

## A Review of Ground Sediment and Calcium Carbide Residue as Primary Materials for Geopolymer

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### Abstract

Sustainability is a crucial issue to be considered in the manufacture of construction materials. There is an increasing demand to produce construction materials by using abundant waste products and production methods which consume low energy. This paper is an overview of new geopolymer synthesized by the combination of two aluminosilicate materials, Ground Sediment (GS) and Calcium Carbide Residue (CCR) activated by Sodium Hydroxide and Sodium Silicate. Based on the comprehensive review, several important conclusions were made and further research were identified. In this review, the collected evidence prepares for further investigation of GS-CCR based geopolymer focusing on the parameters and testing method by referring to previous research using various types of aluminosilicate materials.

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## 1. INTRODUCTION

Geopolymer is an extensive range of alkali or silicate-activated aluminosilicate binders. Geopolymers have received great attention nowadays because of its low porosity, good mechanical properties, durability, thermal stability and low energy consumption to build industry and engineering field [1]. Researchers have conducted many studies regarding the implementation of geopolymers in the civil engineering industry. Currently, the researchers' main consideration is focusing more on the environmental issues especially in which using the combination of waste materials such as CCR. What makes geopolymer material favourable amongst researchers today is its adaptability to different user requirements for instance, the high strength, durability, low cost and environmental-friendly.

According to M. N. S. Hadi et. al [2], since geopolymer does not contain any Ordinary Portland Cement (OPC), it is considered as green material. The production of Ordinary Portland Cement (OPC) releases approximately 7% of the total greenhouse gases and mainly consists of carbon dioxide (CO<sub>2</sub>) [3]. On top of that, according to reports published, it was estimated about one ton of CO<sub>2</sub> was generated for every one ton of OPC produced [4]. A research reported that in 2013, Australia cement production contributes to the emission of 36 billion tonnes of CO<sub>2</sub> in a year [2].

A huge amount of energy is needed when producing one ton of cement which is equivalent to about pounds of coal. In 2020, it is estimated around 4.7 billion metric tonnes of cement will be consumed considering an annual growth of

4% [2]. Therefore, researchers have started to investigate geopolymer concrete and alkali-activated construction materials such as geopolymer concrete, geopolymer mortars or geopolymer bricks for the last few years as alternatives options to replace OPC.

While there has been much research going on with geopolymer, few researchers have taken CCR [2], [5], [6] and Sediments [6]–[9] in geopolymer material into consideration. CCR is known as a waste by-product from acetylene gas production and the high amount of Calcium Hydroxide (Ca(OH)<sub>2</sub>) in CCR promotes the material as a sustainable cementing material [5]. Meanwhile, GS was used as the primary material since it is considered as abundant materials. The combination of CCR and GS in geopolymer material could be beneficial and an initiative to a sustainable built environment. This review focused on five parameters of geopolymer; Sodium Hydroxide (NaOH) concentration, Sodium Silicate to Sodium Hydroxide (Na<sub>2</sub>SiO<sub>3</sub>/NaOH) ratio, solid to liquid ratio, curing time and curing temperature.

## 2. OVERVIEW OF GEOPOLYMER

The word “geopolymer” is commonly used to describe an amorphous alkali aluminosilicate which is used as “inorganic polymers”, “alkali-activated cements”, “geocements”, “hydroceramics” and “alkali-bonded ceramics” [7]. When raw materials react with alkali activator, it will form a geopolymer through the process called geopolymerization. Geopolymerization can be described as a chemically in-

tegrates minerals reaction that involved silico-aluminate source [8]. Geopolymer is produced by polycondensation of an individual  $[\text{SiO}_4]^{4-}$  and  $[\text{AlO}_4]^{5-}$  tetrahedral [7]. Based on the fundamental in which the reaction between high alkaline solution to produce amorphous to semi-crystalline aluminosilicate inorganic polymer is a reassuring innovative technology for geopolymerization [7].

In order to promote alternative binders by utilizing an abundance of alumina-silicate (pozzolanic) wastes from the industrial sector, several studies on different aluminosilicate materials have been done by researchers from all around the world. For example, Chindaprasirt et al. [1] has studied on fly ash based geopolymer, Hardjito and Fung [5] studied on geopolymer utilizing bottom ash, meanwhile, Nuruddin et al. [9] in 2011 conducted a study on geopolymer using Silica fume and rice husk ash and N.S Hadi et. al. [2] reported on ground granulated blast furnace slag (GGBFS). One of the most important criteria that need to be considered to developed a stable geopolymer are the raw materials that will be used must contain high amorphous, require less water and able to release aluminium easily [7]. Optimizing selected raw materials which fulfil the criteria needed in producing new geopolymer materials will shows an excellent-properties of geopolymers. Correct mixing procedure and processing design that is suitable for particular application also plays a big role in producing good geopolymer [7].

### 3. MATERIALS

#### A. Ground Sediment

Sediment can be described as a solid material that was moved from one place to another through the process called erosion or disintegration and transported by water, wind, ice and gravity to a new location. Based on H. Slimanou [6], an average of 1.5 million  $\text{m}^3$  volume of sediments have been dredged in the duration of 6 months which incorporate the annual maintenance and the total amount of sediment that need to be dredged in order to preserve sae navigation in port Bejaia, Algeria [6]. Hence, due to the excessive increase in sediments production volumes, a study on utilising the waste sediments was conducted [10]–[12] On top of that, these sediments have been applied in many parts of infrastructural activities for instance, in building construction and beach replenishment [11].

The chemical composition of sediments is found to be similar to aluminosilicate material [6], which is one of the most important component needed in geopolymer to enhance the geopolymerization process and therefore it is suitable to be used as raw material for geopolymer synthesis. F. Messina [12] stated that in order to enhance the reactivity of the sediments during polycondensation process, heat treatment or calcination is necessary. Calcination or also known as thermal activation can be defined as the heating with high temperature in the limited supply of air and oxygen.

C. Ferone et. al [13] has studied and proved that geopolymer can be synthesised by clay sediments source material. It is reported that the geopolymerization is better when the calcination temperature of the clay sediment was increased to  $750^\circ\text{C}$  which leads to the increasing extent of dissolution for Al and Si, however they conclude that the addition of GGBFS as secondary materials and  $\text{Na}_2\text{SiO}_3$  solution help to increase the mechanical strengths of the geopolymer by improving the degree of geopolymerization [13]. On the other hand, a research on dredged sediment by S. Lirer et. al reported that the sediments was calcined at  $550^\circ\text{C}$  for two hours [10].

#### B. Calcium Carbide Residue (CCR)

CCR is a waste product from acetylene gas production. The production process occurs through the hydrolysis of Calcium Carbide ( $\text{CaC}_2$ ) and it is considered as a sustainable cementing agent [5]. It is reported that CCR is mainly consist of a slurry form of  $(\text{Ca}(\text{OH})_2)$  [4]. In a research done by S. Hanjitsuwan, the CCR was let to dry under the sun for a few days until the slurry form of CCR becoming dried and usually disposed in landfills [14]. CCR has a tendency to effect organisms depends on microbes and their secondary product for new development. In Thailand, there are more than 21,500 tons of CCR has been released annually

which eventually caused environmental problem and water pollution since CCR is high alkalinity where pH value is more than 12 [4].

In a study perform by Phetchuay et al. [15] on Fly Ash and CCR based geopolymer, after the CCR has been sun-dried for a certain period, the dried CCR was then dried in an oven at  $100^\circ\text{C}$  for 24 hours and was then ground using Los Angeles abrasion machine. Then, the CCR was sieved passed through a  $425\mu\text{m}$  sieve. The specific gravity value of CCR for this study is 2.32. The average grain size of CCR is 0.01 mm with the highest chemical composition are Calcium Oxide ( $\text{CaO}$ ) with 69.54% which indicate that it can be used as cementitious material.

Makaratat et al. [4] perform a research on the combination of CCR and Fly Ash (FA) in concrete without using OPC. It is proved that the concrete properties with the combination of CCR and FA were way better than the normal concrete. They also were capable to improve the strength characteristics of silty clay and soil [5]. The CCR contain high amount of  $\text{Ca}(\text{OH})_2$  and  $\text{CaO}$  which indicate that it can react with FA to produce a new cementitious material. A research done by Hanjitsuwan et al. [4] studied the use of OPC and CCR to replace Bottom Ash (BA) and the result shows a high compressive strength of alkali activated BA mortar similarly by using OPC when utilizing CCR to replace BA. However, the geopolymerization degree is better when utilizing BA and OPC compared to CCR.

#### C. Alkaline Activator

The most important factor to be considered in geopolymer formation is the alkaline activator concentration. It is the

determinant for a high compressive strength geopolymer. A research done by Y. Liew et. al [3] stated that an increase in concentration eventually increases the reaction rate and degree leading to a less porous and stronger geopolymer and this occur to fly ash systems. It is also found that a higher alkaline concentration increases setting time and delays polymer formations since excessive ion presence limits the polymer mobility and the ability to interact with available reactive species. Besides, it increased the degree of hydration reactions and improve microstructural properties of the C-S-H product.

Therefore, concentration must be clearly addressed in a geopolymer as it plays the most crucial part of the mix design. The geopolymerization rate may be triggered by a strong alkaline environment [16]. Ghosh and Ghosh [16] stated that the alkali activator solutions influence the dissolution and hydrolysis of the solid aluminosilicate precursor and give adequate alkali metal ions to balance the remaining charges carried by the poly-condensed structure. However, it is also reported that excess alkali content in the mixture could reduce the strength of the geopolymer by weakened the stability of the polymerized network.

The most common alkaline activator used to synthesize geopolymer is NaOH due to the higher percentage of excess Hydroxide ( $\text{OH}^-$ ) in solution which cause the final product non-uniform. However, previous researchers stated that the increased or reduced of strength in specimens is not necessarily depend on the increase of NaOH concentration only, but it also depends on the source of material used [17]. The reaction between NaOH and the amount of  $\text{CaOH}_2$  contain in the raw materials. On top of that,  $\text{Na}_2\text{SiO}_3$  solution is also one of the alkali activators that has been used by many researchers as the binder for the geopolymer. A mixture of NaOH and  $\text{Na}_2\text{SiO}_3$  is the most utilized alkaline activator in geopolymerization. Based on a research done by Feng et al. [17], it is reported that the soluble silicates reduce alkali saturation in pore solutions and also promotes higher inter-particle bonding with geopolymer binders.

## 4. PARAMETERS

### A. NaOH Concentration

The concentration of the NaOH in activator solution determines the geopolymer paste properties. Several researchers used Taguchi method in developing the experimental design, for example, C. Panagiotopoulou et. al [18] used Taguchi experimental designing model on FA-based geopolymers in determining the effect of the selected synthesis parameter on strength development. FA is a pozzolan substance containing aluminous and siliceous. This research used 4 levels of aqueous activation solution containing alkali (Na, K) hydroxide and commercial water silica solution which were 0, 0.35, 0.7, 1.0 ratio. [18].

Next, A. Nazari et. al [1] studied the utilization of Taguchi method in designing the compressive strength tests of geopolymers on OPC as aluminosilicate source [1]. It

was reported that the maximum NaOH concentration, 14M increase the strength of the OPC-based geopolymer. In this research, a mixed alkali activator consists of NaOH and  $\text{Na}_2\text{SiO}_3$  solution was used. A tap water was used to dilute the NaOH in order to produce concentrations of 5M, 8M, 12M and 14M. The result shows that specimen with NaOH concentration of 14M produce a compressive strength of 38 MPa. Meanwhile, the lowest compressive strength equal to 2.3 MPa was produced from a specimen with the minimum amount of NaOH concentration of 5M [1]. However, in a previous works done by Ali Nazari et. al, a maximum concentration of 12M achieve the highest strength by utilizing FA and Rice Husk Ash [7]. Therefore, it is proved that increased in NaOH concentration is depends on the source material used.

S. Riahi et. al. [19] conducted three levels of NaOH concentration, 5M, 8M and 12M. The researchers found that the mixed of  $\text{Na}_2\text{SiO}_3$  and NaOH concentration of 5M or 8 M produced high compressive strength. However, there have been indications that the increase in compressive strength does not fully depends on NaOH concentration as well as oven curing temperature [19]. Metakaolin is ordinary clay and Kaolin clay when thermally activated in a non-purified form. The particle size of Metakaolin is smaller than cement particles as metakaolin is not an industrial by-product like the other admixtures. C. Ferone et. al [12] studied thermal treated clay sediment as geopolymer primary raw material had adjusted 3 levels for NaOH concentration, which were 5, 7, 10 M.

However, some researchers decided to keep NaOH molarity as constant. For example, A. Kumar et. al. used 6 M of NaOH concentration for the preparation of samples and also, it was prepared at least 24 hours before use [20]. Next, J. Kutuniva et. al [21] proposed alkali activator consist NaOH solution of 8 M for GGBFS-based geopolymer and  $\text{Na}_2\text{SiO}_3$  solution mixed together with 1.2 in weight ratio [19]. The solution was then kept for a whole night before use. Next, the alkali activator was mixed with the blast-furnace slag with 0.77 in weight ratio for a duration of 15 minutes by using a top-mounted mixer [19]. Another study by C.Y. Heah et. al [8] proposed a 8M concentration NaOH prepared in a volumetric flask and let it cool down at ambient temperature.

It has been proven that Molarity range between 8 to 16 is adequate due to the formation of stable aluminosilicate network systems following the dissolution of silica and alumina within the formation in the solution from the source material hence, as the molarity of activator increased, the compressive strength of the geopolymer also increased [7]. This statement follows the ASTM Specification Standard. In 2015, Olawela et al. [22] stated the geopolymers that was activated by one to one ratio of  $\text{Na}_2\text{SiO}_3$  and 14M NaOH one with ASTM Specification Standard proved that one of their samples satisfied ASTM Specification Standard C62 and C90.

The combination and concentration of alkali activator will

affect the geopolymer synthesis [6] while high reactivity of raw material allows the development of high mechanical strength [23]. Next, a study between base utilized ash and NaOH concentration showed a strong relationship between these two materials. When excessive NaOH concentration did not consume by the ash, the geopolymerization reaction will be incomplete as the strength was decreased [19]. Thus, increasing the NaOH concentration exceeding this point will only resulted in decreasing and lower strength of the geopolymer paste. This is because of the early precipitation of aluminosilicate products [19]. Calcined materials mostly contain amorphous which manifest a higher reactivity compared to non-calcined materials during the geopolymerization process [6] which eventually makes calcined materials more favourable in geopolymer research. It can be observed that the geopolymerization reaction improved as the increased in surface area of raw materials that dissolved rapidly in the alkaline solution.

As CCR is a calcined material, no doubt it will undergo complete geopolymerization. CCR capitulate a higher strength compared to hydrated lime in terms of soil stabilization due to the richer amount of pozzolanic materials contained in CCR such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ . Hence, this stabilization is beneficial in engineering field, environmental, and economic viewpoints [24]. R. Othman et al. [25] produced precipitated calcium carbonate (PCC) from carbide lime. High purity of PCC can be produced from waste and low impurities in the raw materials. The chemical composition of CCR based on based research as well as other calcined material acted as a raw material in the synthesis of geopolymer. The viability of using CCR in geopolymer as shown high strength and enhanced workability hence it can be used to stabilize geopolymer concrete.

The optimum molarity of NaOH that can be perceived from past researchers is 12 M. 12 M showed positive results as well as gave better strength and mechanical properties mainly to fly ash geopolymer. It is advisable to leave the solution to cool down for 24 hours in ambient condition before use.

#### *B. Sodium Silicate to Sodium Hydroxide ( $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ) ratio*

$\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is very important in determining the workability of geopolymers. Hardjito and Rangan [25] reported that compressive strength increased as  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  increased. However, in a research done by Y.M. Liew [3] on Calcined Kaolin Geopolymeric Powder, five level of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio was considered which ranges 0.24, 0.12, 0.16, 0.20, 0.28. It is found that the highest compressive strength recorded when  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio of 0.24 and decreased with further increments of this ratio [18]. For FA-based geopolymers, the recommended  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is 2.5. Villa et al. [3] reported that as activator ratio increased, the sodium silicate or also known as waterglass content also increase which results in the increase of the occurrence of geopolymerization reactions.

This is because the increase in waterglass led to the increase in the amount of silica gel which contribute to the strength of the geopolymer.

A. Nazari et. al. [1] specified 4 levels of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio for OPC-based geopolymer that ranges from 1, 1.5, 2 and 2.5. Taguchi method is recommended as it was used to design the mixtures and to obtain the optimum mixture design by considering the effects of the parameters on their mechanical properties. The result shows that the optimum  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is 1.5. In the previous work on ash-based geopolymer, the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio was consider constant at 2.5 but the ratio values were reported different for other researches. This is in-line with a report done by Chindaprasirt et al. [1] on considering  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio to achieve higher strength or geopolymer.

Silicate Oxide ( $\text{SiO}_2$ ) content contributed by the  $\text{Na}_2\text{SiO}_3$  solution and the Sodium Oxide ( $\text{Na}_2\text{O}$ ) content came from both the  $\text{Na}_2\text{SiO}_3$  and the NaOH solution will promote the addition of  $\text{Na}_2\text{SiO}_3$  in the activating solution and later bring improvement to the development of the mechanical properties [3]. Hence, increasing the  $\text{SiO}_2/\text{Na}_2\text{O}$  molar ratios of the activating will increase the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios [3]. It was reported that increase in  $\text{SiO}_2$  content provides the silicate species for rapid exchange and oligomerization between aluminate and silicate species from the aluminosilicate sources and the silicate species from the activating solution proving the rise in strength at higher ratios [3]. As a result,  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio is effective on residual compressive strength of geopolymer mortar in both sulphate and acid exposure. The relationship of this ratio is the higher  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio, the higher the residual compressive strength. When the activator ratio increased,  $\text{Na}_2\text{SiO}_3$  content will increase [20].

C.Y Heah et. al. [8] mixed NaOH solution and  $\text{Na}_2\text{SiO}_3$  solution with  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio ranged from 0.16 to 0.36 to prepare alkali activator and left for 24 hours before use. The increment in the  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios increases as  $\text{SiO}_2/\text{Na}_2\text{O}$  molar ratios increase. It is reported that compressive strength optimized at  $\text{SiO}_2/\text{Na}_2\text{O}$  molar ratio of 3.58 and decreased for any further rise in the  $\text{SiO}_2/\text{Na}_2\text{O}$  molar ratio [9]. It is reported at low  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio, the  $\text{Na}_2\text{O}$  was in excess as in the case of a low S/L ratio. Thus, the optimum S/L and  $\text{SiO}_2/\text{Na}_2\text{O}$  molar ratios from the study were 1.09 and 3.58, respectively [9]. However, C. Jaturapitakkul et. al [26] stated the increase of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio tends to increase the occurrence of geopolymerization reaction [26]. Thus, the optimal  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio ranges from 0.16 to 0.36 was chosen depended strongly on the workability of the geopolymer paste. Olawale et. al. [22] studied the compressive strength of geopolymer was activated with 1:1 of activators; sodium silicate and water. This is relatively higher than those activated with activators at 1:0.5. Here, water plays a significant role in the completion of hydrolysis of silicon and aluminium species of the raw materials [22]. In the study, the ratios of calcined clay:  $\text{Na}_2\text{SiO}_3$ : distilled water was taken as 25.0: 5.0: 5.0

(by weight) for the first batch and 25.0: 5.0: 2.5 (by weight) for the second batch of geopolymer binder produced while the third batch ratio of calcined clay:  $\text{Na}_2\text{SiO}_3$ : NaOH was 25.0: 5.0: 5.0 of geopolymer binder [22].

The optimum compressive strength may be obtained at the ratio of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  as the compressive strength of geopolymer soil stabilization seems more affected on  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio compared to S/L ratio. Past research showed that the ratio of S/L and the ratio of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  were influenced the compressive strength of geopolymer soil stabilization. However, there is not clear optimum value that can be deduced as each research depicted various value hence, Taguchi method may assist in setting up this parameter.

### C. Solid to Liquid (S/L) ratio

One of the critical parameters in strengthening and fire resistance of geopolymer paste is S/L Ratio which coincide to the aluminosilicate-to-activator solution ratio [10]. Yao et al. [8] reported that the increased in S/L ratios will increased the geopolymerization period meanwhile, Zuhua et al. [27] reported that low S/L ratios could expedite the dissolution of source materials. Provis et al. [27] stated that extremely high S/L ratios for geopolymers generally failed to achieved high strength due to the low extent of binder formation.

C.Y. Heah et al. [8] recommended the S/L ratio in the range of 0.60 to 1.20 on Kaolin geopolymers and reported that the highest compressive strength achieved with S/L ratio of 1.20. However, solid to liquid ratio of 1.2 is not chosen for further investigation due to its low workability of the geopolymer. Therefore, the most suitable S/L ratio in this research is 1.0 referring to workability and strength of the geopolymer [9]. Meanwhile, Kong et al. [8] research on Metakaolin-based geopolymer used solid to liquid ratio of 0.80 and produce nearly optimum strength and excellent workability. Kong et al. also stated solid to liquid ratio more than 0.80 reduce the workability and strength of the geopolymer and hence will deteriorate the properties of the paste.

Next, A. Nazari et al. [1] studied the raw material of OPC in geopolymer by utilizing Taguchi method. Four levels of S/L ratio were proposed (0.35, 0.38, 0.42, 0.45). The result shows that the optimum S/L ratio is of 0.42. S/L ratio helps geopolymer in their strength development. The strength increases as the  $\text{Na}_2\text{SiO}_3/\text{water}$  ratio increases up until the optimal value and then decreases as the  $\text{Na}_2\text{SiO}_3/\text{water}$  ratio increases. The optimum  $\text{Na}_2\text{SiO}_3/\text{water}$  ratios studied were 1.4 and 1.0, respectively and they provide the highest strength for clay-FA geopolymers without and with FA, respectively for all curing times [28].

The optimum S/L ratio for geopolymer is significant in determining the properties of geopolymer. Mainly, the strength of geopolymer was affected by the S/L ratio. Geopolymer is produced from the alkali activation of materials rich in Si and Al with the addition of the silicate solution to improve the mechanical property. However, not

may researches have been conducted without the presence of silicate solution in the geopolymerization process varying solid/liquid ratio and studies on the mechanical and physical properties based on this condition.

The mechanical properties of geopolymers are hugely affected by S/L ratios and  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio [3]. The soluble silicates content in comparison to the  $\text{SiO}_2$  content that was present in the aluminosilicate was lower as S/L ratio increased [3]. This situation hinders the Calcine Kaolin particle disintegration due to the precipitation of gels on the surface of the particles [3]. Hence, it can be observed that the presence of large voids in the microstructure. However, at a lower ratio, the activating solution with high volume does not promote the dissolution process, but it does help in hindering the polymerization of the dissolved species. In the end, the resulted microstructure was poor with large voids as lower S/L ratio decreased the  $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$  molar ratio [3].  $\text{Al}_2\text{O}_3$  content comes from aluminosilicate sources while the  $\text{Na}_2\text{O}$  content comes from the activating solution and more activator content was presented in the system with lower S/L ratio and this contributed to the workability of the slurry and hence good homogeneity of the geopolymer slurry [3].

Higher S/L ratios have resulted in low viscosity of the slurry and the lower S/L ratios increased the geopolymerization period. However, geopolymer with excessive S/L ratios are likely failed to achieve high strength because of the low extent of binder formation but at the same time, it does not successfully increase the compressive strength when  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio increase. It can be concluded that both the S/L ratio and  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios plays an important role to the workability of geopolymers [8]. Based on Kaolin geopolymers, it proved that the increasing S/L ratio and  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios does not ensure the increasing in workability of the geopolymer paste [9]. The amount of solid contain was higher than the fluid medium in the mix when higher S/L ratio was utilized and thus cause the mix become stiffer. This caused the workability to strongly depends on the particle shape of the solid materials. [9]. The contact between the activating solution and the reacting materials were believed improved and hence showed an increase in the compressive strength measured [9].

The effect of the S/L ratio on the properties of different materials on geopolymers was studied. To conclude, the compressive strength of geopolymers does not significantly affected by S/L ratio. However, the workability is greatly affected by the S/L ratio. For an instant, the compressive strength of FA-based geopolymer for all the S/L ratio increased until 14 days and started to decrease later. This shows that each raw material has different results and different value of S/L ratio must be studied to obtain the optimum value.

### D. Curing Time

Previous research has proved that curing time greatly affect the mechanical development of geopolymer binders. Same

with the OPC, geopolymer responds better to heated curing methods. Geopolymer sets quickly and attains a significant percentage of its total compressive strength within the first few hours of reaction. C. Panagiotopoulou et. al. [18] mentioned that the optimal curing time was 48 hours based on previous work. However, Khale et al. [29] reported that the compressive strength increase for specimen cured more than 48 hours was not significant. The research stated that a compressive strength of 60 MPa achieved with curing time only for five hours at 85°C. Longer curing time will increase the strength of geopolymer but the strength is developing at a much slower rate as time progress due to alkaline saturation and product densification

A. Nazari et. al. [1] considered four level of oven curing time of 2, 4, 6 and 10 h and water curing regime of 1,3,7 and 28 days in designing method and then were then pre-cured for a day (24 h) at ambient temperature because to enhance the strength development of the geopolymer paste. The results show the highest compressive strength of the OPC-based geopolymer is when the specimen was oven cured for 6 hours. Oven curing time of 10 hours shows a reduction in compressive strength [1]. For ash-based geopolymer reported by S. Riahi et al. [19], the oven curing time was reported at 3 levels 2, 4 and 8 hours. For even higher strength development, it is proven that pre-curing for 24 hours in room temperature has found to be beneficial. However, it concludes that oven curing time has no significant effect toward the strength of the geopolymer despite after been cured at room temperature after 2 and 7 days.

Furthermore, M. D. Olawale et. al. [22] studies on CCR-Rice Hask Ash (RHA) mortars, the compressive strength was steadily increased as curing age increased. Therefore, CCR-RHA compressive strength at 1 day was in the range of 0.1 to 0.9 MPa which is relatively lower compared to when cured or 3 days with compressive strength increased from 1.3 MPa to 5.8 MPa, depends on the mix proportion. The highest compressive strength gained for mortar with 50% of CCR and 50% of RHA and the strength was 0.9, 10.0, 15.6, 18.6, and 19.1 MPa for 1, 7, 28, 90, and 180 days. Then, the moulded sample were cured at room temperature for a day and after a day, the samples were cured at different temperatures. A. Kampala et. al. [30] found that the hydrated lime paste strength is relatively low and increase insignificantly with curing time while the strength of the CCR paste is essentially increases with curing time. Moreover, a higher strength gain for CCR stabilized clay when increasing the curing time because of the insignificant strength development with the time of the lime-stabilized clay. Four levels were studied (1,7,14,28 days) and all tests at each curing time and combination of water content and CCR content, at least five samples were tested under the same condition to check for consistency of the test.

The parameters such as curing time and curing temperature affect the compressive strength of the hardened geopolymer concrete as the compressive strength increases with the age in either type of curing considered in the study. It can

be seen as the longer the curing time, the higher the compressive strength. However, extended and longer curing in oven curing could cause cracking as some materials may reach its breaking point and might have harmful effects on the structure, due to loss of structural water. The optimum curing time might suggest between 7 to 28 days for testing of compressive strength.

The curing of freshly prepared geopolymer concrete is the most crucial aspect and it plays an important role in the entire geopolymerization process. The proper curing of concrete has a positive effect on the final properties of the geopolymer concrete. Optimum curing time may produce geopolymer with the highest strength and good workability. It will also reduce the probability of cracking if it was in the correct time setting for each regime.

#### *E. Curing temperature*

Curing temperature is directly influence with curing time in determining the compressive strength of the geopolymer specimens. Temperature in the range of 70-90°C are accepted as the best heating range in order to obtain high strength [1]. C. Panagiotopoulou et al. [18] found that 70°C to be an optimal temperature for curing. Elevated temperature curing methodologies were evaluated on the use of steam-or dry-heat and the results shows that dry curing increase the compressive strength by 15% compared to steam-curing methods. Suksiripattanapong et al. [15] study on FA geopolymer and FA-CCR geopolymer reported that as curing temperature increase, the compressive strength also increases. This is because the temperature increased enhance the geopolymerization reaction. Generally, it is important to consider adequate curing of geopolymeric materials in order to achieve the optimal mechanical performance in maintaining their structural behavior.

A research done by A. Nazari et al. [18] proposed four level of curing temperatures; 2°C, 4°C, 6°C, 10°C. Specimens that been cured at , 40°C, 70°C and 90°C and the time of oven-curing, 25°C, 40°C, 70°C, 90°C were also considered in water curing regime. However, some research adjusted curing temperature to be one of the influential parameters for geopolymerization and determined it by using Taguchi method [1], [7], [31]. When sintering temperature is higher or longer, larger impact can be seen for of vitrification [31]. Hence, removed the test specimen from the mould and let air-dried at room temperature for a day before sintering the specimen. After that, placed the test specimen in a 100°C dry oven for 24 hours [31]. Next, compare the resultant size with the original size of the test specimen and it was found that the total amount o shrinkage is the dry shrinkage percentage oven curing temperature, 25°C, 70°C, 90°C [31]. The mixture obtained for dredges sediments are placed in cylindrical moulds (15-30 mm diameter) and treated for 24 hours at 70°C [6].

Nevertheless, excessive curing at higher temperature for a long period might cause negative effect and failure to the samples after some period. This is due to the thermolysis



of  $-\text{Si}-\text{O}-\text{Al}-\text{O}-$  bond. Hence, it is advised to extend the curing at room temperature before applying heat on the specimen for a better strength development [7]. Next, curing reservoir sludge geopolymer at higher temperatures is beneficial to the 3-day early compressive strengths of reservoir sludge based geopolymer with 50% replacement percentage of metakaolin and calcined reservoir sludge (CRS) or known as RSBG50 geopolymers but harmful to their 28-day and 91-day compressive strengths [28]. As soon as the percentage of metakaolin by CRS rises to 100%, high temperature curing is dangerous to all compressive strengths nevertheless of their age [28]. To overcome this problem, extending the period of curing is essential to produce materials with enhanced strength and reduced water absorption. This is due to the formation of additional geopolymerization products. The commencement of geopolymerization reaction at ambient temperature has been reported as good for cementitious materials even though the rate of reaction is slow [20].

B. Singh et. al. [7] temperature between  $40^{\circ}\text{C}$  to  $85^{\circ}\text{C}$  may achieve the best mechanical performance to maintain their structural behaviour. C. Ferone et. al. [13] confirmed by FTIR and NMR tests that the increase of the calcination temperature of sediments from  $400$  to  $750^{\circ}\text{C}$  resulted in increasing extent of dissolution for both Al and Si. This eventually usher for a better geopolymerization process. In addition, the geopolymers specimen mechanical properties obtained was acceptable for all the samples prepared with heat-treated sediments. However, the usage of both characterization technique (NMR and FTIR) and the method to identify the mechanical strength conclude that a better degree of geopolymerization and good mechanical behavior was obtained with the addition of  $\text{Na}_2\text{SiO}_3$  solution and GGBFS. Even so, geopolymerization products are seen to be more beneficial at a higher curing temperature [32].

## 5. CONCLUSION

It is concluded that the geopolymer based on GS and CCR has a promising potential to be used as a new construction material. Moreover, calcined materials yield higher reactivity which promotes complete geopolymerization. CCR and GS are potential aluminosilicate materials thus help mitigate abundant wastes in Malaysia. The combination of CCR, GS, NaOH and  $\text{Na}_2\text{SiO}_3$  will bring promising results as discussed above. The optimum amount of  $\text{Na}_2\text{SiO}_3$ , NaOH, S/L can increase geopolymer production. As curing time play an important role, 24-hour of pre-curing should be taken under consideration as it can help in strength development. Although the ambient temperature is reported to be optimum, curing at a higher temperature should be considered if it could promote shorter curing time which can help with a larger production of geopolymers. Since waste materials are used, geopolymer will be low cost as well as sustainable. However, few things need to consider regarding the reactivity of alkali activator. Higher molarity with a not suitable ratio of S/L might lead to failure of

geopolymer. Next, the disposal of tested geopolymer should be disposed of correctly as it may be chemically reactive. Nevertheless, this research may show promising results as well as bringing a positive impact to the environment.

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