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Study on the Influence of Alkali Activator Solutions on Strength Improvement of Pozzolan Calcium Hydroxide Binders

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Abstract

Alkali activated binder, commonly known as geopolymer cement, has replaced Portland cement in the production of mortar and concrete globally over the past few years. The density, particle size distribution, and specific surface area (SSA) are important physical parameters affecting strength and durability of alkali activated binders. This study carried out tests for physical and chemical properties of the natural pozzolan and calcium hydroxide and then determines the influence of alkali solution (sodium silicate and sodium hydroxide) on strength development of natural pozzolan calcium hydroxide binders. The particle size distribution (PSD), relative densities (RD), and specific surface areas (SSA) of powder natural pozzolan and calcium hydroxide materials and for the mixture of natural pozzolan and calcium hydroxide were determined by using Blaine air permeability apparatus. The optimum proportion of 75% natural pozzolan and 25% calcium hydroxide was obtained which produces the compressive strength of 7.5 MPa at 28 days cured paste. The mixture of natural pozzolan and calcium hydroxide were further grinded at three different finenesses and the particle size gradation, specific densities, specific surface areas and mean particles sizes for the mixture were determined. The compressive strength of alkali activated binders increased with increasing curing period and fineness. The maximum compressive strength for 28 days cured specimens was 26.1 MPa which was obtained at a solution of 8 moles sodium hydroxide concentration. The test results showed that natural pozzolan materials can be used to make geopolymer binders for mortars and concretes. The geopolymer binders for mortars and concretes reduce green gas emission from cement factory but also it can be used to produce durable mortar and concrete with comparable strengths with mortars and concrete made from conventional Portland cement.

Keywords

Alkali Activated Materials, Natural Pozzolan, Calcium Hydroxide, Geopolymer Binders, Material Properties, Compressive Strength, Paste Specimens

1. Introduction

Pozzolan materials (artificial and natural) are extensively used as supplementary cementitious materials for mixing with industrial cements for producing mortars and concretes (Moon et al., 2014). In the recent years the use of pozzolanic materials has been extended for making geopolymer mortars and concrete through activation with alkali solution. The use of alkali activators on making geopolymer binders for concrete and mortar mixes has found to increase durability and reduce green gases emission from cement factories (Alp et al., 2009). Alkali activated cement (AAC) which is known as geopolymer cement has been extensively studied in terms of its properties and characteristics. However, few researches have been conducted on natural pozzolan-based alkali activated binders (Alraddadi & Assaedi, 2020).

Some studies conducted to activate pozzolanic materials using alkali solutions having substantial amount of silicates and aluminates have indicated promising results on strength development and durability (Zheng et al., 2016). Pozzolan are siliceous and aluminous materials which themselves possess little or no cementitious values but, when finely grounded chemically react with calcium hydroxide in the presence of water at ordinary temperature to form calcium silicates hydrates (CSH) and calcium aluminates hydrates (CAH) (Robayo-Salazar & De Gutiérrez, 2018). When calcium reacts with silicate and aluminum from pozzolanic materials the process is called pozzolanic reaction and when the mixture of pozzolan and calcium oxide or hydroxide is activated by alkaline elements the process is called geopolymer reaction.

Pozzolanic reactions occur over long time scales (months to years). The main mechanism involves the transportation of calcium hydroxide via water to combine with silicate and/or aluminate in pozzolan minerals (Duxson et al., 2007) The pozzolan, which in the presence of water having alkaline environment (e.g. presence of calcium) produce cementitious materials, comprise calcium silicates and calcium aluminate hydrates as the main pozzolanic compounds produced (Zheng et al., 2016). The dissolved Ca^{2+} ions react with any dissolved SiO_2 and Al_2O_3 on pozzolan to produce hydrated gels of C-S-H and C-A-H. Under normal curing environment of pozzolanic binders, the following reaction process and cementitious products may occur (Alp et al., 2009).

$$CaO + H_2O \rightarrow Ca(OH)_2\,(CH) \quad (1)$$

$$2S + 3CH \rightarrow C_3S_2H_3\,(CSH) \quad (2)$$

$$A + 4CH + 9H \rightarrow C_4AH_{13}\,(CAH) \quad (3)$$

However, in the pozzolan-lime system, other products of pozzolanic reaction may develop such as C_2SH_2, CAH_{10}, C_3AH_6 (katoite) and C_2AH_8 (mayenite), gehlenite (C_2ASH_8) and hydrogarnet (C_3ASH_6) (Juenger et al., 2011).

The pozzolanic reaction are greatly affected by physical, chemical, morphology and mineralogical composition (Chengula, Msambichaka, & Middendorf, 2018; Arvaniti et al., 2015a). The density, particle size distribution, and specific surface area (SSA) are important physical parameters affecting pozzolanic reaction and geopolymer reaction (Sharma & Khan, 2016). Adequate physical characterization of binder materials is important to better predict their performance and optimize their use in mortar and concrete production (Juenger et al., 2011). Fineness is one of the most essential physical parameters determining binder materials' reactivity (Mboya et al., 2017). The rate of dissolution is increased by reducing the average particle size, which improves pozzolanic reactivity and therefore makes for greater strength (Walker & Pavía, 2011). The effects of density, specific surface area and particle size distribution were discussed in detail by previous researcher (Chengula, Msambichaka, & Middendorf, 2018). The study encouraged the materials with variances in densities to be proportioned by volume (Chengula, Msambichaka, & Middendorf, 2018). It was noted that for large specific surface area the rheological, compressive strength and durability were improved (Arvaniti et al., 2015a). The flow properties of fresh paste, mortars and concrete are improved by uniformly graded particle sizes. The packing density and compressive strength development are also improved (Arvaniti et al., 2015b).

The pozzolanic reaction which occurs in the setting of the mixture of slaked lime and pozzolanic materials has also features similar to the alkali-silica reaction (geopolymer reaction), mainly the formation of calcium silicate hydrate (C-S-H) (Ibrahim et al., 2019).

The geopolymer reaction is the chemical reaction involving alkaline (base) elements in solution with acidic elements (Gharzouni et al., 2015). The common alkaline elements considered for geopolymer reactions are sodium, potassium and manganese and common acidic elements considered for geopolymer reactions are silica and alumina (Djobo et al., 2016). The alkali-acidic reactions can take place in cement and pozzolanic materials provided there are presence of reactive chemicals and suitable environment (Gharzouni et al., 2015). The literature demonstrates that, when alkali reacts with silica in a hardened concretes and mortars is called alkali-silica reactions and it is harmful to the concrete and mortars because it causes severe cracks and deterioration of concrete and mortars due to volume increase.

The alkali-silica gel formed during early age of pozzolanic and geopolymer reactions are harmless to the concrete or mortar (Akbari, Mensah-Biney, & Simms, 2015). This is because the stresses induced pressures by alkali-silica gels formation are absorbed in the fresh concrete or mortar. The cracks formed due to extra stress in concrete or mortar are filled immediately by pozzolanic gels

such as CSH and CAH and geopolymer chain gels such as NSH and NAH during the process of hardening which results into high strength development (Irshidat, Abdel-Jawad, & Al-Sughayer, 2018; Walker & Pavía, 2011). Increase in volume due to alkali-silica formation at early age of concrete or mortar is limited due to confinement in formworks or moulds. Apart from alkali-silica reaction in pozzolanic binders but also alkali-aluminum reaction can take place in the same system provided there are reactive alkali and aluminum elements in the solution (Chen et al., 2021). There have been no reports of concrete and mortar being destroyed because alkali-aluminum gels formed during the early and late days of curing.

The simplest scheme of geopolymer reactions in pozzolanic binders under normal environment of pressure, temperature, humidity and alkaline concentration can be as follows:

$$2\mathrm{NaOH} + \mathrm{SiO_2} + \mathrm{H_2O} \rightarrow \mathrm{Na_2SiO_3} \cdot 2\mathrm{H_2O}\left(\mathrm{NSH}\right) \tag{4}$$

$$2\mathrm{NaOH} + \mathrm{Al_2O_3} + \mathrm{H_2O} \rightarrow \mathrm{Na_2Al_2O_4} \cdot 2\mathrm{H_2O}\left(\mathrm{NAH}\right) \tag{5}$$

Polymerization process involves a substantially fast chemical reaction under alkaline conditions on silicon-aluminum minerals that results in a three-dimensional polymeric chain and ring structure (Davidovits, 2017). The reaction takes three stages; stage 1 is dissolution of Si-O-Si, Al-O-Al, and Si-O-Al bonds provided by the precursor (often referred as nucleation stage), stage 2 is coagulation or polycondensation in which a coagulated structure between the disbanded/disaggregated composition from precursor takes place and stage 3 is crystallization, in which crystals begin to develop and shape an inorganic hardened and 3-dimensional polymer structure (Allahverdi & Ghorbani, 2006).

The geopolymer chain product is an amorphous three-dimensional network polymer, formed by the condensation of silicon oxygen tetrahedrons and aluminum oxygen tetrahedrons. The general formula of alumino-silicate materials that provide polymeric Si-O-Al bond is given as follows (Bondar et al., 2012):

$$M_n[(\mathrm{SiO_2})_z\mathrm{Al_2O_3}]_n \cdot w\mathrm{H_2O} \tag{6}$$

where:

M—is an alkali cation (such as $\mathrm{Na^+}$, $\mathrm{K^+}$ or $\mathrm{Ca^{2+}}$),

n—is the polymerization degree,

n—is 1, 2, to 3 and

w—is the number of moles of water.

The main parameter which influences the properties of geopolymer binder is alumino-silicate source (Oyebisi et al., 2018). The common alkaline activator used is sodium hydroxide and sodium silicate or potassium hydroxide and potassium silicate (Hajimohammadi & van Deventer, 2016).

The binders made from pozzolan and calcium hydroxide which have been activated by alkali solution both products C-(A)-S-H and N(K)-A-S-H might co-exist (Davidovits, 2017). But also there might be intermixing of the gels due to modification process taking place within the systems leading to a partial or

total replacement of sodium with calcium to form a giant geopolymer chain (N,C)-A-S-H gels (Kropyvnytska et al., 2019).

2. Materials and Method

The precursor materials used for this study were locally available volcanic ashes and the activators of the geopolymer reactions were industrial alkali solution. Materials characterizations, mixing process of binders and tests for compressive strengths of cured specimens were conducted under laboratory condition.

2.1. Materials Used for This Study

The materials used for mixing geopolymer binders are natural pozzolan from Songwe region in Tanzania, industrial processed calcium hydroxide from local suppliers. In order to improve reactions process of pozzolanic binders and improve strengths of cured specimen then alkali solutions were used as activators to mix the pastes. The alkali activators used are sodium silicate solution and sodium hydroxide pellets obtained from local supplier in Mbeya region.

Water was added into solid sodium hydroxide pellets (NaOH) at three different concentrations of 6 moles, 8 moles and 10 moles to make sodium hydroxide solution. The two alkali solutions were then mixed together for mixing pozzolan calcium hydroxide paste. The sodium hydroxide pellets (NaOH) had a purity of 97% with proportions of 77.53% of Na_2O and 22.47% of H_2O by mass. The Sodium silicate (Na_2SiO_3) in solution form had a purity of 98% with proportions of 34.78% of SiO_2, 16.22% of Na_2O and 49.00% of H_2O by mass.

2.2. Determination of Physical and Chemical Properties of Materials

Natural pozzolan from Songwe region and industrial calcium hydroxide from supplier were used to prepare paste for determination of compressive strengths of cured specimens. The natural pozzolan were air dried and grinded into powder form using disc grinder machine while calcium oxide were obtained in powder form.

Physical and chemical properties of natural pozzolan and calcium hydroxide were determined. The chemical compositions of the materials were determined using XRF equipment conducted at Government Chemistry Laboratory located in Mbeya Region. **Table 1** gives the chemical oxides of natural pozzolan and calcium oxide used for this study.

The physical properties of materials were determined by using Blaine air percolation apparatus, the method described by Chengula, Msambichaka and Middendorf (2018). The properties determined are specific densities, specific surface areas, particle size distribution, mean particle sizes, median, mode, maximum and minimum particle sizes. The specific densities and specific surface areas of powder natural pozzolan and calcium hydroxide were determining using Equation (7) and Equation (8) respectively (Chengula, Msambichaka, & Middendorf, 2018). However Equation (9) and (10) were used to determine particle size dis-

tribution of powder materials (Juimo Tchamdjou et al., 2018). The physical properties of the raw natural pozzolan and calcium hydroxide powder materials are summarized in Table 2.

Table 1. Chemical composition of materials.

Chemicals	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	LOI	Total
Natural pozzolan	55.84	19.5	8.88	1.5	0.4	0.02	1.44	3.54	0.05	8.83	100
Calcium hydroxide	0.4	0.6	0.6	74.7	0.8	0.2	0.6	0.3	0.05	21.75	100

Table 2. Physical properties of natural pozzolan and calcium hydroxide powdered materials.

Properties	Specific density (gm/cm³)	Specific surface area (cm²/gm)	Mean particle size (μm)
Pozzolan	2.496	5560	1.745
Calcium hydroxide	2.269	7080	1.444

$$\rho = \frac{2M}{V} \tag{7}$$

where: M—Weight of sample at turning point,

V—Volume of Blaine tin (1.628 cm^3).

$$SSA = K\frac{\sqrt{m_i M_i}}{\rho_{si}} \tag{8}$$

where: SSA—Specific surface area (cm^2/g),

m—Curve slopes of time air flow versus weight of sample (sec/g),

M—Mass of sample in Blaine tin at turning points,

ρ_s—Densities of materials at turning points,

K—Apparatus and measurement constant (1050).

$$G_{ps} = \mathcal{K}\left[\frac{1}{\eta_a\left(m_1 + m_2\right)}\right] \times \left[\frac{M_i - \alpha M_o}{M_f - M_o}\right] \tag{9}$$

$$\%CP = 100\frac{T_i}{T_f} \tag{10}$$

where: G_{ps}—Grain particle size (g),

$\mathcal{K}$—Constant of equation (13,650),

η_a—Dynamic viscosity of air at room temperature,

m_1 & m_2—gradient at lower and middle curve,

M_o—Weight of sample at zero time,

M_f—Weight of sample at second turning,

α—factor for sample weight at zero air flow (0.99),

T_i—Time air flow for each measurement,

T_f—Time air flow at second turning.

2.3. Determination of Optimum Proportion of Natural Pozzolan and Calcium Hydroxide

The paste specimens were prepared by mixing natural pozzolan and calcium hydroxide powder. Different mixtures were prepared by varying the proportions of pozzolan contents from 20% to 90% as indicated in Table 3. The paste was mixed at constant water to binder ratio of 0.48.

Three specimens for each proportion of natural pozzolan and calcium hydroxide mix of the sizes 50 mm cubes were casted and cured for 28 days. Table 3 gives the amount of natural pozzolan, calcium hydroxide and water for each mix proportion of pozzolan-lime mixtures.

The variation of pozzolan and calcium hydroxide on paste specimens were done in order to determine optimum proportions of pozzolan and calcium hydroxide to which the maximum compressive strength of paste specimens can be obtained.

2.4. Geopolymer Paste Specimens Made from Natural Pozzolan and Calcium Hydroxide

The powdered natural pozzolan and calcium hydroxide were mixed together at mix proportions of 75% natural pozzolan and 25% calcium hydroxide to prepare geopolymer paste specimens. In order to increase reactivity, the mixture of natural pozzolan and calcium hydroxide materials were further grinded on which three different fineness were obtained. The physical properties of the mixture of natural pozzolan calcium hydroxide binders are summarized in Table 4. The alkali materials used for geopolymer binders are the mixture of sodium silicate solution and sodium hydroxide solution.

The pellets of sodium hydroxide were hydrated with water to form solution at different concentrations. The solution of sodium hydroxide was prepared at concentration of 6 moles, 8 moles and 10 moles of sodium hydroxide pellets. Figure 1 is the photos of the materials used to make geopolymer paste specimens for this study.

Three specimens of the sizes 50 mm cubes were casted and cured for 7 days, 14 days, 21 days and 28 days. Table 5 gives the amount of binder, natural pozzolan, calcium hydroxide, total solution, sodium hydroxide solution and sodium silicate solution for making geopolymer pastes.

2.5. Mix Design of Alkali Solution

Geopolymer paste specimens were prepared at solution to binder ratio of 0.52. The solution was made from the mixture of sodium silicate solution and sodium hydroxide solution. The sodium hydroxide solution was prepared 24 hours prior to use. The sodium hydroxide solution thus prepared was mixed well with sodium silicate solution to get desired alkaline solution. The ratio of sodium silicate solution and sodium hydroxide solution used for this study was 2.5. The amount of alkali solution (AS) used for mixing paste specimens were determined from 2000 gm of binders as indicated in Table 5. The amounts of constituent materials are calculated as follows:

Figure 1. Raw materials used for making geopolymer paste specimens.

Table 3. Mixing proportions and contents of natural pozzolan and calcium hydroxide powder.

S/N	Sample ID	Pozzolan (gm)	Lime (gm)	Water (gm)
1	20P80L	400	1600	960
2	40P60L	800	1200	960
3	60P40L	1200	800	960
4	80P20L	1600	400	960
5	90P10L	1800	200	960

Table 4. Physical properties of pozzolan: lime powder at three different fineness.

Description	Specific density (gm/cm^3)	Specific surface area (cm^2/gm)	Mean particle size (μm)
Fineness No. 1	2.463	6059	1.681
Fineness No. 2	2.460	6148	1.674
Fineness No. 3	2.462	6642	1.432

Table 5. Contents of materials for geopolymer pastes.

Materials	Binder	Total solution	Pozzolan	Calcium hydroxide	Sodium silicate solution	Sodium hydroxide solution
Amount	2000	1040	1500	500	743	297

Solution = Binder × 0.52 = 2000 × 0.52 = 1040 gm,

Pozzolan = 0.75 × 2000 = 1500 gm; Calcium oxide = 2000 × 0.25 = 500 gm,

Sodium silicate solution = 2.5 × 1040/3.5 = 743 gm; Sodium hydroxide solution = 1040/3.5 = 297 gm.

The amount of sodium and silicon dosage in the paste for each concentration of sodium hydroxide were determined from molar weights and compositions in the solution:

The compositions of the sodium silicate solution from the manufacturer are SiO_2 = 34.78%, Na_2O = 16.22% and H_2O = 49.00% with purity of 98%. The molecular weights are 60 gm for SiO_2, 62 gm for Na_2O and 18 gm for H_2O.

The amount of sodium and silicon in sodium silicate solution are determined as follows:

$$\text{Silicon} = \frac{28}{60} \times 0.3478 \times 0.98 \times 743 = 118.18 \text{ gm}$$

$$\text{Sodium} = \frac{46}{62} \times 0.1622 \times 0.98 \times 743 = 87.63 \text{ gm}$$

The molecular weights are 40 gm for NaOH and 18 gm for H_2O. The compositions of the sodium hydroxide solution for 1mole concentration of NaOH are 3.85% for NaOH and 96.15% for H_2O with purity of 97%.

The amount of sodium in sodium hydroxide solution for 6 moles, 8 moles and 10 moles are determined as follows:

1) For 6 moles of sodium hydroxide in a litter of water

$$\text{Sodium} = \frac{240}{1240} \times \frac{23}{40} \times 0.97 \times 297 = 32.06 \text{ gm}$$

2) For 8 moles of sodium hydroxide in a liter of water

$$\text{Sodium} = \frac{320}{1320} \times \frac{23}{40} \times 0.97 \times 297 = 40.16 \text{ gm}$$

3) For 10 moles of sodium hydroxide in a liter of water

$$\text{Sodium} = \frac{400}{1400} \times \frac{23}{40} \times 0.97 \times 297 = 47.33 \text{ gm}$$

Therefore the amount of sodium, silicon and water for each concentration of sodium hydroxide pellets in the geopolymer paste specimens are given in Table 6.

3. Results and Discussion

The characterization of raw materials which are natural pozzolan and calcium hydroxide to determine chemical composition and physical properties were conducted. The physical properties determined for natural pozzolan and calcium hydroxide are specific densities, specific surface areas, mean particle sizes and particle size distribution curves. The physical properties of the blended natural pozzolan calcium hydroxide were also determined. The compressive strengths and densities of cured specimens made from natural pozzolan calcium hydroxide mixtures were determined under laboratory condition. In order to increase the compressive strengths of natural pozzolan calcium hydroxide mixtures, the materials were activated using alkali solution of sodium silicate and sodium hydroxide at different concentration.

Table 6. Contents of sodium, silicon and water in geopolymer pastes specimens.

Alkali	Sodium	Silicon	Water	Na/Si	Na/Water	Si/Water
6 moles of NaOH	119.69	118.18	802.13	1.013	0.149	0.147
8 moles of NaOH	127.79	118.18	794.03	1.081	0.161	0.149
10 moles of NaOH	134.96	118.18	786.86	1.142	0.172	0.150

3.1. Chemical Compositions of Natural Pozzolan and Calcium Hydroxide

The chemical compositions of the raw materials for this study were determined using XRF technique. Table 1 shows the chemical compositions of natural pozzolan and calcium hydroxide. The feasibility of pozzolanic materials as binders for construction purposes are checked by determining chemical index from major chemical elements responsible for pozzolanic reactions which are oxides of silicon, aluminum and iron in which $SiO_2 + Al_2O_3 + Fe_2O_3 > 70.0\%$, $SO_3 < 4.0\%$, moisture content < 3.0% and loss on ignition (LOI) < 10% (Alp et al., 2009).

The results indicate that the chemical index of natural pozzolan materials is 84.14% which is greater than 70% minimum required. Therefore the natural pozzolan materials can be used to make binders for construction purposes. Densities, specific surface areas and particle size distribution cures of natural pozzolan and calcium hydroxide were determined.

3.2. Physical Compositions of Natural Pozzolan and Calcium Hydroxide

The physical compositions determined for raw natural pozzolan and calcium hydroxide are specific densities, specific surface areas, particle size distribution and mean particle sizes. Figure 2 shows graphs for time air flows versus weights of sample and graphs for particle size distribution. The graphs for time air flows versus weights of sample depict "S" curves for both materials with two turning points, the results similar to other researchers (Chengula, Msambichaka, & Middendorf, 2018). The particle size distribution curves for natural pozzolan and calcium hydroxide (Figure 2 right) indicates that particle sizes of calcium hydroxide are finer than particle sizes of natural pozzolan.

Table 2 gives specific densities, specific surface areas and mean particle sizes for natural pozzolan and calcium hydroxide powder.

The results shown in Table 2 indicates that the specific density of pozzolan materials is 2.496 g/cm^3 which is within the range of the densities of natural

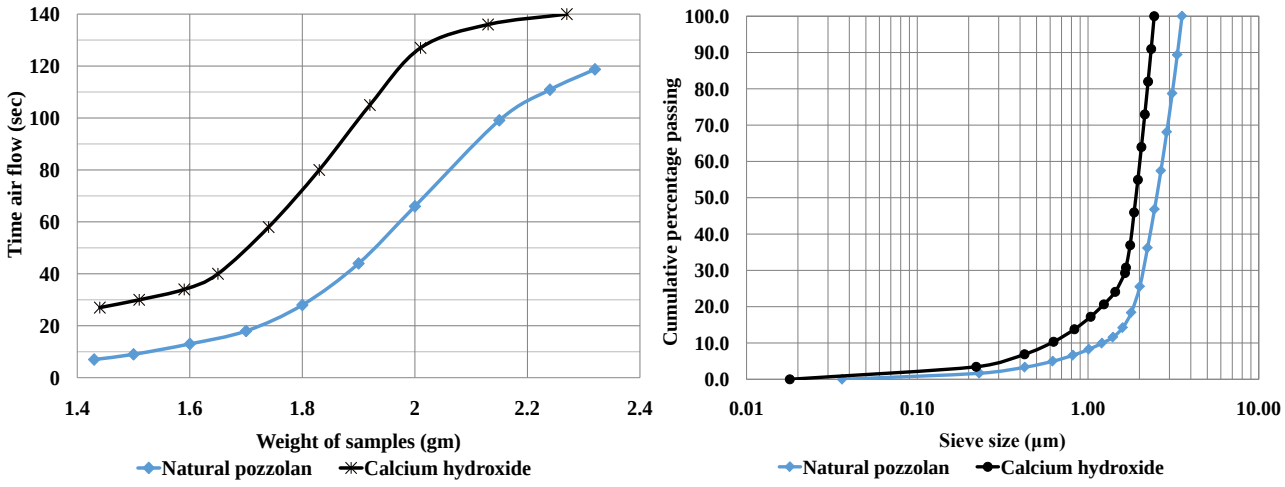

Figure 2. Graphs of time air flows versus weights of samples (left) and particle size distribution (right).

pozzolan of 1.8 kg/m^3 to 2.9 kg/m^3 determined by other researchers (Chengula, Msambichaka, & Middendorf, 2018). The density of calcium hydroxide determined (**Table 2**) is 2.269 g/cm^3 which is also within the range of 2.2 g/cm^3 to 2.4 g/cm^3 determined by other researchers (Cordeiro et al., 2011). The variations of densities of natural pozzolan from different sources and within the same source are due to change in porosity and mineralogical content and composition (Chengula, Msambichaka, & Middendorf, 2018). Therefore due to existing variation of physical and chemical properties of natural pozzolan it is important to characterize materials before use as binders for construction.

The specific surface area of calcium hydroxide is higher than specific area of natural pozzolan which indicates that mean particles size of calcium hydroxide is less compared to mean particle size of natural pozzolan. From **Table 2**, the mean particle sizes for calcium hydroxide and natural pozzolan are 1.444 μm and 1.745 μm, respectively.

Physical properties of natural pozzolan calcium hydroxide mixtures were determined. The pozzolan were mixed with calcium hydroxide at a proportion of 75% natural pozzolan and 25% calcium hydroxide. The mixtures were grinded together and three different fineness were obtained. The physical properties determined are specific densities, specific surface areas, particle size distribution and mean particle sizes. **Figure 3** shows the graphs of the air time flow versus weights of the sample and graphs of particle size distribution for the fineness No. 01, fineness No. 02 and fineness No. 03.

The same phenomenon of "S" curve has been depicted for pozzolan calcium hydroxide mixtures similar to individual raw materials (refer **Figure 2**). Therefore the "S" curve of the powdered material from air time flow versus weights of the sample is the material properties. Three different particle size distribution curves have been shown in **Figure 3** (left) which indicates from different grinding effort and duration the curves have different specific surface areas and mean particle sizes from the same mixture of pozzolan calcium hydroxide.

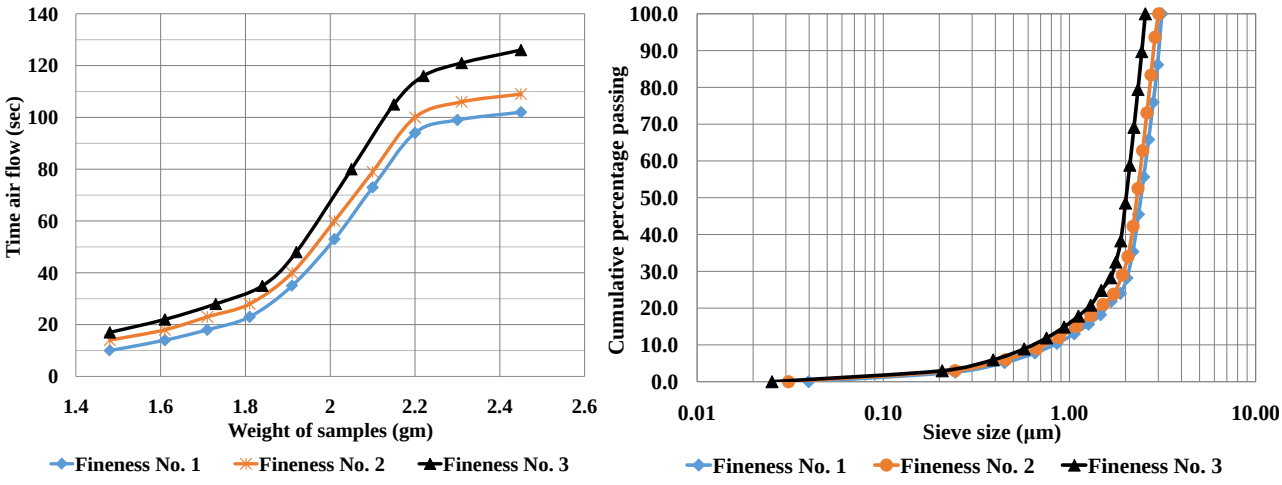

Figure 3. Graphs of time air flows of varying fineness of pozzolan (left) and their gradation curves (right).

Results of specific densities, specific fineness and mean particle sizes of the natural pozzolan calcium hydroxide mixed at a proportion of 75% natural pozzolan and 25% calcium hydroxide grinded at different fineness are indicated in Table 4. The specific densities of the mixtures for three different fineness are the same (refer Table 4) which indicates that the specific density of powdered materials does not change with change of fineness. However, the specific surface areas and mean particle size are different for each grinding effort and time as indicated in Table 4.

The compressive strengths and densities of cured specimens made from the mixtures of natural pozzolan calcium hydroxide mixed with water and other specimen with alkali solution were determined.

3.3. Compressive Strengths and Densities of Natural Pozzolan and Calcium Hydroxide Mixtures

Paste specimens were made from the mixtures of pozzolan and calcium hydroxide at varying mix proportions of 20%, 40%, 60%, 80% and 90% natural pozzolan content as indicated in Table 3. The pastes were mixed at constant water to binder ratio of 0.48 and cured for 28 days at a moist condition in plastic bags. This was done in order to get variation of compressive strengths and densities with varying content of natural pozzolan material.

Figure 4 shows the variation of compressive strength and densities of cured specimens with varying content of natural pozzolan cured for 28 days. The results indicates that the compressive strength and density of natural pozzolan calcium hydroxide mixtures increases with increasing content of natural pozzolan and then the values decreases thereafter. This situation indicates that there is an optimum proportion of natural pozzolan calcium hydroxide mixtures which produces maximum compressive strength (Chengula, Msambichaka, & Middendorf, 2018). For this study the proportion of 75% natural pozzolan and 25% calcium hydroxide were found to produce maximum compressive strength of 7.5 MPa. At this proportion of 75P25CH the density of the cured specimen were determined to be 1623 kg/m^3 (refer Figure 4). From these results of compressive strengths and densities of cured specimens made from varying contents of natural pozzolan and calcium hydroxide, indicates that the optimum combination of calcium hydroxide and silicon dioxide and aluminum oxide for maximum pozzolanic reaction occur at a proportions between 60% to 80% of natural pozzolan materials (Ibrahim et al., 2019).

The mixture of natural pozzolan and calcium hydroxide at a proportion of 75P25CH were grinded together at different grinding effort and time and three different fineness were obtained (refer Figure 3). The grinded mixtures of natural pozzolan calcium hydroxide were activated by alkaline solution for the purpose of making geopolymer binder specimens. The geopolymer binders were mixed at solution to binder ratio of 0.52. Three different concentration of sodium hydroxide solution which are 6 moles, 8 moles and 10 moles were prepared as indicated on Table 5 and Table 6. Each concentration of sodium hydroxide

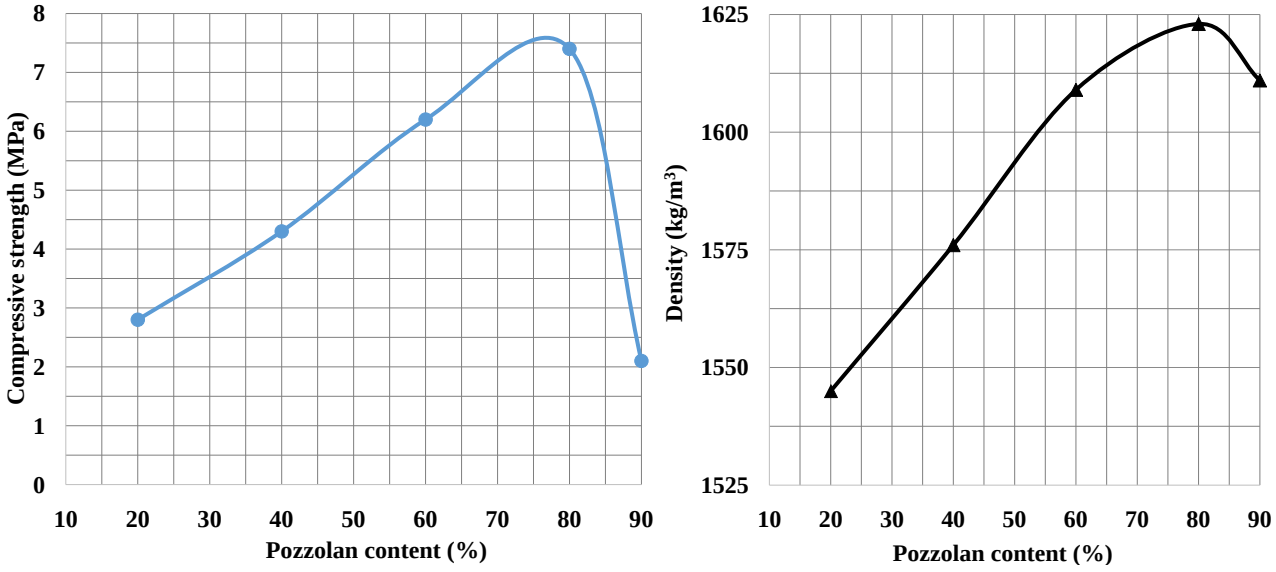

Figure 4. Compressive strength (left) and densities (right) of cured pozzolan-calcium hydroxide paste specimen.

solution were mixed with solution of sodium silicate for mixing of paste specimens. The sodium hydroxide solutions were prepared at three different concentrations of 6 moles, 8 moles and 10 moles. For each moles of sodium hydroxide solution was mixed with sodium silicate solution at a mix ratio of 1:2.5. **Figure 5** shows the compressive strengths and densities of alkali activated binders for 6 moles sodium hydroxide concentration cured for 7 days, 14 days, 21 days and 28 days. The results indicates that the compressive strength of cured specimens increases with increasing curing period and increases with increasing fineness of power mixtures. The increasing compressive strength with increasing curing period is because of formation of cementations compounds with time which are pozzolanic compounds and geopolymer compound (Allahverdi & Ghorbani, 2006). The increased compressive strengths with increased fineness is because the reactions of pozzolanic materials is high when the grain particles are finer (Cordeiro et al., 2011). However, the densities of cured specimens decreased with increased curing periods for all three fineness which is mainly due to removal of mixing water from the specimens (Walker & Pavía, 2011).

Figure 6 shows the compressive strengths and densities of alkali activated binders for 8 moles sodium hydroxide concentration cured for 7 days, 14 days, 21 days and 28 days. The results indicates that the compressive strength of cured specimens increases with increasing curing period and increases with increasing fineness of power mixtures. The values of compressive strengths and densities are higher at 8 moles sodium hydroxide concentration than for 6 moles and 10 moles (refer **Figures 5-7**) and it is depicted for all three finenesses. The sodium hydroxide concentration used for this study lies within the range of most researchers which is between 5 moles to 12 moles (Ibrahim et al., 2019). Higher concentration of sodium hydroxide results into excess alkali into solution which reacts with other elements to form salt of crystallization, efflorescence and brittleness which spoil the strength of cured specimens (Ibrahim et al., 2019).

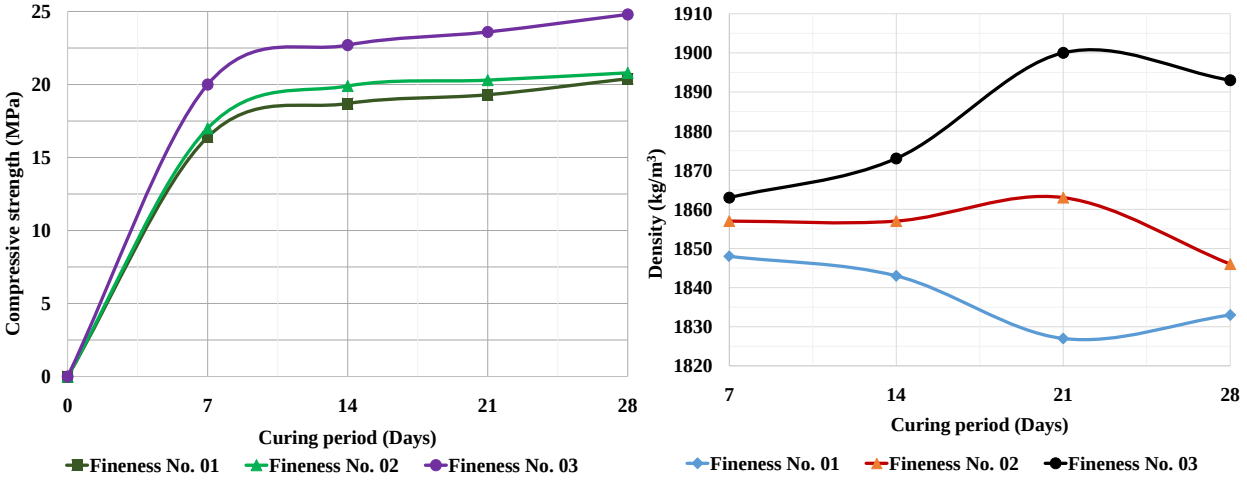

Figure 5. Compressive strength (left) and densities of cured specimens for 6 moles of NaOH concentration.

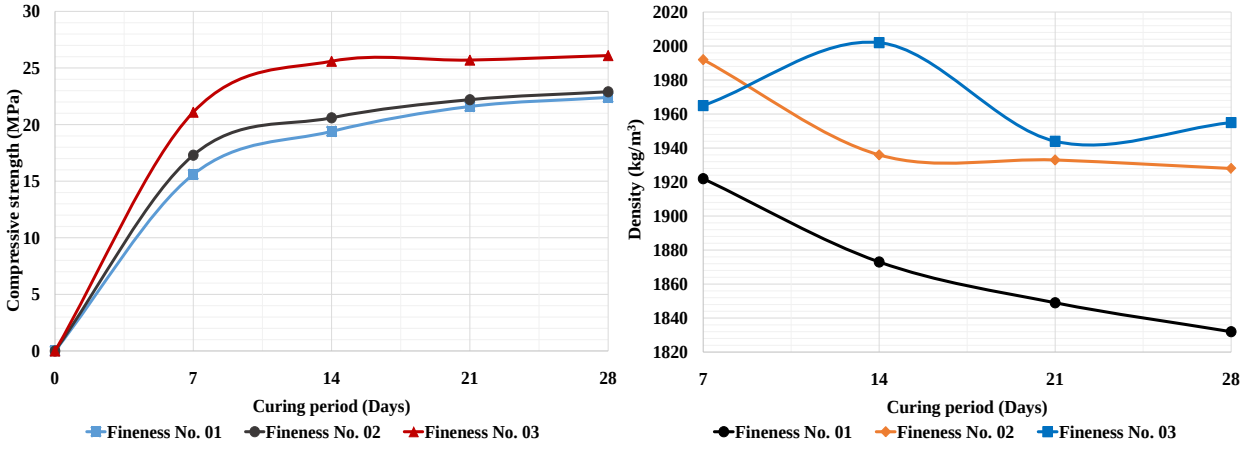

Figure 6. Compressive strength (left) and densities of cured specimens for 8 moles of NaOH concentration.

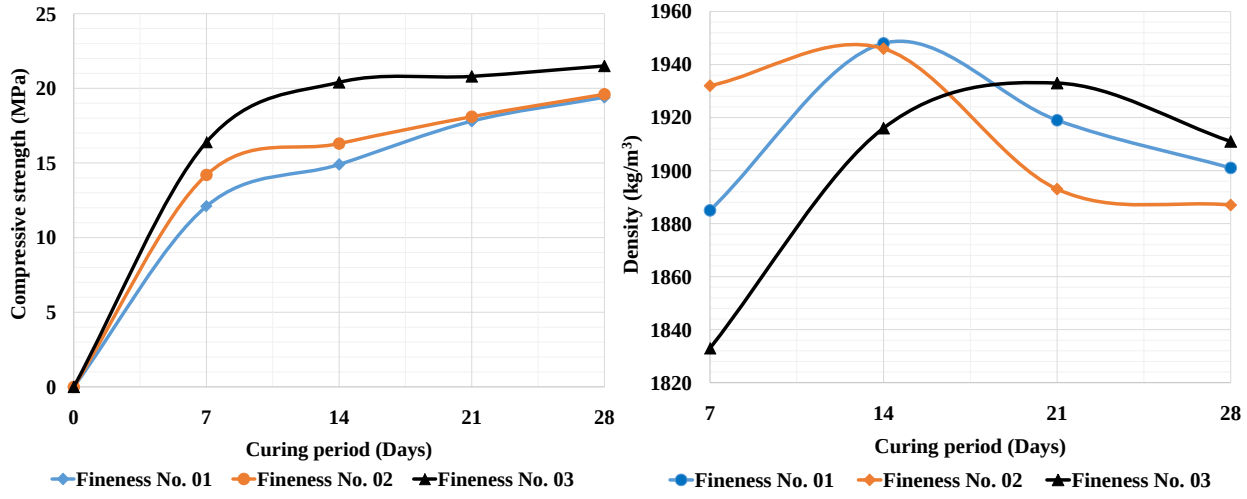

Figure 7. Compressive strength (left) and densities of cured specimens for 10 moles of NaOH concentration.

The values of compressive strengths for 28 days curing periods for fineness No. 01 are 20.4 MPa, 22.4 MPa and 19.4 MPa for 6 moles, 8 moles and 10 moles

of NaOH concentration respectively. The compressive strengths for 28 days curing periods for fineness No. 02 are 20.8 MPa, 22.9 MPa and 19.6 MPa for 6 moles, 8 moles and 10 moles of NaOH concentration respectively. The compressive strengths for 28 days curing periods for fineness No. 03 are 24.8 MPa, 26.1 MPa and 21.5 MPa for 6 moles, 8 moles and 10 moles of NaOH concentration respectively.

The values of densities for 28 days curing periods for fineness No. 01 are 1833 kg/m^3, 1832 kg/m^3 and 1901 kg/m^3 for 6 moles, 8 moles and 10 moles of NaOH concentration respectively. The densities for 28 days curing periods for fineness No. 02 are 1846 kg/m^3, 1928 kg/m^3 and 1887 kg/m^3 for 6 moles, 8 moles and 10 moles of NaOH concentration respectively. The densities for 28 days curing periods for fineness No. 03 are 1887 kg/m^3, 1955 kg/m^3 and 1911 kg/m^3 for 6 moles, 8 moles and 10 moles of NaOH concentration respectively.

The use of alkali solution as activator of natural pozzolan calcium hydroxide binders for this study have increased compressive strength of 28 days cured specimens from 7.5 MPA to 26.1 MPa at 8 moles sodium hydroxide concentration. The use of locally available natural pozzolan to make geopolymer binders for mortar and concretes mixed reduces green gases emissions from cement factory which also reduces environment pollution.

4. Conclusion and Recommendation

For this study geopolymer binder was made by activating natural pozzolan calcium hydroxide mixtures with alkali solution. The alkali activator solution used was sodium silicate and sodium hydroxide at a varying concentration of sodium hydroxide at 6 moles, 8 moles and 10 moles. The particle size distribution (PSD), relative densities (RD), and specific surface areas (SSA) of powder materials were determined by using Blaine air permeability apparatus.

The specific densities of 2.496 gm/cm^3 and 2.269 gm/cm^3, specific surface areas of 5560 cm^2/gm and 7080 cm^2/gm and mean particle sizes of 1.745 μm and 1.444 μm for natural pozzolan and calcium hydroxide respectively were determined. The natural pozzolan and calcium hydroxide powders were mixed at varying proportions to make paste specimens and cured for 28 days. The optimum proportion of natural pozzolan calcium hydroxide mixtures was determined to be 75% natural pozzolan and 25% calcium hydroxide and at this proportion the maximum compressive strength of cured paste specimen was 7.5 MPa. The optimum proportion of natural pozzolan and calcium hydroxide was milled at three different finenesses. It was observed that specific surface area increased as the grinding effort and time increased, the mean particle size decreased with increasing specific surface areas while the specific density does not change with the change of specific surface areas. The results indicated that, specific surface areas increased from 6059 cm^2/gm to 6642 cm^2/gm and mean particle size decreased from 1.681 μm to 1.432 μm.

The optimum proportion of 75% natural pozzolan and 25% calcium hydrox-

ide binder was activated by the mixtures of alkali solution of sodium silicate and sodium hydroxide at varying concentration of sodium hydroxide of 6 moles, 8 moles and 10 moles. The compressive strength of 28 days cured geopolymer binders reached 26.1 MPa at 8 moles sodium hydroxide concentration. It is therefore important to use the available natural pozzolan materials to make geopolymer binders for mortar and concretes which will then reduce green gases emission and environmental pollution.

Recommendations for Future Work

The present study focused on the influence on physical properties of geopolymer binder, more studies are recommended on the influence to micro structure, mineralogical composition and durability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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