A Study on Properties of Fly Ash-Rice Husk Ash Based Geopolymer Using Recycled Waste Glass as Fine Aggregate

Methawee Sriwattanapong Photisan[a]* and Onanong Sangphong[a]

Received: September 22, 2021; Accepted: October 17, 2021; Published online: October 30, 2021

Abstract

This research studied the compressive strength and fire resistance of geopolymer mortars using waste glass as a partial fine aggregate replacement. Fly ash (FA) and rice husk ash (RHA) that were the starting materials synthesized with a liquid alkali activator, is a mixture of 10 molar sodium hydroxide and sodium silicate solutions. Rice husk ash was used to replace fly ash at percentages of 0, 10, 20, 30, 40, and 50 by weight. Waste glass was ground to obtain sand-like particle sizes. Sand substitution with waste glass at 20% by weight was prepared. The results indicate that the workability and compressive strength of mortars decreased with an increase in rice husk ash content. The strengths of fly ash-rice husk ash geopolymer mortars at 28 days were in the range of 34 to 59 MPa, which are acceptable for some engineering applications. The geopolymer mortars retained their shapes up to 1,000°C that suitable for high temperature applications.

Keywords: Geopolymer; Fly Ash; Rice Husk Ash; Waste Glass; Compressive Strength; Fire Resistance

Introduction

Ordinary Portland cement (OPC) is the main material used in the production of concrete. However, it contributes to about one ton of carbon dioxide for each ton of ordinary Portland cement, leading to 5-8% of global emissions of carbon dioxide (Matalkah et al., 2020), which the main cause of global warming. Using geopolymer concrete is expected to solve environmental problems due to its ability to reduce carbon dioxide emissions and reduce high energy consumption (Haddad et al., 2018).

Geopolymer is an innovative building material produced by alkaline activation. Wide range of materials is being used for geopolymerization including materials rich in silicon (Si) and aluminium (Al) such as fly ash, granulated blast furnace slag, and kaolin clay (Provis & van Deventer, 2009). The alkali geopolymerization of a material depends on both physical and chemical factors like its degree of crystallinity, the solubilities of silicon and aluminium and their ratio (Davidovits, 2008). An alkali hydroxide or alkali silicate solution is often used. The choice of sodium (Na) or potassium (K) as the alkali to use depends on desired properties and economics (Erdoğan, 2011). The strength of geopolymer is of the same order as that made with normal ordinary Portland cement. The texture and appearance are similar. Furthermore, it is known that geopolymer possesses excellent performance with respect to fire resistance and acid resistance (Duxson et al., 2007a).

Fly ash (FA) has been used as a precursor in geopolymer cement and binder production throughout the world. Based on plant type and combustion temperatures, the final chemical composition of fly ash may differ. In this regard, the properties of appropriate fly ash for alkali-activation have been suggested (Solouki et al., 2020). In Thailand, the main source of fly ash is that produced from Mae Moh coal-burning power station located in Lampang province. The annual output of fly ash from Mae Moh power plant is in around 3 million tons (Chindaprasirt et al., 2011). This fly ash has been used quite extensively in concrete construction in Thailand as partial replacement of ordinary Portland cement.

[a] Department of Construction Engineering, Faculty of Industrial Technology, Nakhon Ratchasima Rajabhat University, Muang, Nakhon Ratchasima, 30000 Thailand
*Corresponding author: E-mail: methawee.p@nrru.ac.th Tel.: (66) 816699945

Thailand is one of the world's largest producers of rice products and such the by-product material from this industry is also widely available. Rice husk ash (RHA) is an industrial by-product material produced by burning rice husk for the generation of electricity, a kind of sustainable biomass energy (Kroehong, 2012). With proper burning and grinding, the amorphous reactive rice husk ash could be produced and used as pozzolan (Della et al., 2002). In general, rice husk ash contains over 80 wt% silicon dioxide (SiO_2) and only small proportion of impurities such as potassium oxide (K_2O), sodium oxide (Na_2O), and Iron oxide (Fe_2O_3) (Real et al., 1996, Stroeven et al., 1999). Being rich in silica, rice husk ash can also be used as a source material for producing geopolymer (Detphan & Chindaprasirt, 2009). Because rice husk ash usually contains very little aluminium of about <1 wt%, an additional source of aluminium is needed. Fly ash was used in this study as an additional source of aluminium.

Currently, municipal solid waste in Thailand is increasing every year. In 2017 approximately 27.4 million tons of the waste glass was generated, increasing from about 340,000 tons in 2016 (Warnphen et al., 2019). As the usage of the glass increases, the amount of waste glass also increases. Glass is primarily in the form of containers such as soft drink and beer bottles, wine and liquor bottles, bottles and jars for food, cosmetics, and other products, which is disposed of in landfills and dumped as waste material, and this causes environmental pollution. To prevent this, it can be recycled and reused for various purposes. Waste glass has competency to use as raw materials in building constructions (Wattanapornprom & Stitmannaithum, 2015). Many research studies have been conducted on replacing sand (fine aggregate) with waste glass. Batayneh et al. (2007) studied using recycled waste glass as a fraction of aggregates of 0-20% in the concrete mix in relation to compressive strength; they found that up to 20% waste glass as a substitute for fine aggregates showed the best performance. Ali and Al-Tersawy (2012) also reported that the performance decreased with the increase of waste glass content; this was due to the internal structure as there was poor contact between the cement paste and waste glass causing high smoothness of the waste glass, thereby leading to cracks.

From the viewpoint of locally available materials, this work aimed at studying the compressive strength and fire resistance of geopolymer mortars using fly ash and rice husk ash as their powder binder and managing recycled waste glass used as a partial fine aggregate replacement in geopolymer mortar production.

Experimental Design

Materials

The main materials used in this study consisted of fly ash, rice husk ash, alkali activator, river sand, and waste glass.

Fly ash from Mae Moh power station was used. The average size of fly ash was 25.6 μm. Rice husk ash was ground in a laboratory ball mill in order to obtain mean particle size of about 36.3 μm. The chemical and physical characteristics are given in Table 1. Sodium silicate solution (Na_2SiO_3) and 10 molar (M) sodium hydroxide solution (NaOH) were used as alkali activator.

The fine aggregate was river sand, having specific gravity of 2.65 and fineness modulus of 2.68. The waste glass used as replacement of fine aggregate was crushed with the size close to river sand. The particle size distribution curves of the materials are shown in Figure 1. The waste glass in this study was from clear and colored soda-lime bottles obtained from the post-consumer stage.

Methods

The geopolymer mortars used in the study were from a mixture of fly ash-rice husk ash with a liquid alkali activator, which is a mixture of 10 molar sodium hydroxide solution and sodium silicate solution.

The ground rice husk ash was used to replace fly ash at percentages of 0, 10, 20, 30, 40, and 50 by weight, designated as 100FA, 90FA10RHA, 80FA20RHA, 70FA30RHA, 60FA40RHA, and 50FA50RHA, respectively. Sand substitution with waste glass at 20% by weight was prepared.

The geopolymer mortars were prepared using Na_2SiO_3-to-10 M NaOH solution ratio of 1.50 and alkali activator solution-to-binder ratio of 0.67. The workabil-

Table 1. Chemical compositions and physical properties of fly ash and rice husk ash.

Chemical compositions (%)	Fly ash	Rice husk ash
SiO_2	45.2	91.4
Al_2O_3	24.0	0.1
Fe_2O_3	10.6	0.5
CaO	12.6	0.6
MgO	2.92	0.4
Na_2O	0.07	0.05
K_2O	2.56	1.9
SO_3	1.58	0.04
LOI	0.53	4.3
Physical properties		
Mean particle size (μm)	25.6	36.3
Specific gravity	2.21	2.24

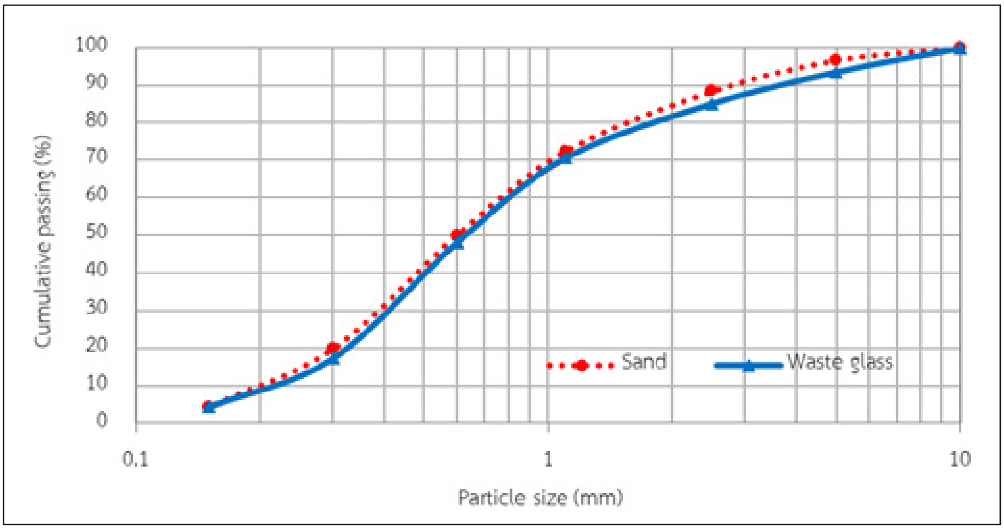


Figure 1. Particle size distributions of sand and waste glass

ity of fresh mortars was controlled by keeping the percentage flow of 110±5%. All geopolymer mortars were made with fine aggregate-to-binder of 1.50.

The mixing procedures, fly ash and rice husk ash were thoroughly mixed dry to obtain a homogeneous powder. Alkali activator solution was then added to the mixture for 7 minutes. This was followed by the addition of fine aggregate with a final mixing of 3 minutes. Flow value of fresh geopolymer mortars was determined in accordance with ASTM C1437 immediately after the completion of mixing.

After the determination of flow, the fresh mortar was molded into 50-mm test cubes. The mortar specimens were compacted with two-layer placing and tamping. The specimens were covered with a polyethylene foil to avoid moisture loss. After casting for 24 hours, the mortar samples were removed from the mold and cured at approximately 23°C until the testing age. The compressive strength tests were carried out at the ages of 1, 7, and 28 days as described in ASTM C109. The reported strength results were the average of three samples.

The fire resistance tests were performed after 28 days of curing. The mortar specimens were heated in an electric furnace to temperatures of 500 and 1,000°C with a heating rate of 5°C/min. Once the desired temperatures were attained, they were maintained for 60 minutes before the mortar specimens were allowed to cool at the same rate to room temperature in the furnace.

Results and Discussion

Workability of mortar

The results of the workability of fly ash-rice husk ash fresh geopolymer mortars containing amounts of waste glass up to 20% as fine aggregate are shown in Table 2. The flow of geopolymer mortar decreased with increasing content of rice husk ash. The flows of 60FA40RHA and 50FA50RHA were 78 and 3% respectively, which were less than 110±5% prescribed by ASTM C1437, whereas the others were in the range of 106 to 114%. 60FA40RHA was quite difficult to fill and compact the mold. 50FA50RHA was unable to mix due to lower workability. As such, replacements of above 30% were not possible for the rice husk ash due to the high water demand. Addition of rice husk ash decreases workability due to water absorbent property because it has high specific surface area (Sathawane et al., 2013). It is generally accepted that fly ash increases the workability of fresh mortar or reduces water requirement of mortar for the same flow (Chindaprasirt et al., 2011). The fly ash with spherical particle shape and smooth surface would act as roll bearing and hence increases the flow of mortar (Federal Highway Administration, 2017). From our experience, it has been observed that this only has limited applicability when the rice husk ash has an irregular shape after the grinding process. The obtained results suggest that the particle shape has a dominant influence on the workability of the geopolymer mortars.

Table 2. Workability of the fly ash-rice husk ash geopolymer mortars.

Specimen	Flow of mortar (%)
100FA	114
90FA10RHA	112
80FA20RHA	110
70FA30RHA	106
60FA40RHA	78
50FA50RHA	3

Compressive strength

The effect of the fly ash-based geopolymer mortars incorporated with rice husk ash prepared with mixing 20% waste glass on strength development is presented in Figure 2. The results revealed that compressive strength varied from 14 to 59 MPa with the highest value obtained from 90FA10RHA geopolymer mortar, which had slightly decreased by only 1.7% as compared with the mortar without rice husk ash (100FA) at 28 days. However, the mortar containing rice husk ash up to 30% had a significant effect on the compressive strength. The strength obviously decreased with an increase in rice husk ash content. As expected, the compressive strength of specimens developed with the curing time.

Furthermore, there have been many studies investigating the role of the silica-to-alumina ratio and how it relates to the mechanical properties of geopolymer. There is a strong correlation between the silica-to-alumina ratio and the strength of a geopolymer (Davidovits, 1991). It has been shown that strength is related to composition and nanostructure of geopolymer. In this section of the work, the silica-to-alumina ratios and compressive strength of fly ash-rice husk geopolymer mortars are plotted in Figure 3. The compressive strength of fly ash-based geopolymer mortars decreased from 60 to 34 MPa when the ratio of silica-to-alumina increased from 1.88 to 3.51. The obtained results supported the suggestion that the metakaolin-based geopolymer with a silica-to-alumina ratio lower than 1.40 that the geopolymer had a very porous matrix, which led to low compressive strength results. When the silica-to-alumina ratio was increased over 1.65 the geopolymer had an increase in strength, before decreasing again at the highest silica-to-alumina ratio of 2.15. The increase was attributed to a homogenous microstructure in the geopolymer, whereas the reduction in strength for high silica-to-alumina ratio mixes was the result of unreacted material, which was soft and acted as a defect in the binder phase (Duxson, 2005a). In addition, the results also indicate that the effect of strength development of the geopolymer mortar is dependent on the fineness of the binders. The dissolution of fly ash in sodium silicate and sodium hydroxide medium was faster and more effective for fly ash with finer particle size (Sinsiri et al., 2006).

It should be noted that reasonable later age strength of the geopolymer mortar can be achieved. The strengths of fly ash-rice husk ash geopolymer mortars at 28 days were in the range of 34 to 59 MPa which are acceptable for some engineering applications.

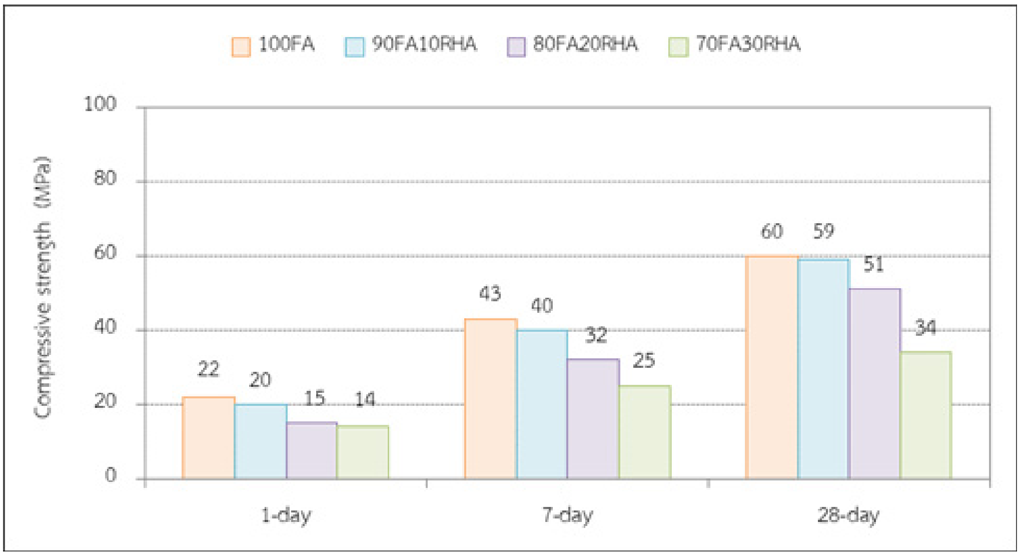


Figure 2. Compressive strength of fly ash-rice husk ash geopolymer mortars at different ages of curing up to 28 days

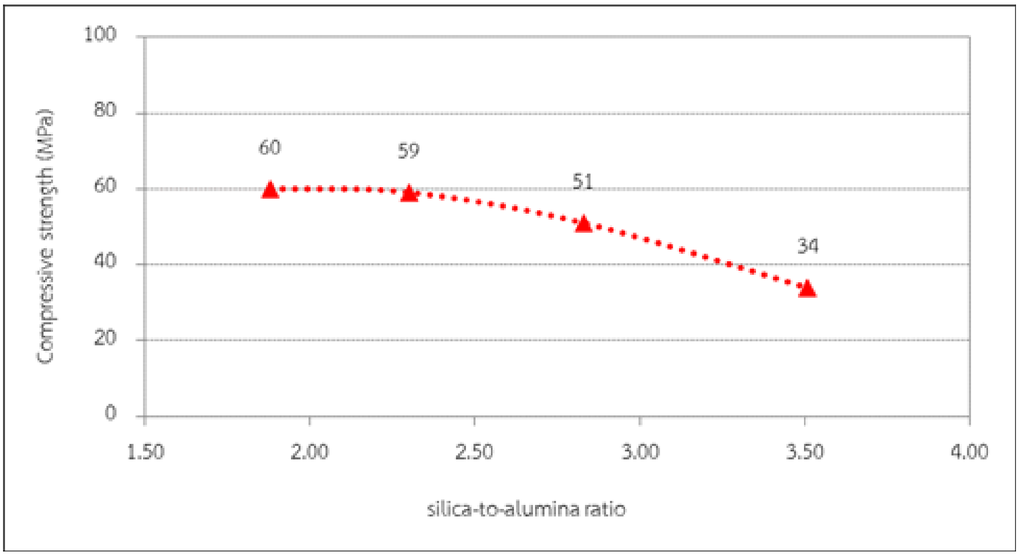


Figure 3. Compressive strength development of fly ash-rice husk ash geopolymer mortars at different silica-to-alumina ratios

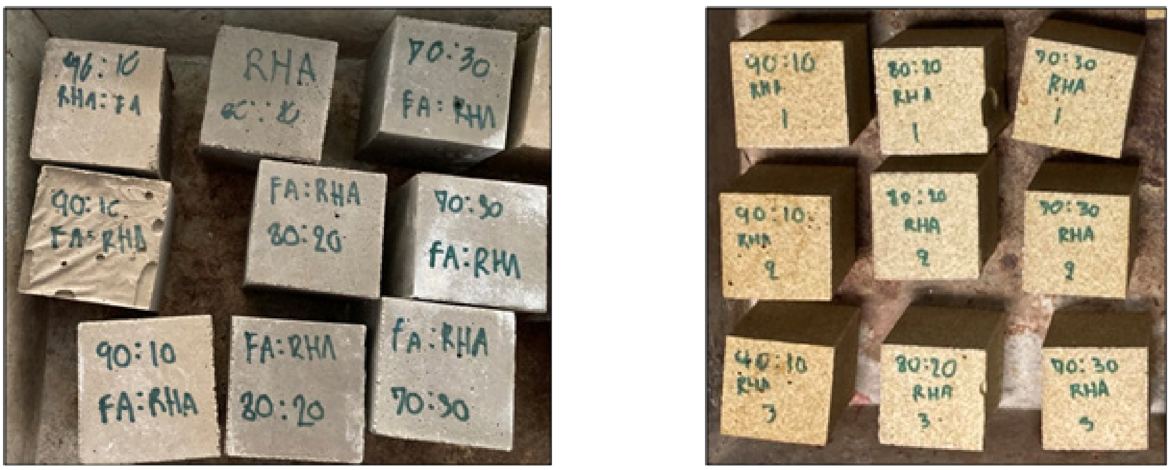
Fire Resistance

Physical observation

Figure 4 presents the physical observation of fly ash-rice husk ash geopolymer mortars including waste glass after being exposed to the elevated temperatures of 500 and 1,000°C. Fly ash and rice husk ash are grayish black in color and are the major source materials used in this work, mixing of the ashes content make the specimens dark before exposure to high temperatures. However, after being exposed to high temperatures the mortars became lighter. The mortars had a light gray to yellowish brown color with smooth surface. Hager (2013) suggested that the color changes in these geopolymer mixtures are similar to those observed in ordinary Portland cement mixtures after high temperature exposures, which primarily results from gradual dehydration of geopolymer binders and microstructural transformations occurring within the aggregate. Moreover, all the specimens kept their original dimension that there was no distortion, no peeling, and even no cracks on the surface.

Compressive strength

The compressive strength results before and after elevated temperature exposures for fly ash-based geopolymer mortars prepared using rice husk ash with 20% waste glass used as a partial fine aggregate replacement are presented in Figure. 5. The results showed that the geopolymer samples gained their strength



(a) after exposed to 500°C (b) after exposed to 1,000°C

Figure 4. Photographs of fly ash-rice husk ash geopolymer mortars after exposed to (a) 500°C and (b) 1,000°C

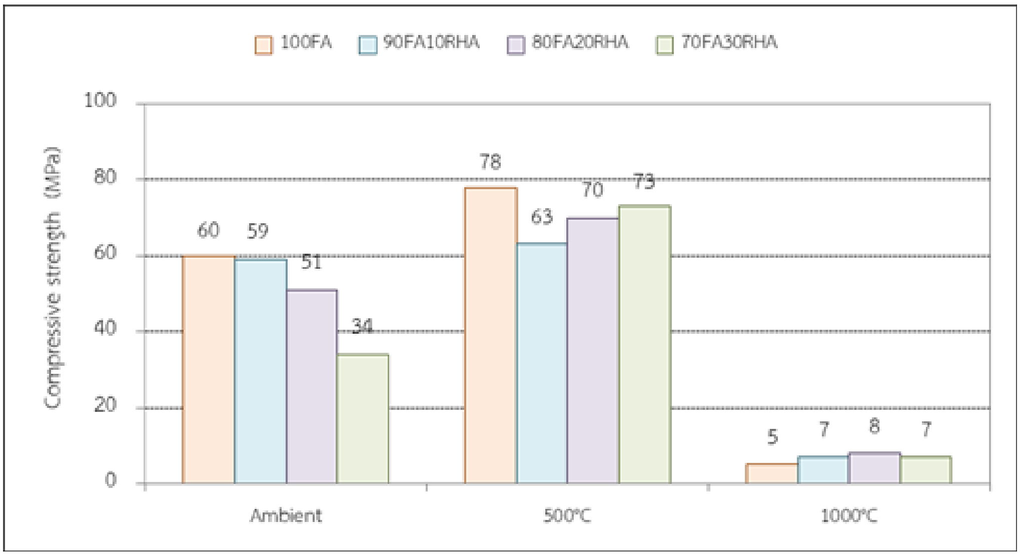


Figure 5. Compressive strength of fly ash-rice husk ash geopolymer mortars at various temperatures

after heating to 500°C. It can be seen that the compressive strength of the geopolymer mortars increased by 39% on average of ambient compressive strength. This attributed to the increase in combination of polymerization reaction and sintering at high temperature (Abdullah et al., 2013). However, after exposure to 1,000°C, thermal incompatibility between geopolymer paste and fine aggregate affected strength (Bhowmick & Ghosh, 2012). The geopolymer mortars showed different tendency in evolution of strength, which decreased in strength. The specimens had a strength drop of 87%. Pan et al. (2009) also found that the strength evolution of geopolymer mortars after exposure to elevated temperatures depends on the dominant process of the following two factors: (1) further geopolymerization of the unreacted raw materials and/or sintering process leading to strength increase; (2) damages caused by thermal incompatibility leading to strength decrease. These two opposing processes are occurring simultaneously in the geopolymer mortars at elevated temperatures and whether the strength increase or decrease is dependent on the dominant process.

Conclusions

The compressive strength development of the geopolymer mortars using fly ash and rice husk ash as their powder binder made with waste glass as a partial fine aggregate replacement has been investigated as well as their resistance to high temperatures. The following conclusions were drawn:

1. Fly ash and rice husk ash can be used to produce geopolymer mixtures. The fly ash-based geopolymer mortars incorporated with rice husk ash; the maximum percentage of replacing fly ash with rice husk ash is 30%.

2. The characteristics of rice husk ash can significantly affect workability and strength development of the geopolymer mortars.

3. Waste glass can be used an aggregate for geopolymer mortar production.

4. The fly ash-rice husk ash geopolymer mortars keep their original dimension up to 1,000°C

5. The fly ash-rice husk ash geopolymer mortar strength can either be increased or reduced depending on the dominant process.

Acknowledgements

The authors gratefully acknowledge the financial support from the Department of Construction Engineering, Faculty of Industrial Technology, Nakhon Ratchasima Rajabhat University.

References

Abdullah, M.M.A.B., Jamaludin, L., Hussin, K., Binhussain, M., Ghazali, C.M.R., Izzat, A.M. (2013). Study on fly ash based geopolymer for coating applications. Advanced Materials Research, 686, 227-233.

Ali, E.E., Al-Tersawy, S. H. (2012). Recycled glass as a partial replacement for fine aggregate in self-compacting concrete. Construction and Building Materials, 35, 785-791.

Batayneh, M., Marie, I., Asi, I. (2007). Use of selected waste materials in concrete mixes. Waste Management, 27, 1870-1876.

Bhowmick, A. Ghosh, S. (2012). Effect of synthesizing parameters on workability and compressive strength of fly ash based geopolymer mortar. International Journal of Civil and Structural Engineering, 3, 168-177.

Chindaprasirt, P., Chareerat, T., Hatanaka, S., Cao, T. (2011). High strength geopolymer using fine high calcium fly ash. Journal of Materials in Civil Engineering, 23, 264-270.

Davidovits, J. (1991). Geopolymers-Inorganic polymeric new materials. Journal of Thermal Analysis, 37, 1633-1656.

Davidovits, J. (2008). Geopolymer Chemistry and Applications. Institut Géopolymère, Saint-Quentin, France.

Della, V.P., Kuehn, L., Hotza, D. (2002). Rice husk ash as an alternative source for active silica production. Materials Letters, 57, 818-821.

Detphan, S. Chindaprasirt, P. (2009). Preparation of fly ash and rice husk ash geopolymer. International Journal of Minerals, Metallurgy and Materials, 16, 720-726.

Duxson, P., Fernandez-Jimenez, A., Provis, J.L., Lukey, G.C., Palomo, A., van Deventer, J.S.J. (2007a). Geopolymer technology: the current state of the art. Journal of Materials Science, 42, 2917-2933.

Duxson, P., Provis, J.L., Lukey, G.C., Mallicoat, S.W., Kriven, W.M., van Deventer, J.S.J. (2005a). Understanding the relationship between geopolymer composition, microstructure and mechanical properties. Colloids and Surfaces A Physicochemical and Engineering Aspects, 269, 47-58.

Erdoğan, S.T. (2011). Use of perlite to produce geopolymer. Proceedings of the 31st Cement and Concrete Science Conference, Imperial College London, United Kingdom

Federal Highway Administration. (2017). Fly ash facts for highway engineers. [Online]. Available: https://highways.dot.gov/ (February 06, 2021)

Haddad, R.H., Ashteyat, A.M., Lababneh, Z.K. (2018). Producing geopolymer composites using oil shale ash. Structural Concrete, 1-11.

Hager, I. (2013). Colour change in heated concrete. Fire Technology, 1, 1-14.

Kroehong, W. (2012). Effect of rice husk ash and palm oil fuel ash on microstructure and chloride penetration of blended cement pastes. PhD Thesis, Suranaree University of Technology, Thailand

Matalkah, F., Aqel, R., Ababneh, A. (2020). Enhancement of the mechanical properties of kaolin geopolymer using sodium hydroxide and calcium oxide. Procedia Manufacturing, 44, 164-171.

Pan, Z., Sanjayan, J.G., Rangan, B.V. (2009). An investigation of the mechanisms for strength gain or loss of geopolymer mortar after exposure to elevated temperature. Journal of Materials Science, 44, 1873-1880.

Provis, J.L., van Deventer, J.S.J. (2009). Geopolymers: Structures, processing, propertiesand industrial applications. Woodhead Publishing and CRC Press, USA.

Real, C., Alcala, M.D., Criado, J.M. (1996). Preparation of silica from rice husks. Journal of the American Ceramic Society, 79, 2012-2016.

Sathawane, S.H., Vairagade, V.S., Kene, K.S. (2013). Combine effect of rice husk ash and fly ash on concrete by 30% cement replacement. Procedia Engineering, 51, 35-44.

Sinsiri, T., Teeramit. P., Jaturapitakkul, C., Kiattikomol, K. (2006). Effect of finenesses of fly ash on expansion of mortars in magnesium sulfate. Science Asia, 32, 63-69.

Solouki, A., Viscomi, G., Lamperti, R., Tataranni, P. (2020). Quarry waste as precursors in geopolymers for civil engineering applications: a decade in review. Materials (Basel), 13, 3146.

Stroeven, P., Bui, D.D., Sabuni, E. (1999). Ash of vegetable waste used for economics production of low to high strength hydraulic binders. Fuel, 78, 153-159.

Warnphen, H., Supakata, N., Kanokkantapong, V. (2019). The reuse of waste glass as aggregate replacement for producing concrete bricks as an alternative for waste glass management on Koh Sichang. Engineering Journal, 23, 43-58.

Wattanapornprom, R. Stitmannaithum, B. (2015). Comparison of properties of fresh and hardened concrete containing finely ground glass powder, fly ash, or silica fume. Engineering Journal, 19, 35-48.