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Article

Potentials of LUSI Volcanic Mud as Construction Materials

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Abstract. This year of 2014 is marked as the eight anniversary of Sidoarjo or LUSI volcanic mud eruption. More than 640 hectares of productive land has been submerged, and yet the eruption is still continue. This paper reviews the search to uncover its potential as construction materials. The mud is in semi-crystalline state in its original form, and it is rich in silicon and aluminium oxides, with the total amount of SiO_2, Al_2O_3 and Fe_2O_3 is more than 80%. Calcination at 600-800^{0}C for a certain period of time, followed with grinding to reduce the particle size to less than 63μm convert the mud to be an amorphous and reactive material. The treated mud is an excellent pozzolanic material, suitable for making high volume pozzolanic mortar or concrete. At the same time, it is a strong candidate for precursor of geopolymer material.

Keywords: Construction material, geopolymer, pozzolanic material, Sidoarjo mud, volcanic mud

1. Introduction

The year 2014 is marked as the eighth anniversary of volcanic mud eruption in Sidoarjo, East Java, Indonesia. Locally, the mud is called as **LU**mpur **SI**doarjo or LUSI volcanic mud, meaning volcanic mud from Sidoarjo. This eruption is widely believed as an industrial disaster, resulted from a hydrocarbon exploration. After eight years, the eruption has swamped more than 640 hectares of fertile land, human settlements and industrial areas, schools and other infrastructure facilities. Several initiatives to staunch the flow of mud have been unsuccessful. Furthermore, the eruption was predicted to last for several more decades [1].

To ease the lateral pressure to the cover dam encircled the swamped area, the mud has been channeled to a nearby river, causing a newly formed island on its mouth. Currently the height of the cover dam is about 12 meters, and it is unlikely to be increased anymore [2]. At its peak, the daily discharge was about 150,000 m^3; while right now it is about 10,000-25,000 m^3. With the enormous volume of volcanic mud available, attempts have to be carried out to innovatively utilize this material, among them is for construction material.

Several studies have been done to characterize LUSI volcanic mud and to evaluate its potentials to be construction materials. Initially, the efforts were unsuccessful, although its chemical compositions have been very promising. Most likely, it was due to its un-reactive crystalline microstructure [3]. Recent reports reveal that the treated mud is very reactive. It has high potential to be used as construction materials. This paper reviews the progress of recent studies on LUSI volcanic mud as construction materials.

2. Characteristics of LUSI Volcanic Mud

The mud is grey in color, flake-shape structure, with the particle size of the dried mud is dominated by very fine particles less than 10-25εm [4, 5]. The mud is mostly of clay minerals, while the amount of organic material, quartz and feldspars are small [4]. X-ray Diffraction (XRD) analysis reveals the semi-crystalline structure of the mud in its original form, due to the presence of quartz, feldspars and kaolinite [5, 6], and thus it is not reactive [3]. XRD results also identify the presence of sulfur from two intense diffraction peaks at 2 thetha values of 35.6^0 and 70.4^0 [7]. Fourier Transform Infrared Spectroscopy (FTIR) analysis identified the presence of quartz in the mud, as also observed from the XRD analysis [5].

The main contents of LUSI volcanic mud are SiO_2, Al_2O_3 and Fe_2O_3, whereby the total of them is more than 80%, with SiO_2 content ~55%, Al_2O_3 ~20%, while Fe_2O_3 ~ 10% [8-10]. This composition practically does not vary significantly from year to year [3, 8, 10], and from various horizontal locations [9]. Table 1 shows the chemical composition of the calcined mud as measured by X-ray Fluorescence (XRF) analysis [8, 11]. The radioactive concentration of ^{226}Ra, ^{232}Th, ^{40}K and ^{238}U were found to be in acceptable limits for construction material, whereas the exposure of ɔ radiation and the radium equivalent activity were also within the safe limit [12].

Table 1. The chemical composition of calcined volcanic mud as measured by XRF (% by mass)

SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	CaO	K_2O	SO_3	TiO_2	MnO_2	Cr_2O_3	LOI
56.75	23.31	7.37	2.95	2.70	2.13	1.04	0.96	0.38	0.14	0.01	1.20

2.1 Calcination of LUSI Volcanic Mud

LUSI volcanic mud in its original form does not reactive due to its semi-crystalline structure, although it contains enough compounds required by a pozzolanic material. Attempts to utilize the mud in its original form to be construction materials ended in un-favorable results [3]. Calcination at 600°C for an hour has turned the mud to be more reactive pozzolanic material [10]. From the XRD observation, Rafiza et al. [6] found that after calcination at 800°C for two hours, the mud has been transformed to be more amorphous one. However, calcination does not change the particle shape, it maintains its plate-like structure, similar to kaolin.

During calcination, the LUSI volcanic mud experiences loss of mass with the increase of heating temperature, with the peak was recorded at 55°C, and stabilized in between 510 to 1000°C. The observation was carried out by conducting a Thermogravimetry Analysis (TGA) [12]. The authorsô previous study [13] on the effect of calcination temperature confirmed the change in the reactivity of volcanic mud. Calcination at three different temperatures, i.e. 700°C, 800°C and 900°C, for five hours in the laboratory electrical furnace, revealed the change in the micro structure of volcanic mud as examined by XRD analyses. Geopolymer mortar manufactured by utilizing volcanic mud calcined at 800°C produced the highest compressive strength at 7th day. The strength significantly decreased when the calcination temperature was increased to 900°C. SEM image analyses on Sidoarjo volcanic mud-based geopolymeric artificial aggregate revealed that sintering the aggregate at higher temperature up to 1000°C for an hour in the laboratory electrical furnace resulted in more and larger pores, and thus lowered the density of the material [7].

There should be an optimum range of calcination temperature and period to convert the mud to be reactive material. It seems that calcination in between 600°C-800°C is the most effective, while the effect of calcination period is still not clear.

2.2 Grinding of LUSI Volcanic Mud

Particle size is one key factor determining the reactivity of a material [14, 15], whereby the finer the particle size, the more reactive the material, as its specific surface area is bigger. The authorsô previous studies on the influence of fineness of LUSI volcanic mud have been reported elsewhere [8, 11], covering a broad range of particle fineness from 10-600µm. Although it has been reported that the particle size of the original mud is very fine [4, 5], however due to calcination at high temperature the mud agglomerated.

Figure 1: Rod Mill used for grinding the material

A rod mill has been fabricated to cater the purpose, as shown in Figure 1. Milling process has been performed by utilizing the mash force between the iron bars in the steel drum and the mud material, by rotating the drum at constant speed for a certain duration. It was found that calcined mud with particle size bigger than 150µm is not reactive enough, and thus further milling process has to be done to finer the particle size. The authors suggested the use of calcined mud finer than 63µm to ensure the reactivity of LUSI volcanic mud, both for pozzolanic material and raw material for geopolymer.

Table 1: Particle Size Distribution for the milled volcanic mud

Milling Duration	D10 (µm)	D50 (µm)	D90 (µm)	Specific Surface Area (m^2/g)
2 hours	1.832	15.180	475.604	1.30
4 hours	0.937	7.991	114.402	2.24
8 hours	0.768	6.632	342.661	2.58

Study on the reactivity of the calcined volcanic mud finer than 63μm has been performed covering mud with three different Specific Surface Areas (SSA) as shown in Table 1 [11]. By using the finest calcined mud with Specific Surface Area of 2.58 m^2/g, high volume LUSI volcanic mud mortar has been produced with high Strength Activity Index (SAI) of more than 85% at 28th day. The SAI was increased at later age, higher than 90% at 56th day.

The finer the particle size also resulted in better workability of the fresh high volume calcined Sidoarjo volcanic mud mortar, in contrary to what was expected before. Study on this rheology phenomenon is still on the way, and will be reported elsewhere. All of these confirm that the treated LUSI volcanic mud possesses high potential to be used as construction material and perhaps also for other purposes.

3. LUSI Volcanic Mud as Pozzolanic Material

The first successful attempt to utilize LUSI volcanic mud as pozzolanic material was reported by Nuruddin et al. [10]. After calcinations at 600^{o}C for an hour to convert its crystalline microstructure into more amorphous form, the mud ground mud was successfully utilized as pozzolanic material to partially replace the use of cement in making mortar, with 10% replacement as the optimal replacement level.

Significant progress was reported by the authors [9], whereby the calcined LUSI volcanic mud was successfully utilized in the making of semi high volume pozzolanic mortar, up to 40% of cement replacement, by mass. The mud was calcined at 910^{o}C for five hours, and then bar-milled to obtain the various particle sizes, i.e. <63μm, 63-150μm, and 150-300μm. We found that the smaller the particle size of the LUSI volcanic mud, the higher the compressive strength and the Strength Activity Index (SAI) of the mortar. This indicated that the finer the volcanic mud particle size increases its pozzolanic reactivity. Another important finding was the fact that the larger the percentage of cement replacement by LUSI volcanic mud, the higher the workability, revealing the absence of adverse effect of using LUSI volcanic mud on water demand.

Further reduction of particle size of LUSI volcanic mud finer than 63μm improves the reactivity of the calcined mud significantly. This achieved by prolonging the milling duration. High volume LUSI volcanic mud mortar has been produced successfully with 60% mud content, excellent workability and high SAI value of more than 85% at 28th day and more than 90% at 56th day.

4. LUSI Volcanic Mud as Raw Material for Geopolymer

Geopolymer requires amorphous raw materials rich in silicon and aluminium. In most cases, pozzolanic materials are good candidates for precursor of geopolymer. In the preceding sections, calcined Sidoarjo volcanic mud has been proven to be an excellent pozzolanic material, and thus it has potential to be used to manufacture geopolymer.

Initially, the use of original Sidoarjo volcanic mud as precursor for geopolymerization ended unsuccessfully, especially due to its crystalline structure [3]. Calcination and grinding were found to be the required processes to carry out to convert the material to be an excellent raw material for geopolymer. To date, the available reports on Sidoarjo mud-based geopolymer are about geopolymer mortar and artificial aggregates.

Our earlier study has found out that using calcined Sidoarjo volcanic mud as raw material, geopolymer mortar with compressive strength of 37MPa at 7th day has been produced. The raw material was calcined at 800^{o}C for five hours using laboratory electrical furnace [13]. In this study, a combination of sodium hydroxide solution and sodium silicate solution were used as the alkaline solution. This finding was confirmed by another report [8]. In addition, it was recommended to use calcined mud with particle size less than 63μm to ensure the reactivity of the raw material.

Few reports available on the use of calcined mud to produce artificial geopolymer aggregates. In this case, crude Sidoarjo volcanic mud was mixed with the alkaline solution, followed by pelletizing. The pellets were then calcined in high temperature [6, 7, 11, 12]. The artificial aggregates produced were stable after soaking in the tap water for 24 hours. The unit weight and compressive strength of artificial aggregate varied widely in between 1470-1800 kg/m^3 and 0.3-8.7 MPa, respectively, depending on the mixture composition. The higher the content of the alkaline reactor, the higher the unit weight and the compressive strength of the artificial aggregate. Further study to refine the process of making the artificial aggregate, to lower the unit weight to be less than 1000 kg/m^3 and to evaluate its use as aggregates in concrete is on-going, and the results will be reported elsewhere. A prototype of furnace utilizing a burner to perform the calcination has been manufactured.

5. Concluding Remarks

This paper reviews the potential of Sidoarjo volcanic mud to be used as construction material. Due to its semi-crystalline microstructure, the mud needs to be calcined at high temperature in between 600-800^{0}C for few hours to convert it to be more amorphous and reactive material. Grinding to reduce the particle size of calcined mud is required to increase the material reactivity, i.e. to be less than 63µm. The treated Sidoarjo volcanic mud possesses excellent pozzolanic properties and suitable for use as precursor for geopolymer material.

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References

[1]. M. L. Rudolph, L. Karlstrom, and M. Manga, A Prediction of the Longevity of the Lusi Mud Eruption, Indonesia. *Earth and Planetary Science Letters*, vol. 308, pp. 124ï130, 2011.

[2]. D.S. Agustawijaya and Sukandi, The Stability Analysis of the Lusi Mud Volcano Embankment Dams using FEM with a Special Reference to the Dam Point P10.D. *Civil Engineering Dimension*, vol. 14, no. 2, pp. 100-109, 2012.

[3]. Triwulan, J. J. Ekaputri, and T. Adiningtyas, Analisa Sifat Mekanik Beton Geopolimer Berbahan Dasar Fly Ash dan Lumpur Porong Kering Sebagai Pengisi. *Jurnal Torsi*, vol. 27, no. 3, pp. 33-45, 2007.

[4]. G.S. Plumlee, T.J. Casadevall, H.T. Wibowo, R.J. Rosenbauer, C.A. Johnson, G.N. Breit, H.A. Lowers, R.E. Wolf, P.L. Hageman, H. Goldstein, M.W. Anthony, C.J. Berry, D.L. Fey, G.P. Meeker, and S.A. Morman, *Preliminary Analytical Results for a Mud Sample Collected from the LUSI Mud Volcano, Sidoarjo, East Java, Indonesia,* 2008, U.S. Geological Survey and U.S. Department of the Interior.

[5]. A.M. Mustafa Al Bakri, A. R. Rafiza, D. Hardjito, H. Kamarudin, and I. Khairul Nizar, Characterization of LUSI Mud as Geopolymer Raw Material. *Advanced Materials Research*, vol. 548, pp. 82-86, 2012.

[6]. A. R. Rafiza, A. M. Mustafa Al Bakri, H. Kamarudin, D. Hardjito, and I. Khairul Nizar, Comparison of original and sintered LUSI Mud volcano as Geopolymer Raw Material. *Advanced Science Letters*, vol. 19, no. 1, pp. 174-178, 2012.

[7]. A. R. Rafiza, A. M. Mustafa Al Bakri, H. Kamarudin, I Khairul Nizar, D. Hardjito, W.H. Wan Badaruzzaman, and Y. Zarina, Microstructure Study on Volcano Ash Geopolymer Aggregate at Different Sintering Temperature. *Key Engineering Materials*, vol. 594-595, pp. 83-87, 2014.

[8]. D. Hardjito, Antoni, I.V. Bunanta, and K. Wicaksono, Geopolymerisation of Volcanic Mud, in *The 4th International Conference of Euro Asia Civil Engineering Forum 2013 (Eacef 2013)*, Singapore, 2013

[9]. D. Hardjito, Antoni, Gunadi M. Wibowo, and Danny Christianto, Pozzolanic Activity Assessment of LUSI (LUmpur SIdoarjo) Mud in Semi High Volume Pozzolanic Mortar. *Materials*, vol. 9, no. 5, pp. 1654-1660, 2012.

[10]. M.F. Nuruddin, R. Bayuaji, M.B. Masilamani, and T.R Biyanto, Sidoarjo Mud: A Potential Cement Replacement Material. *Civil Engineering Dimension*, vol. 12, no. 1, pp. 18-22, 2010.

[11]. Antoni, D. Hardjito, L. Chandra, and T. H. Widodo, On The Development of High Volume Volcanic Mud Mortar and Concrete, in *The Thirteenth East Asia Pacific Conference on Structural Engineering and Construction (EASEC13)*, Sapporo, Japan, 2013

[12]. A. R. Rafiza, A. M. Mustafa Al Bakri, H. Kamarudin, I. Khairul Nizar, I. Sandu, D. Hardjito, and Y. Zarina, Study on Radioactivity Components, Water Quality and Microstructure Characteristics of Volcano Ash as Geopolymer Artificial Aggregate. *Revista de Chimie*, vol. 64, no. 6, pp. 593-598, 2013.

[13]. Antoni, R. Geman, R. T. Tjondro, J. Anggono, and D. Hardjito, Effects of Calcination Temperature of LUSI Mud on the Compressive Strength of Geopolymer Mortar. *Advanced Materials Research*, vol. 626, 2012.

[14]. C. Hea, B. Osbzckb, and E. Makovicky, Pozzolanic Reactions of Six Principal Clay Minerals: Activation Reactivity Assessments and Technological Effects. *Cement and Concrete Research*, vol. 25, no. 8, pp. 1691-1702, 1995.

[15]. A. Tironi, M. A. Trezza, A. N. Scian, and E. F. Irassar, Kaolinitic Calcined Clays: Factors Affecting Its Performance as Pozzolans. *Construction and Building Materials*, vol. 28, pp. 276ï 281, 2012.