Civil Engineering and Architecture 11(6): 3520-3526, 2023 http://www.hrpub.org
DOI: 10.13189/cea.2023.110621

Optimizing Fiber Reinforced Geopolymer Concrete: Investigating Alkaline-Activator Liquid to Fly Ash and Sodium Silicate to Sodium Hydroxide Ratio

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Received May 30, 2023; Revised July 29, 2023; Accepted September 8, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Greg Blasiak, Yureana Wijayanti, Martin Anda , "Optimizing Fiber Reinforced Geopolymer Concrete: Investigating Alkaline-Activator Liquid to Fly Ash and Sodium Silicate to Sodium Hydroxide Ratio," Civil Engineering and Architecture, Vol. 11, No. 6, pp. 3520 - 3526, 2023. DOI: 10.13189/cea.2023.110621.*

(b): *Greg Blasiak, Yureana Wijayanti, Martin Anda (2023). Optimizing Fiber Reinforced Geopolymer Concrete: Investigating Alkaline-Activator Liquid to Fly Ash and Sodium Silicate to Sodium Hydroxide Ratio. Civil Engineering and Architecture, 11(6), 3520 - 3526. DOI: 10.13189/cea.2023.110621.*

Abstract The construction industry is placing significant emphasis on finding alternative binders to completely replace ordinary Portland cement (OPC) due to its environmental consequences. In this study, an experiment for the geopolymer concrete (GPC) made with fly ash and reinforced with glass fibers was conducted. GPC, in contrast to OPC which utilizes water for its binding effect, relies on an alkaline activator. This activator comprises solutions of sodium silicate (SS) and sodium hydroxide (SH) to achieve the binding process. The experiment investigated the specific combination of alkali activator liquid to fly ash ratio and, SS to SH ratio to produce the highest compressive strength result as well as the best workability performance. The aggregates used in the concrete are subject to grading and classification as per Australian standards and fly ash used in the production of concrete using Collie coal power stations, Western Australia, derived fly ash (Class F) activated by Sodium Silicate (SS) and Sodium Hydrate (SH) as the alkaline solution at 14 M. Glass fibers were added in a proportion of 2% by weight of concrete. The design mixes were applied by altering the SS to SH ratio of 1.25, 1.5, and 2.6, the alkaline activator liquid (AA) to fly ash (FA) ratio of 0.4, 0.5, 0.57, and 0.58. Also, the percentage of water to alkaline solution of 11%, 18%, and 20%. Concrete samples were cured in an oven at 60°C for 24 h and at room temperature. The result indicated alkali activators liquid with SS to SH ratio of 1.5 and 2.6 achieved a maximum compressive strength after 28 days of 35 MPa and 40 MPa, respectively. Compressive strength decreases as the alkaline liquid to fly ash ratio is increasing. The workability for AA to FA of all ratios and for all percentages of water to AA shows good workability specified by Australian Standard.

Keywords Alkali-Activator Liquid, Fly Ash, Compressive Strength, Workability

1. Introduction

In the past, alternatives to ordinary Portland cement (OPC) have been proposed by blending cement with supplementary cementitious materials (SCM) and using these as binders for concrete. Such examples are ground granulates blast furnace slag from steel making and fly ash (FA) from coal-fired power stations, but these blends have only shown a reduction of emissions by 13-22% [1].

As Geopolymers concrete (GPC) is being considered a full substitute for OPC, the relative embodied energies need to be analyzed. This results in a wide range of estimates ranging from 80% less CO_2 emissions [2,3] all the way down to only 26-45% less CO_2 emissions than OPC [4]–[6]. Fly ash (FA) is a waste byproduct and the CO_2 emissions surrounding this terminology have allowed the contribution of CO_2 emissions to remain at zero [7]. An analysis has been conducted on the energy consumption associated with bagging, collecting, and transporting activities at power stations, resulting in a relatively low emission factor of 0.027 kg of CO_2 per kg of collected fly ash. Fly ash has been widely applied in the geopolymer concrete design mix [8]–[10].

The construction industry has witnessed significant progress over time, one of which is the utilization of fibers as an alternative to traditional steel reinforcement [11]. Due to the rising costs associated with steel reinforcement, there is a growing interest in considering fibers of either artificial or natural origin for reinforcing concrete [12]. Glass fiber reinforcement in GPC has been studied in much research [13,14]. Glass fiber and fly ash are the primary materials under investigation in the current study, as opposed to the commonly used materials such as steel and polypropylene, for the creation of geopolymer concrete. Previous research indicates that the inclusion of fiber in concrete leads to decreased workability while enhancing its density, compressive strength, and flexural strength [15]–[17]. Kumar et al [18] have researched the use of fibers within GPC for the purpose of reinforcement. The fibers had significantly contributed towards crack resistance and an increase in compressive strength. Fly ash is usually mixed with alkali activator liquid to obtain alumina and silica precursors. When it comes into contact with an alkali solution, the dissolution of silicate species starts. The silicate will begin accelerating the dissolution of FA material then, the aluminum and silicate in the FA are available for binding. In geopolymerisation, the alkali activator plays an important role. Activators are commonly made from soluble metal bases such as Sodium or Potassium. Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) are used to create the alkali activator to activate the geopolymers. The Sodium Hydroxide (SH) helps to dissolve the aluminosilicate materials whilst the Sodium Silicate (SS) supports the hydroxide as a binder [18]. Therefore, this study investigates the specific combination of alkali activator liquid to fly ash ratio and, SS to SH ratio to produce the highest compressive strength result as well as the workability performance.

2. Materials and Methods

The research aim is to improve the compressive strength of fiber GPC by finding the optimum ratio of water and SS to SH in the mixture. Acknowledgments [19,20] made to various studies around the world contribute to the justification of changes made to the inputs to achieve a range of results. Thus, the collection of the overarching outcome, among many, from the results is in the form of a compression test. To reach this conclusion, there are many procedures that are put into place that adhere to Australian Standards for testing concrete. The laboratory component of this research starts with sorting out and classifying each of the raw materials that will be placed into the mix. Once classified and correctly sorted, the raw materials undergo the procedure of manufacturing the concrete as per the required process outlined in the relevant Australian Standards. The experimental procedures consist of several stages, as follows: 1) preparation of the raw material, fly ash (FA), and alkaline activator; 2) Mixing; 3) Oven curing 60ºC for 24 hours [17] and room temperature curing until the test time; and 4) compressive strength and slump test.

2.1. Materials

Aggregates used will be classified to a certain grade before being used to conform to the Australian Standard for testing concrete AS 2758.0:2020 [21]. FA is the solid material extracted from the flue gases of a boiler with pulverized coal and is graded into Special Grade, Grade 1, or Grade 2 as per compliance with AS 3582.1:2016 [22] Supplementary Cementitious Materials. The FA that is being used originates from Bluewaters coal power station in Collie, Western Australia, and is classed as class F FA as per the international Standard Specification for Coal Fly Ash ASTM C618-12 [23]. This classification is due to the high alumina:silicon: iron concentration, along with the fine particle size due to the high moisture content of the initial coal. Class C FA will typically have a higher calcium composition as a result of the lower alumina:silicon:iron concentration. The FA is captured and bagged from the flue at the power station, as opposed to being collected from pond ash which contains bottom ash (particles from the bottom of the boiler) and other minerals that lead to less pozzolanic properties.

Figure 1. Coarse aggregate, fine aggregate, and fly ash from Bluewater Power Station in Collie, WA (center bucket)

2.2. Fiber Reinforcement

Glass fiber reinforcement is done in the form of 2 types: hard and soft fibers. Both types come from melting silica sand, limestone, kaolin clay, fluorspar, dolomite, and other minerals until a liquid is formed. Then using brushes, it is extruded into bundles of long fibers of ~10-micrometer diameter. It is coated with a chemical solution (zirconium) for alkaline resistance, and then the soft fibers are chopped up randomly and bundled together. The hard fibers are further processed as larger quantities of soft fiber held together with a binder to form a continuous long filament and cut into lengths of approx. 4 cm. The result is a white fiber in appearance (Figure 2). Both types are used simultaneously in the concrete mix. A mix of 50% soft fiber and 50% hard fiber was used throughout the experiments. The glass fiber is made by Sika Australia and has no water absorption, a 550 MPa tensile strength, and excellent resistance to alkalinity. The SikaFiber Force PP-65 complies with ASTM C1116 [24] Type 3. Glass fibers were added to the geopolymer concrete in proportions of 1% by weight of the concrete.

Figure 2. Glass Fiber

2.3. Preparation of Alkaline Solution

SH solution is a clear water white solution, the chemical formula of NaOH is highly alkaline, and has a pH greater or equal to 14. Its typical uses are for gold mining (pH adjustment and carbon stripping), alumina (bauxite digestion), and manufacturing of numerous chemical components. It has a specific gravity (S.G) of 1.5, and a molar concentration of 14M [10]. SS solution is under the chemical formula Na_2SiO_3 and is a common name "Waterglass". It is a colorless to light brown inorganic chemical. It is a H-grade silicate and has a S.G. of 1.50. Alkali Activator created by mixing SH solution with water. This allows the dissolution of OH- ions to occur. The solution will heat up to over 50 ℃, let it cool then add the appropriate required amount of SS and extra water. This will heat up again, once it is cooled the alkali activator is ready for use.

2.4. Design Mix

The purpose of the different series is to see the performance of the concrete when: The ratio of SS to SH changes in the alkali activator solution with the ratio of 2.26, 1.5, and 1.25. This ratio was referred to a study by Hardjito et.al [25] that used SS/SH ratios of 0.4 and 2.5 at a molarity of 14M. It was discovered that the compressive strength increased from 47.9 MPa to 67.6 MPa as the ratio change from 0.4 to 2.5. However, this past study did not incorporate fiber. So, in this study, the ratio of SS/SH was kept between 0.4 and 2.5. The ratio of alkali activator solution (AA) to fly ash (FA) changes with the ratio of 0.4, 0.5, 0.57 and 0.58. The % of water added in the alkali activator solution for these two purposes is 18%. This mixture proportions are modified from a study conducted by Sathanandam et.al [14]. The % of water in the alkali activator solution was varied for 11%, 18%, and 20% to see the influence on the slump test. The specimen proportion for the mix design was shown in Table 1 and the designed capacity is ranging from 84-94 kg.

Table 1. Design mix of geopolymer concrete

I. Proportion for Na_2SiO_3 (SS) to NaOH (SH) variation					
Series	SS:SH ratio	Na_2SiO_3 (kg0	NaOH (kg)	H_2O (kg)	Fly Ash (kg)
B3-F	2.26	3.6	1.59	1.15	15.46
B4-F	1.5	4.4	2.94	1.65	15.46
B9-F	1.25	1.99	1.59	0.79	11.18
II. Proportion for Alkali Activator (AA) to fly ash (FA) variation					
Series	AA:FA ratio	Na_2SiO_3 (kg)	NaOH (kg)	H_2O (kg)	Fly Ash (kg)
B2-F	0.4	3.6	1.59	1.15	15.46
B7-F	0.5	4.42	2.94	1.57	16.05
B5-F	0.57	4.42	2.94	1.65	14.99
B4-F	0.58	4.4	2.94	1.65	15.46
III. Proportion for %water to Alkali Activator variation					
Series	water %	Na_2SiO_3 (kg)	NaOH (kg)	H_2O (kg)	Fly Ash (kg)
B6-F	11%	4.42	2.94	0.919	14.99
B5-F	18%	4.42	2.94	1.65	14.99
B7-F	18%	4.42	2.94	1.57	16.05
B1-F	18%	3.6	1.59	1.15	14.23
B2-F	18%	3.6	1.59	1.15	15.46
B9-F	18%	1.99	1.59	0.79	11.18
B4-F	18%	4.4	2.94	1.65	15.46
B3-F	18%	3.6	1.59	1.15	15.46
B8-F	20%	4.42	1.59	1.47	16.05

2.5. Compressive Test

To evaluate the impact of varying mix proportions on compressive strength, all mixtures were prepared in accordance with Table 1 and shaped into cylindrical specimens measuring 200 mm in height and 100 mm in diameter. These specimens were then allowed to harden and cure under standard temperature conditions, after which compressive strength testing was conducted in accordance with AS 1012.8.1:2014 [26]. Testing was carried out at curing ages of 7, 14, and 28 days, respectively, for each specimen.

2.6. Workability Test

The flowability of the mixed specimen was determined by conducting a slump test in accordance with the mixing conditions outlined in Section 3.5, with reference to AS1012.3.1:2014 [27]. To perform the test, the paste was poured into the upper split conical ring, and the flow table was then subjected to 25 strokes within a 15-second timeframe following the removal of the conical ring. The impact of the mixture's flowability on workability was investigated across various ratios of alkali-activated liquid to fly ash and % water in the alkali liquid.

3. Result and Discussion

3.1. Compressive Strength

3.1.1. Sodium Silicate (SS) to Sodium Hydroxide (SH) Ratio

The effect of reducing the ratio of SS to SH can be seen in Figure 3, where we end up with a weaker compressive result. Within the first 7 days of curing the gradient of the trendline is very steep as compared to the 28-day result. This means as time progresses the lower ratio of SS / SH has a greater strength realization.

After 28 days of curing, there is little difference between the highest compressive strength samples. Increasing the ratio shows that the compressive strength increases 66% from 1.25 to >1.5. This is due to the increase of sodium oxide content that occurs with higher concentrations of SS since sodium is the main requirement for the formation of geopolymers as it acts as charge-balancing ions. This result is in alignment with Hardjito [25] which shows an increase in SS results in the higher compressive result. Also, as the ratio decreases, an increase in SH is required. Whilst increasing the SH concentration yields higher compressive results, evidence [28] suggests a smaller effect of SH in the activator composition compared to the amount of SS used. A change in the SS gives a resultant change in the workability, compressive strength, and the setting time of the activated mix.

3.1.2. Alkaline Activator Liquid to Fly Ash Ratio

The effect of liquid to fly ash content in the concrete is changed by increasing the amount of alkali activator to the amount of FA that is used in the concrete mix. As per [19] conclusion, compressive strength decreases with increasing Liquid to Solid ratio and is due to the high liquid content attributing to the low strength because of the void volume caused by the liquid. Manaf et al [29] show a similar relationship in alkaline liquid to fly ash ratio and resulting compressive performance. The present experiment similarly concludes that the highest compressive results occurred with a 0.4 L/S ratio and a decrease in compressive strength as the liquid to fly ash ratio increases. In Figure 4 the results are depicted with ratios of 0.5 – 0.58 showing a lowering of strength due to high alkali activator producing an excess of hydroxide ions that was not needed in the reaction, hence weakening the polymerized structure.

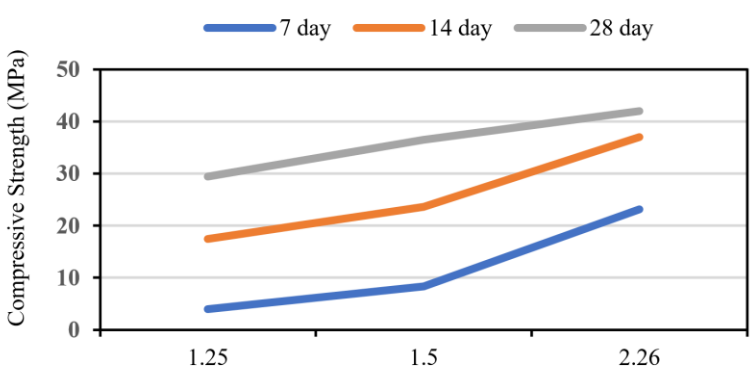


Figure 3. Compressive strength vs SS to SH ratio

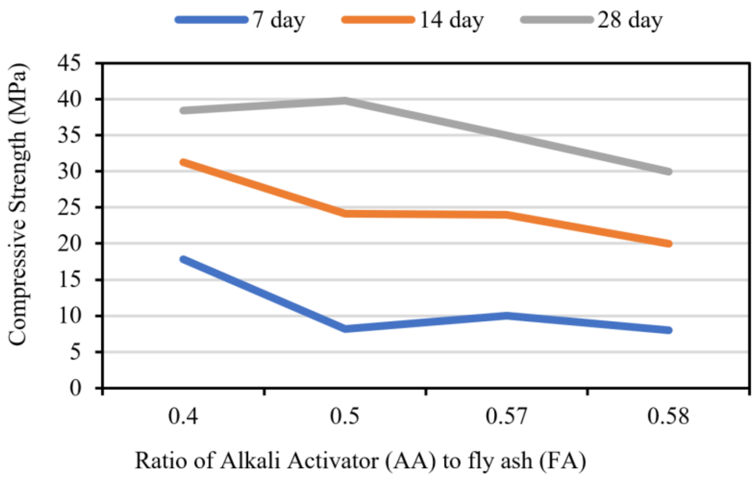
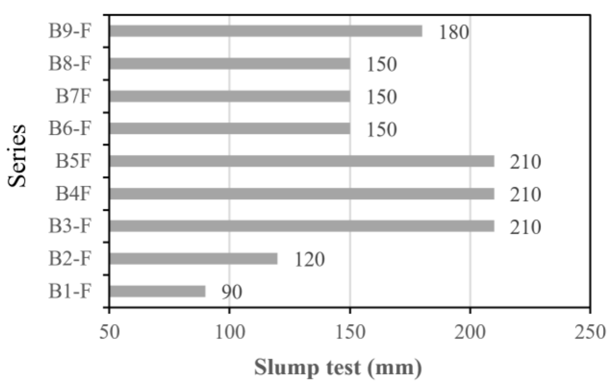


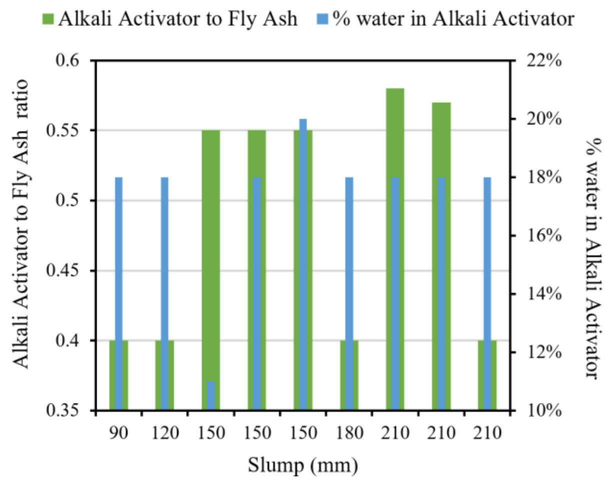
Figure 4. Compressive strength vs. Alkali Activator to FA ratio

3.2. Workability

The workability was measured with a slump factor. The slump test from the experiments allows us to visually inspect the workability of the concrete by the behavior of the shapes it takes. All of the results of the sample ranged between 90 mm and 210 m (Figure 5a), showing that the concrete had formed correctly and workable characteristics of ordinary concrete. This test gives an insight into what causes a different slump result based on differing the liquid to fly ash ratio. Looking at Figure 5b, the slump results are given with indicators of the relevant alkali activator to FA ratio on the right and also the % water in the alkali activator on the left. We can see there are instances of medium (17.5%) water used in the alkali activator and low (0.4) ratio of liquid to fly ash ratio but it still gave the highest slump value (210mm). Akin to results with the highest water % and highest liquid: fly ash ratio. This means there is no direct correlation between slump value and liquid: fly ash ratio, nor is there a direct correlation between slump value and % of water used in alkali activator. Within each of these specimens there is a chemical reaction occurring with differing values of water and liquid: fly ash ratios whilst being influenced by the SS / SH ratio leading to a wide range of results.



(a)



(b)

Figure 5. Slump test result (a) and slump test result vs Alkali Activator to FA and % water in alkali activator

The flowability is not so much based on the liquid to fly ash ratio nor is it based on the % of water in the alkali activator but is an aggregate of them both. In Australia, the minimum mm for good workability concrete in slump test is specified by the Australian Standard AS 1379 [30] - Specification and Supply of concrete. According to this standard, the minimum slump value required for good workability of concrete depends on the type of construction project and the method of placement. For example, for general-purpose concrete that is to be placed by vibration methods, a minimum slump value of 80 mm (3.15 inches) is recommended. For concrete that is to be placed by pumping, a minimum slump value of 100 mm (3.94 inches) is recommended. However, it's important to note that the exact minimum slump value required for good workability may vary depending on the specific mix design and aggregate type, as well as factors such as temperature, humidity, and the presence of admixtures.

Environmental factors such as ambient temperature, humidity, and other environmental conditions during the mixing and curing process can impact the geopolymerization reaction and influence the final properties.

4. Conclusions

The present study has confirmed that alkali-activated GPC using Collie derived Fly ash is not just a supplementary cementitious material, but the main raw component for the creation of a geopolymer binder is an effective construction material. This confirmation has surfaced due to the performance outcomes of compressive strength results showing the load and impact resistance of GPC, the good workability using slump tests, the ability to increase strength over time, and the inclusion of noncorrosive glass fiber reinforcement to further increase performance characteristics. By changing various ratios of Sodium silicate and Sodium hydroxide inputs, alkaline activator liquid to fly ash ratios, and moisture levels an optimum design mix is realized. It exhibits greater compressive strength performance than commercial-grade OPC.

In future studies, further testing of leachates is required to see what other ions and minerals can escape the geopolymer matrix. This is particularly important within a marine environment where an unbalance in the delicate ecosystem can occur if toxic minerals such as arsenic, lead, or mercury are allowed to enter the waterways. As performance is improved, production is scaled up and new applications will be proposed for the future of GPC implementation.

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