio of fine sand are shown in Fig. (4). It can be noticed that MK/slag geopolymer specimen incorporate 15% sand form a homogeneous matrix without any apparent interfacial transition zone (ITZ) near the aggregates; also there is coexistence of geopolymer chains along with CSH binding gel that acts as seeding agent for geopolymer accumulation and so results in a more compact and dense structure [Figure (4A)]. On increasing the added sand, results in the formation of heterogeneous structure with an increase in the unreacted silica as well as decrease in amorphous geopolymer structure as depicted from [Figure (4B)]. Further increase in the added fine sand [Figure (4C)], results in low matrix cohesion with increased heterogeneity as the increased pores in interfacial transition zone (ITZ) between binder and aggregate prevailed, also an increased carbonate appears on the surface of the binder which is in agreement with both XRD and FTIR investigations.

**Figure (3):** FTIR spectra of MK - Geopolymer brick specimens having 40% slag and incorporating various fine sand ratios. [1]: Stretching vibration of O-H bond, 2: Bending vibrations of (HOH), 3: Stretching vibration of CO₂, 4: Asymmetric stretching vibration (Si-O-Si), 5: Asymmetric stretching vibration (T-O-Si), 6: Symmetric stretching vibration of CO₂, 7: Symmetric stretching vibration (Al-O-Si), 8: Symmetric stretching vibration (Si-O-Si), 9: Bending vibration (Si-O-Si and O-Si-O)]
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Figure (4): SEM micrographs of 28 days alkali activated Mk-slag (60-40%) Geopolymer specimens having various sand content. A) 15%, B) 25%, and C) 50% sand.

The compressive strength values of Mk/slag geopolymer brick mixes containing different amount of sand, 15: 50 wt. % and with curing times from 7 up to 60 days, 40 °C and 100% relative humidity are illustrated in Fig. (3). The compressive strength of geopolymer mixes having various sand ratios gives with SiO$_2$/Al$_2$O$_3$ = 2.02, results in the formation of more dense and compact structure giving values exceed 85 MPa after 60 days. This can be related to the previously summarized the ratios (i.e., SiO$_2$/Al$_2$O$_3$, Na$_2$O/SiO$_2$, Na$_2$O/Al$_2$O$_3$, and H$_2$O/Na$_2$O), where H$_2$O/Na$_2$O increases with sand ratio increase as the increased sand results in formation of more porous structure and so acquire much water that affect negatively on compressive strength. Khater et al. [34] and Barbosa et al. [53] have conducted a test on calcined kaolin geopolymers found that Na$_2$O/SiO$_2$ ratio of 0.25, and H$_2$O/Na$_2$O ratio of 10.0 were the optimum chemical composition, which can be observed from table (2) where 15% sand almost satisfy the previous limits.

It is obvious that the compressive strength of Geopolymer brick with 15%, 25% and 50% of sand reaches about 853, 767 and 461 kg/cm$^2$, respectively, after 60 days of curing, with enhancement in their mechanical performance about 14%, 34.7% and 75.8%, respectively, compared to the 7 days cured specimens. This indicates that with addition of more sand with percentage up to 50% significantly reduced the mechanical performance of the Geopolymer specimens, owning to a decrease in percentage of binder and increase of water/binder ratio. Thus reducing the binder need.
to combine the sand grains together, so it is clear that most of the samples in this section can be classified according to IS:1077 [54] as a heavy duty bricks that can be used for heavy duty structures as bridges, foundation, or industrial buildings.

This indicates that with addition of more sand with percentage up to 50% significantly reduced the mechanical performance of the Geopolymer specimens, owning to a decrease in percentage of binder and increase in water/binder ratio. Thus reducing the binder need to combine the sand grains together. The compressive strength trend in alignment with FTIR and XRD investigations where the increased crystalline feldspars as well as decreased amorphous geopolymer constituents and CSH phases with sand increase as the binder decrease as well as segregation of the current binder prevailed.

![Figure(5): Compressive strength of alkali activated MK - Geopolymer brick specimens having 40% slag and incorporating various fine sand ratios.](image)

The water absorption values of MK slag (60: 40 wt., %) Geopolymer brick specimens with 15%, 25% and 50% sand is presented in Fig. (6), while data tabulated in Table (5). It points out that water absorption increase with sand increase and decreases with increasing curing time; the increase with sand resulted from a decrease in the binder content, whilst a notable reverse trend of water absorption to bulk density can be identified as the porosity increase. Water absorption values after 28 and 60 days for control mixes are 11.20, 11.70, 12.79 % and 11.10, 11.31, 11.75 % at 28 and 60 days for 15, 25 and 50 respectively, these data revealed the decrease of absorption with time where they are lower than required for sever weathering building bricks as specified by ASTM C62 [55].

![Figure(6): Water absorption of alkali activated MK - Geopolymer brick specimens having 40% slag and incorporating various fine sand ratios](image)
3.2. Effect of cement kiln dust

XRD pattern of 28 days alkali-activated water cooled slag based geopolymer brick specimens incorporating various cement kiln dust content and activated with 3% sodium hydroxide, illustrated in Figure (7). There is a clear decrease in the broadness of amorphous geopolymer band lying in 17.35° 2θ, where it diminishes with increasing of cement kiln dust up to 75%, with the presence of excess unreacted portlandite at about 18.1° and 34.1° in addition to an increase in the crystalline peaks due to calcite as a result of decreasing amorphous slag constituents in addition to increased free lime as well as alkalis which will hinder the geopolymer formation and propagation by consuming the surface species leading to lowering in oligomer structure and its stability upon time [46], also the free unreacted alkalis will undergo efflorescence forming more carbonate constituents in addition to carbonate within CKD. It can be noticed that the presence free lime with the increase of CKD confirming the decrease in the amorphous slag constituents that capable of consuming free lime. It can be noticed that, mix incorporating 0% ckd possess an increasing in the amorphous hump within 17-35°, in addition to the formation of CSH binder phase resulting from the dissolution and interaction of Ca and Si species, which favours homogeneous nature of the formed geopolymer.

The pattern indicates the decrease in the main asymmetric band at 940 cm⁻¹ confirming the decreased geopolymer content with CKD; this is in alignment with the increase of carbonate bands attributed mainly to the increased CKD content as well as carbonation of free unreacted alkalis within CKD, also there is an increased intensity of shoulder at about 3590 cm⁻¹ for portlandite content as illustrated clearly in XRD

![Figure (7): XRD pattern of 28 days alkali-activated water cooled slag – CKD geopolymer brick specimens](http://www.iaeme.com/IJCIET/index.asp)
pattern. It can be seen an increase in the intensity of unreacted silica at about 1100 cm\(^{-1}\) with CKD confirming the dilution effect of cement kiln dust as well as the decrease in the amorphous slag content as reflected on the decreased intensity of the T-O-Si asymmetric band.

It is noticed also that the intensity of the carbonation bands located at 1429 and 875 cm\(^{-1}\) in slag 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. This reflected positively on the increased broadness of H\(_2\)O and hydration materials bands at 3434 and 1635 cm\(^{-1}\) giving an indication about an increased hydration products formed upon using solely slag precursors as a result of dissolution of calcium ions within WCS forming CSH that acts as a nucleating agent for geopolymer precipitation of dissolved species, so that lead to rapid hardening, forming a fine and homogeneous structure \([56]\) also the small left shoulder in the H\(_2\)O band reflects the O-H of hydrated lime which is here mostly consumed in the hydration product formation.

The decrease in the CSH binder phase confirmed by the splitting of the carbonate vibration band at about 1430 cm\(^{-1}\) into two peaks which may be due to the carbonation of the formed CSH binder phases by increased porosity and entrained air indicates the distorted nature of CO\(_3\) mineral \([51, 52]\). This could be attributed to partial carbonation of C-S-H gel in air atmosphere. It can be seen also, an increase in the intensity of the carbonate 867 cm\(^{-1}\) (\(\delta\) C–O) with CKD increase confirming the increased dilution as well as increased unreacted carbonate content as well as carbonation of the free alkalis that not shared in the geopolymer formation. The main asymmetric band for T-O-Si related to the amorphous geopolymer structure decreased sharply with kiln dust increase as a result of dilution effect and segregation within the matrix, this accompanied by the increased intensity of the non-solubilized silica at about 1100 cm\(^{-1}\), this confirm the XRD analysis where the an increased in feldspar with the decrease in the amorphous geopolymer as well calcite increase are the main features.

\[ \text{Figure (8): FTIR spectra of 28 days alkali activated water cooled slag – CKD geopolymer brick specimens. (1, 2: Stretching vibration of O-H bond, 3: Bending vibrations of (HOH), 4: Stretching vibration of CO}_2, 5: Asymmetric stretching vibration (Si-O-Si), 6: A symmetric stretching vibration (T-O-Si), 7: Symmetric stretching vibration of CO}_2, 8: Symmetric stretching vibration (Al-O-Si), 9: Bending vibration (Si–O–Si and O-Si-O)} \]
The compressive strength values of geopolymer mixes having various cement kiln dust content as partial replacement of water cooled slag precursor with 25% sand, and cured up to 60 days, 40 °C and 100% relative humidity are illustrated in Figure (9). From the figure, it can be noticed a sharp decrease in compressive strength values with cement kiln dust, whilst the strength increase with curing time as a result of increased polymerization and hydration progress with time. The decrease in strength with cement kiln dust may be related to a decrease in percentage of amorphous slag precursors as well as increased unreacted free lime as well as free alkalis as indicated from the mix design table (2) where the total alkalis to alumina oxide increased from 0.666 to 2.169, whilst the optimum range of oxide molar ratios \([41, 42]\): 

\[
0.2 < \text{M}_2\text{O}/\text{SiO}_2 < 0.48, \quad 3.3 < \text{SiO}_2/\text{Al}_2\text{O}_3 < 4.5, \quad \text{H}_2\text{O/M}_2\text{O}, \quad 10–25
\]

resulting in three dimensional networks with a more branched structure and so homogeneous and compact structure formed and \(\text{M}_2\text{O}/\text{Al}_2\text{O}_3\), 0.8 to 1.6 \([43]\). So the increased alkalis content to about 2.2 when using 75 % CKD results in the formation of oligomer chains than long polymeric chains with three dimensional structure \([56]\) and so be more prone to carbonation, increase the dilution as well as segregation of reacting geopolymer structures, in addition to the increase of water/binder ratio which may be linked directly to an increase in the porosity as illustrated from the increased total water to alkalis from 17.6 to 28.2 as indicated in table (2)

It is obvious that the compressive strength of geopolymer mixes with 0%, 25%, 50% and 75% of cement kiln dust give values of about 549, 387, 198 and 145 kg/cm\(^2\), respectively, after 60 days of curing, with an enhancement in their mechanical performance of about 25.6%, 22.5%, 67% and 59.5 %, respectively, compared to the 7 days cured specimens. From the compressive strength table, it is clear that the control geopolymer mix that has no cement kiln dust content can be classified according to \(\text{IS:1077}\) \([54]\) as a heavy duty bricks at all curing times, that can be used for heavy duty structures as bridges, foundation, or industrial buildings.

However, increasing the cement kiln dust to 25% can be classified according to the previously mentioned standards as in the range between grades 30 to 35. On the other hand further increase in cement dust leads to lowering in the grade and class of the resulting geopolymer structure to be under grade 20. This indicates that with addition of more cement dust reduced the mechanical performance of the Geopolymer specimens, owning to a decrease in binder percentage, increase in the free unreacted alkalis, and increase of water/binder ratio. Thus reducing the matter need to combine the sand grains together.
The water absorption values of water cooled slag geopolymer bricks incorporating various cement kiln dust content is presented in Fig. (10). It points out that water absorption increase with ckd increase and decreases with increasing curing time; the increase with ckd resulted from a decrease in the binder content as well as increased efflorescence of unreacted free alkalis that in turn participate in increasing matrix porosity, whilst a notable reverse trend of water absorption to bulk density can be identified as the porosity increase. The water absorption confirmed from the increased water to alkalis content to 28.12 when using 75% cement kiln dust which in alignment with an increased alkalis to both silicon oxide and aluminum oxide that reversely affect the polymerization reaction by hindering the formation of polymeric chains and consumes the geopolymer chains as stated before [56].

Water absorption values after 28 and 60 days are 8.33, 12.15, 18.99, 21.05% and 4.55, 10.28, 17.63, 19.55% at 28 and 60 days for 0, 25, 50 and 75% ckd, respectively, these data revealed the decrease of absorption with time where they are lower than required for sever weathering building bricks as specified by ASTM C62 [55].

4. CONCLUSION
This research has been performed with main target in lowering the production of geopolymer bricks made from industrial by-products as a base materials and investigating its physical, mechanical and micro structural characteristics. In relation to the objectives of this research, the major findings are summarized as follows:

1. It was found that variation in sand ratio in Mk/slag in Geopolymer brick specimens results in the formation of well compacted dense structure in spite of increasing the sand ratio up to 25% giving compressive strength values exceed 75 MPa after 90 days of curing, while further increase in sand to 50% results in decreasing the compaction within the matrix and giving strength values of about 45 MPa after 90 days, which can be used for production of heavy duty bricks as well as refractory bricks [54], also can be applied in a severe weathering conditions ASTM- C62 [55].

2. SEM micrographs have proved an enhanced geopolymer performance by using sand to 25%, while further increase in sand content results in an increase in water absorption that negatively affect the matrix cohesion.
3. XRD and FTIR spectra confirm the intense amorphous geopolymer structure up on using 15 to 25% sand, while the increased crystalline quartz and anorthite phases are predominant with further sand increase.

4. It was found also that uses of cement kiln dust in addition to lower dose of sodium hydroxide activator can initiate the geopolymerization process as cement kiln dust acquire much alkalis content that are more helpful in the reaction propagation.

5. Uses of cement dust up to 25%, in spite of decreasing the compressive strength as compared with blank, but still possess higher values reaching to about 31.6 and 38.7 MPa after 7 and 90 days, respectively.

6. Increasing cement kiln dust beyond 25% results in an increase in the free alkalis and decrease in the amorphous constituents from slag; those alkalis results in termination of the geopolymerization reaction in addition to consuming the surfaces by forming short oligomer chains.

7. The produced geopolymer bricks possess more than 90% reduction in carbon dioxide as well as with more economical production costs as compared with other traditional clay bricks.

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